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Julien Renoult · Moreno Andreatta
Editors

Exploring Transdisciplinarity in Art and Sciences

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Preface

This book is based on the Rencontres Art & Sciences, an international event that brought together artists and researchers from various fields—cognitive neurosciences, evolutionary biology, music, mathematics and philosophy—all sharing an interest for questions relative to aesthetics, to perception and neurophysiological impact of artworks and the neural bases of creativity.

Exploring Transdisciplinarity in Art and Science raises questions on epistemological aspects inherent to crossing sciences with the arts. In experimental sciences, scientists carry out research in laboratory conditions, following Cartesian paradigms relying on conceptual, theoretical and operational standards. While they are designing experiments, collecting and analysing data, and facing critical reviewers to have their articles published, researchers continuously experience the delicate balance between meeting and exceeding these established standards and paradigms. The highly challenging research questions on the arts and their making are particularly prone to such an epistemological dilemma. How can we articulate the reductive but rigorous experimental procedure with a necessary evolution towards new paradigms that are simultaneously complex and open? Are artists also facing paradigms of their time? Or does engaging in the arts imply breaking free from constraining paradigms?

This book is organized into four parts. The first part deals with the creativity and its neural bases (Responsible Editor: Emmanuelle Volle) and gathers four chapters from world-renowned experts in cognitive sciences, neuroimaging, brain networks. These chapters attempt to address some of the most essential questions in the field of creativity from a neuroscientific perspective. These questions include: What is creativity? Can we measure the creativity of a production, of an idea, of a person? What are the cognitive mechanisms that underlie creative capacity? What are the relationships between creativity and semantic memory or the organization of our knowledge? How the brain allows the emergence of creative ideas? Are there different creativities for different domains, or for instance what can musical creativity tell us about the cognitive and brain mechanisms of creative abilities? What brain regions are associated with the generation of novel ideas? How do large-scale brain networks interact during creative performance? Although all answers are not elucidated, the recent advances in cognitive neurosciences related to these questions are presented and discussed in this part.

The second part concerns the neurophysiology of aesthetics (Responsible Editor: Zoï Kapoula). It covers a large spectrum of different experimental approaches including architectural creation and issues of architectural impact on the gesture of the observer. Neurophysiological aspects of the reception of artwork such as space navigation, gesture and body posture control are investigated in the experiments described as well as epistemological questions about terminology and valid methodology.

The third part contains studies on music, in relationship with mathematics, computer science and neuroscience (Responsible Editor: Moreno Andreatta). If music and mathematics share a long common history, the question can be raised about the singularity of the musical practice with respect to other artistic disciplines, such as literature, whose relationships with mathematics has been pointed out in the past by several members of the OuLiPo (Ouvroir de Littérature Potentielle). One chapter (the second one) reactivates this question within the perspective of the OuMuPo (Ouvroir de Musique Potentielle), an active group of musicians, composers and computer scientists suggesting new ways of making use of constraints in the artistic domain. The third chapter of the part shows how one can approach music improvisation by building computational models and creating interactive systems where musicians dialogue in a dynamic way with computers. The question of the link between computational musical models and brain activity is addressed by the very first chapter through the more general concept of data sonification. Recording and sonifying the brain activity not only shows the hidden rhythms of human neurons, but suggests that different families of neurons may be studied and characterized through their inner musicality, which opens new interesting perspectives in computational creativity.

The final part deals with evolutionary aesthetics (Responsible Editor: Julien Renoult). Recent findings on the neurobiology of the aesthetic experience have opened new perspectives on how aesthetics evolves and how artists have adapted to temporal variations in the aesthetic receptivity of people. The two chapters of this part present new paradigms for evolutionary aesthetics, which merge models of sexual selection, signalling theory and psychological investigations of the attractiveness of human faces, bodies and of artworks displaying them.

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Emmanuelle Volle is a Neurologist and an INSERM Researcher at the FrontLab team, ICM, Salpétrière hospital, Paris, France. Her current research is focused on the brain networks subserving complex cognitive functions, such as creativity, reasoning, problem-solving. She uses a variety of cognitive neuroscience methods, including human experimental psychology combined with functional imaging and functional connectivity, voxel-based morphometry, anatomical connectivity, with a particular interest in human neuropsychology and patient studies.

Julien Renoult is a Visual Ecologist and Evolutionary Biologist interested in the evolution of organic communication systems. He is mainly studying the role of animal perception as a selective agent of communication signals. In aesthetics, his research aims at understanding how the dynamics of neural encoding drives aesthetic preferences (efficient coding theory of aesthetics) in humans and other animals, and how natural and cultural signals exploit these preferences.

Moreno Andreatta is a Researcher specialized in the relationships between mathematics and music, specifically the algebraic and topological formalization of harmonic and rhythmic structures. A CNRS Research Director within IRCAM Music Representations Team, he is currently the Principal Investigator of the SMIR (Structural Music Information Research) Project supported by the University of Strasbourg Institute for Advanced Study and hosted by IRMA (Institut de recherche mathématique avancée). In parallel of his research activity, he pursues a career as a singer and pop-music composer.

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Keywords

The transdisciplinarity of the chapters is nicely reflected by the key elements of their titles. These are listed below as keywords:

Creativity, Creative cognition, Neurocognitive model, Creative capacity, Semantic networks
Creative brain, brain connectivity and network science
Creative brain, creative mind, creative person
Terminology and methodology issues on empirical aesthetics
Architecture and Fiction
Performative gesture, Art and Science aspects
Hearing and paintings
The gesture of space perception and navigation
Perception of 3D space
Visual perspective trough scientific and artistic disciplines
Visual perception of museum artefacts
Mathematical models of musical practice
Computer-aided Improvisations and interactive systems
Constraints in Music Composition
Music from neuronal activity
Expertise and evolutionary aesthetics
Evolutional theory and feminine beauty

Part I
Creativity and Neural Basis (Emmanuelle Volle)

Creative Brain, Creative Mind, Creative Person

Serena Mastria, Sergio Agnoli, Marco Zanon, Todd Lubart and Giovanni Emanuele Corazza

Introduction

Creativity is increasingly recognized as a key competency in professional and everyday life contexts. Several international survey studies of business (IBM 2010, 2012) and education (Adobe 2012a, b, 2016; World Economic Forum 2016) have highlighted high levels of interest in identifying creative potential and fostering its expression. Creativity refers to the ability to produce ideas, actions, or outcomes that are novel and original but also meaningful, relevant, and valuable in their context (Runco and Jaeger 2012). This basic definition can be enhanced by taking into account that there are different degrees of "novelty" and different facets of "value," and the appreciation of these characteristics may depend on context. The "holy grail" of research on the creative person has been and continues to be an

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integrated model that bridges brain functioning to the creative mind and creative behavior. This chapter will attempt to contribute to this effort, by reflecting on research on brain activity and creativity within a multivariate approach.

The Multivariate Approach

More than a century of work on creativity has examined the nature of creative people, their characteristics—their particular cognitive abilities, personality traits, motivations, and emotions. The earliest work looked at creative geniuses, through case studies. For example, Binet investigated several great writers including Emile Zola, and Freud conducted an in-depth study of Leonardo da Vinci. Numerous correlational studies followed, looking at more everyday samples of people engaged in jobs that required creative thinking (such as architects, writers, artists, engineers) or general samples of people who could show creativity during general problem-solving situations. By the 1980s, a rich set of individual difference variables including cognitive abilities, personality traits, cognitive styles, motivations, and affects had been identified as relevant to creativity (Barron and Harrington 1981). It became clear, however, that a model was needed to organize the findings and to clarify how these variables fit together. In this context, several componential theories emerged (Lubart 1999). In general, creativity is conceptualized as a complex activity that requires a particular combination of factors. Several of these factors are "person-centered," such as intellectual abilities, personality traits, and emotional styles. However, there are also contextual factors, expressed in the environment in which an individual lives and works.

The nature of the factors and their possible interactions vary according to the specific theory proposed. For example, for Amabile (1996), there are three underlying components for creativity: motivation, capacity in a field, and skills related to creativity. Motivation encompasses the intrinsic and extrinsic reasons why an individual engages in a task and the attitude of a person toward the task to be accomplished. Capacities in a field refer to knowledge, technical abilities, and particular talents. For example, in the field of science, there may be knowledge about a specific problem, technical abilities for laboratory procedures, and a special talent for mental imagery. Creative skills include a cognitive style that makes it easier to cope with the complexity knowledge of heuristics to generate new ideas, and a perseverant style when engaged in a task. Creativity skills are considered to apply to all tasks, whereas field-defined capacities and motivation are more task-specific. The level of a person in these three components determines his or her creativity. If one of the components is absent, creativity cannot be exercised.

According to the multivariate approach to creativity, developed by Sternberg and Lubart (1995) and Sternberg (2005) and then extended by Lubart and collaborators (Lubart et al. 2015), several distinct types of resources are needed for creativity. These resources are specific aspects of cognition, conation, emotion, and the environmental context. Table 1 lists some examples of each resource.

Table 1 Exemplary list of resources from the multivariate approach

Multivariate resource for creative potential	Examples
Cognition	Abilities (e.g., mental flexibility, analogical–metaphorical ability, associative ability) Knowledge (e.g., rich, diverse knowledge base)
Conation	Personality traits (e.g., risk taking, tolerance of ambiguity) Motivation to create (e.g., intrinsic motivation, need for achievement, curiosity drive)
Emotion	Rich affective life (e.g., emotional idiosyncrasy, affect intensity) Mood states (e.g., positive mood during divergent thinking)
Environment	Stimulating physical world (e.g., books, museums available) Stimulating social context (e.g., multicultural setting)

As for the confluence of resources, there is more than the simple additive result of the level of an individual for each resource component. Some components may have thresholds (such as knowledge) below which creativity is impossible. There may be partial compensation between components: A strong component (such as motivation) may counterbalance the weakness of another component (such as knowledge). A component always acts in the presence of other components, and this interaction can have interactive effects. For example, high levels of intelligence and motivation can have a multiplier effect on creativity.

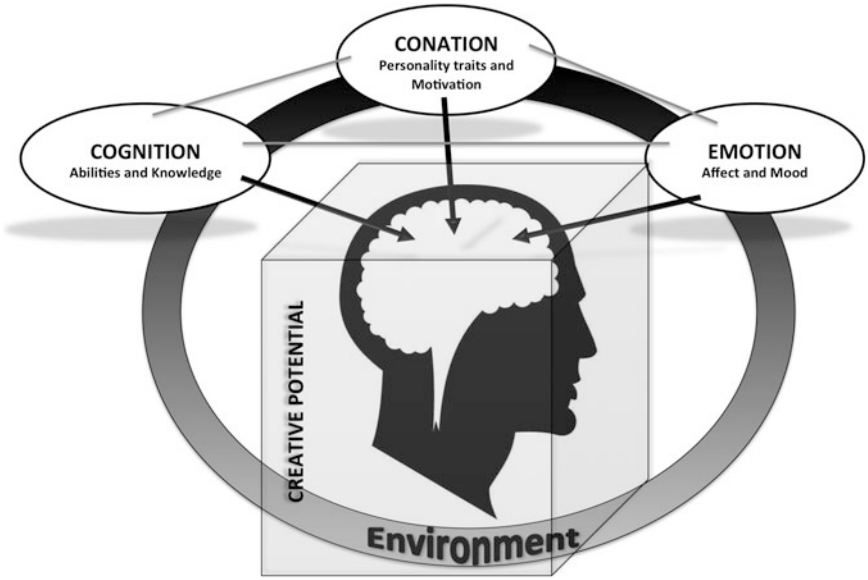

Fig. 1 Schematic representation of the multivariate approach to creativity

According to the multivariate approach (see Fig. 1 for a schematic representation), creativity depends on cognitive, conative, emotional, and environmental resources. Each person has a particular profile on these different resources. This profile may be more relevant to the requirements of a given task within a certain area. Thus, the creative potential of an individual in various fields of activity results from the interactive combination of the different factors related to the characteristics needed for creative work in that field or specific activity. We focus on creative potential, which is a latent state referring to that which could be expressed. Through the work process (the creative process), creative potential is deployed and expressed in productions. These productions will be more, or less, original and valuable, as judged within the social context.

Productions reflect the potential, which has been catalyzed during the creative process. This creative process can itself be described through two main modes of thinking and acting. The first is divergent-exploratory action, which is expansive by nature, leading to many ideas or paths from an initial starting point. The second, complementary mode is convergent-integrative action, in which several elements are brought together in a new whole, a synthetic form of thought and action.

Neuroscience of Creative Cognition: An Approach Looking for a Theoretical Framework

The neuroscientific study of the creative behavior, and in particular of creative cognition, has produced in the last two decades a number of results on the dynamics and organization of the cerebral structures subsuming the creative process. Neuroscience in particular provides an embodied foundation to creative behavior. Through the exploration of the underlying neural structures, neuroscience reveals that creative thinking is driven by basic cerebral interconnections between areas associated with specific cognitive functions. Monitoring the brain activity during the execution of a creative task, or during creative behavior in general, allows to highlight the cerebral interconnections between areas associated with specific cognitive functions as well as the temporal dynamics within specific brain regions. Clearly, a neuroscientific experimental approach to the study of creativity must be interpreted in light of an in vitro approach to a complex behavior for which the in vivo experience is importantly affected by the environment. However, scientific rigor and replicability are essential in order to advance our knowledge efficiently.

Notably, the results produced by neuroscientific studies that aim at identifying possible brain mechanisms related to creative thinking are sometimes difficult to compare, to the point that the lack of agreement in brain regions associated with creativity across different studies has been defined as “striking” (Arden et al. 2010). This difficulty stems presumably from two main problems: the variety of methodologies used to detect neurologically creative behavior (that produced outputs of a different nature) and the difficulties in operationalizing creative performance during neurological measurements (Dietrich and Kanso 2010). Neural correlates of creativity have been indeed explored by different brain imaging techniques, varying from electrical signals (electroencephalography, EEG; Razoumnikova 2000), blood oxygen levels (functional magnetic resonance imaging, fMRI; Ellamil et al. 2012; Takeuchi et al. 2012), cerebral blood flow (regional cerebral blood flow, rCBF) to brain metabolites (magnetic resonance spectroscopy, MRS; Arden et al. 2010; Sawyer 2011). There is considerable heterogeneity of findings across studies of creative cognition conducted with all these different methodologies, which renders it difficult to interpret and integrate their results. Recent quantitative meta-analyses, investigating neuroimaging studies on creativity, tried to combine the variety of these results (Gonen-Yaacovi et al. 2013; Wu et al. 2015; Boccia et al. 2015). These works have suggested that diverse creative tasks share the activation of similar brain regions, including frontal and parietotemporal areas, and that some specific brain regions are dedicated to distinct kinds of creative thinking processes. In particular, whereas the ability to combine ideas creatively involves rostral brain regions, the free generation of novel ideas engages more posterior brain areas (Gonen-Yaacovi et al. 2013). Similarly, musical, verbal, and visuospatial domains of creativity seem to involve the activation of functionally specialized different brain regions, with clusters of bilateral activations ranging from the occipital to the frontal lobe (Boccia et al. 2015). As highlighted from these meta-analyses, a variety of brain regions as well as of cerebral activities emerged as being involved in creative behavior, testifying the multidimensional nature of the creativity phenomenology not only at a behavioral level but also at a cerebral level. For example, fMRI or Positron Emission Tomography (PET) studies suggested increased activation in frontal (right medial frontal gyrus and dorsal lateral prefrontal cortex; Howard-Jones et al. 2005; Kowatari et al. 2009), temporal (right superior temporal gyrus; Jung-Beeman et al. 2004; Mashal et al. 2007), and limbic regions (left anterior cingulate; Fink et al. 2009) during the execution of different creative cognitive tasks. Similarly, neuroscientific studies on creativity using EEG associate different frequency bands with creative cognition, from very low-frequency delta/theta (Bhattacharya and Petsche 2005), alpha (Fink and Benedek 2014), to beta (Sheth et al. 2009) and gamma (Jung-Beeman et al. 2004; Sandkuhler and Bhattacharya 2008) oscillations. Despite the fuzzy picture emerging from these EEG studies, the involvement of alpha oscillation seems to be particularly consistent with various processes involved in creative idea generation, which has been interpreted as reflecting top-down activity, as we will describe in the following section (Fink and Benedek 2014).

A pressing problem emerging in neuroscientific studies seems to derive from the apparent lack of a theoretical framework to interpret the heterogeneity of data emerging from research: indeed, a model of the creative process would be instrumental in integrating the large body of neuroscientific findings. This necessity seems today particularly important because the neuroscientific approach to creativity reached in these years a significant level of maturity to establish some results as robust within the plethora of findings concerning the exploration of the creative brain. In this chapter, we try to make some initial steps in this direction. The replication and replicability of specific effects in the EEG and fMRI study of creative cognition allow reliable conclusions to be drawn about the functioning of the brain during a creative task. Starting from these results, we will organize the emerging data in light of the multivariate approach (Lubart et al. 2013; Sternberg and Lubart 1996). This theoretical model will serve to structure the neuroscientific data under a single framework, and allow us to provide a coherent picture of the neurological phenomenology of creativity. We will in particular concentrate our analysis on the data emerging from fMRI and EEG research, because of the proven reliability of results emerging from the use of these two methodologies in the study of creative behavior. fMRI has the advantage of high spatial accuracy, allowing to explore the involvement of specific brain regions and networks in the creative behavior at both cortical and subcortical levels. EEG allows fine-grained temporal analyses in brain activation while performing a creative task. Beside the most recent neuroscientific results on the creative brain extracted from the literature, results derived from a project[1] devoted to the mapping of the brain structures associated with creative behavior will also be reported.

Neuroscientific Evidence for the Multivariate Approach to Creativity

Following the multivariate approach (Lubart et al. 2013), creativity is considered to be an ability, which emerges from a dynamic interaction between cognitive, conative, and environmental factors in relation to goal-directed tasks. In other words, the level of "creative potential" of an individual depends on which cognitive (and conative) resources are engaged by the task at hand. This is in line with a dynamic definition for creativity as potential originality and effectiveness (Corazza 2016). Interestingly, it seems possible to find a correspondence between the multivariate view of creative potential and the neuroscientific results concerning creativity. Studies investigating the neural mechanisms underlying creative thinking have employed a wide variety of experimental contexts, producing highly diversified results (see Dietrich and Kanso 2010 for a systematic review). Despite their heterogeneity, data on the neural substrates of creative thought can be organized as a function of the nature of the processes involved in a specific task, in this way exploiting as a conceptual guideline the multivariate model of creative potential (Lubart et al. 2013). Therefore, in the present chapter, recent neuroscientific findings on creativity will be organized following the components specified by the multivariate approach to creativity. We will discuss in order: (i) cognitive factors, focusing on neuroscientific evidences on divergent thinking and assessment, as well as on convergent thinking and insight; (ii) conative factors, considering results on the brain structures subsuming creative personalities, and exploring the influence of emotion and motivation on creative performance; and (iii) environmental factors,

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defining the role of domain specificity on cerebral structures and activities. Finally, we will focus on understanding the ways by which neuroscientific methods may enhance the individual's creative potential, focusing on studies which investigate the enhancement of cognitive factors underlying creativity via brain stimulation techniques.

Cognitive Factors

Divergent Thinking and Assessment

Focusing on a specific modality of creative thought, a number of fMRI studies have confirmed that divergent thinking tasks engage diverse and separate patterns of brain activity as a function of the cognitive processes involved (e.g., working memory, executive attention; see Beaty et al. (2016) for a detailed description). Divergent thinking can be specifically defined as the ability to generate many possible solutions to an open-ended problem, in other words, the mind "*goes off in different directions*" (Guilford 1959). One of the most popular tasks used for the assessment of divergent thinking performance is the Alternative Uses Test (AUT; Guilford 1967), in which participants think of many diverse uses for an common object (e.g., "bottle"). The resulting outcomes are generally assessed in terms of fluency (i.e., number of generated ideas), flexibility (i.e., number of different categories), and originality of ideas (Guilford et al. 1978). It is worth noting that prototypical divergent thinking tasks (e.g., AUT) have to be adapted according to the constraints of the neuroscientific approach (i.e., timing, response modality). This may raise concerns about the full ecological validity of the experimental paradigms used in neuroscientific laboratory, as they cannot be translated to ''real-life'' creative behavior. However, currently these adapted versions of the AUT (Guilford 1967; Fink et al. 2007, 2009) constitute the best way to explore brain correlates underlying divergent thinking.

In order to obtain a coherent overview, it is reasonable to look at the increasing body of neuroscientific research focusing on: (i) studies in which different experimental paradigms were used to discriminate between diverse cognitive processes (e.g., memory, attention) underlying divergent thinking and (ii) studies that differentiate between different processing stages (e.g., idea generation, idea evaluation) that are presumed being involved in divergent thinking. Depending on the degree of goal-directedness of a specific divergent thinking task, a different level of cooperation between the *default* and *executive control* brain networks has been found. To briefly introduce these networks, the default network, which includes the medial prefrontal cortex (MPFC), posterior cingulate cortex (PCC)/precuneus, and temporoparietal junction (TPJ), seems to be mainly engaged in self-generated thought, possibly derived from long-term memory (e.g., Benedek et al. 2014; Fink et al. 2009); on the other hand, the executive control network, which comprises the dorsolateral prefrontal cortex (DLPFC) and dorsal anterior cingulate cortex (dACC), is specifically recruited during conditions of high cognitive control, such as strategic and/or controlled functions (i.e., directed attention, working memory, and relational integration; see Desimone and Duncan 1995; Miller and Cohen 2001). In divergent thinking, the spontaneous generation of candidate ideas, which entails the involvement of episodic memory retrieval and mind wandering (Mason et al. 2007; Buckner et al. 2008; Gruberger et al. 2011; Christoff 2012), shows greater activation of the default network, compared to the executive control network. The key role of the default network was clearly observed during a task in which participants were asked to spontaneously generate novel ideas, in contrast to the mere recollection of old ideas from memory (Benedek et al. 2014). In a similar vein, generating alternative uses for a given object (i.e., the AU task), compared to simply naming ordinary characteristics for an object (i.e., the OC task), was associated with the activation of the angular gyrus (AG), and the medial prefrontal cortex (PFC), brain regions which are critically involved in the default network (Fink et al. 2009). Divergent thinking tasks not only require generative processes, but also cognitive control systems, in particular to achieve high levels of attentional focus and flexibility. In other words, creative thought at some level needs to involve strategic functions in order to meet specific task demands, such as category switch or focus control. The dynamic functional connectivity between the executive control network and the default network in highly creative individuals has been reported in a number of neuroimaging studies (e.g., Beaty et al. 2015). A recent study used an Alternative Uses Test in order to understand how such opposing default and control executive networks cooperate (or compete) with each other in the brain. Temporal connectivity analysis revealed strong cooperation between the default and executive control networks particularly at the end of the divergent thinking process, possibly reflecting the engagement of controlled functions at later stages of the ideation process (Beaty et al. 2015).

The contribution of default and executive brain activity varies not only as a function of the specific mental process underlying a given divergent task, but also as a function of the specific processing stage (e.g., idea generation, idea evaluation) involved in creative thinking. In general, idea generation involves the production of new ideas, which is associated with diffuse attentional resources, whereas idea evaluation includes the ability to assess the originality and usefulness of an idea, which involves focused and controlled attentional resources. A recent fMRI study employed an interesting experimental procedure in which it was possible to distinguish between generative and evaluative components of creative thought, asking participants to draw and/or write down their ideas or their evaluations in different time periods. Results revealed that the creative generation period was mainly associated with the activation of medial temporal brain regions (i.e., default network), whereas creative evaluation was related to the coupling activity of default and executive brain areas, as well as limbic regions, reflecting top-down and affective information processing (Ellamil et al. 2012). From the above neuroimaging results, it seems clear that the default and executive brain networks play a central role in creative divergent thinking, and their distinct contributions to the diverse components of creative thought seem to be in line with the multivariate approach of creativity.

The involvement of specific networks of brain structures in divergent thinking emerges also from EEG studies on creative cognition. Particularly, EEG research, similarly to fMRI studies, shows multicomponential brain activity in association with divergent thinking, but with significant differences. EEG signals represent oscillations across a wide band of frequencies, divided usually in specific frequency bands; in particular, changes in the alpha band (8–12 Hz) have been found to be specifically related to higher cognitive abilities such as divergent thinking (Fink and Benedek 2014; Neubauer and Fink 2009). This frequency band emerged to be particularly important in distinguishing between different components of creative thinking. Among other, event-related alpha synchronization (i.e., event-related power increase above a reference in the alpha band) has been indeed demonstrated over the frontal and posterior cortical sites in divergent thinking conditions. This result is now a quite stable effect in the study of creative thinking, although a controversy has been associated with its functional significance. Initially, the association of a task-related decrease in alpha activity in a number of cognitive tasks led to the assumption that alpha activity is related to a cognitive default state (Pfurtscheller et al. 1996), reflecting reduced active information processing in the neural network (Pfurtscheller and Lopez da Silva 1999). Contrasting data showing task-related increase of alpha activity during cognitively demanding tasks (e.g., Jensen et al. 2002; Klimesch et al. 1999) suggests instead a more active role of this activity in brain functioning, proposing that alpha activity reflects attentional processing and it is higher for tasks with an internal attentional focus than for tasks with an external focus. It was indeed suggested that the increase in alpha activity may reflect active top-down inhibition of task-irrelevant brain functions, such as the inhibition of long-term semantic memory or irrelevant visual stimuli (Jensen et al. 2002). This top-down active inhibition reflects data from fMRI studies, highlighting again the complex activity related to divergent thinking. Interpreting these data in light of the multivariate approach, EEG findings suggest that not only creativity relies on different components, but also that these components, such as divergent thinking, are themselves composed of a set of activities in different brain regions subsuming a dynamic activity under the control of the creative focus which acts as a strong controller of the process itself. As shown in a recent study by Benedek et al. (2014), the increase of alpha activity over the parietal regions (in particular in the right hemisphere) might be associated with the strength of task-focused attention rather than reflecting only the direction of the attention (internal vs external). According to this interpretation, alpha increase in the right parietal region might be read as an indicator of the depth of an ongoing mental imagination process, representing therefore a valid indicator of the cognitive process specific for creative cognition and in particular for divergent thinking (Benedek et al. 2014). The reason why alpha activity during divergent thinking is more pronounced in the right than in the left posterior parietal regions is today a question that still needs to be answered. This represents indeed a classical effect associated uniquely with the creative process. The different interpretations of this result, however, could bring some valid insights in the understanding of the creative process, which could shed light on the components involved in the creative process as suggested by the multivariate approach. Starting with Martindale (1999), the right hemisphere has been suggested to be related to a parallel or holistic processing mode, in contrast to the more sequential and analytical mode of the left hemisphere. More recently, the left hemisphere has been associated with fine semantic coding processes, whereas the right hemisphere seems to be associated with a more sketchy semantic coding characterized by a diffuse activation of alternative or more distant associations (Bowden and Jung-Beeman 2003; Fink and Benedek 2014). This function of the right hemisphere seems therefore to be particularly important in divergent thinking, which is indeed the ability to generate many alternative solutions in the search of the most original one.

Further data coming form EEG research highlighted, in line with the multivariate approach, that ideation is not an isolated phase in the creative process but that it works dynamically in joint action with other components, such as the evaluation of ideas. Hao et al. (2016), in particular, demonstrated that the iteration between idea generation and idea evaluation helps to develop ideas. They demonstrated that reflecting on generated ideas was associated with a strong increase in alpha activity, most prominent in the frontal region. This activity could be related to the absence of a stimulus-driven, external bottom-up stimulation, or rather, to a top-down activity driven by internal attention. This effect and this interpretation are in line with fMRI results (Ellamil et al. 2012) which demonstrated that idea evaluation was associated with a joint activity of default and executive network regions. Interestingly, Hao et al. (2016) demonstrated that after a period of idea evaluation, subsequent idea generation was associated with an increase of alpha activity in the frontal regions compared to a pre-evaluation period. As theorized by the multivariate approach, this finding seems to suggest a dynamic interaction between different components of the creative process, and specifically, that idea evaluation might iteratively influence idea generation by enhancing a top-down activity in subsequent idea generation and inhibiting the retrieval of common, typical information (Hao et al. 2016).

Convergent Thinking and Insight

The main difference between divergent and convergent thinking processes is that in the former we explore many possible solutions to generate creative ideas, whereas in the latter we need to converge to a unique solution (possibly creative) for a given problem. A specific form of creative thinking is *insight*, often described as a subjective “Eureka!” or “Aha!” experience (Schooler et al. 1993). Insight leads to a sudden identification of the solution to an ill-defined problem. In this sense, insight is a creative behavior that leads to a solution, which is not necessarily creative per se. The role of insight in creativity research has been widely discussed, as the feeling of insight is extremely subjective and is not necessarily the most important determinant in problem solving. Problems can be indeed unraveled through different strategies, such as deliberate research schemes or retrieving old memory information, which gradually lead to the right solution. The achievement of a successful solution involves a number of integrated mental processes, such as restructuring the problem state, verbal associations, or linking to a semantic network that might eventually generate distant or remote associations and consequently trigger the right solution. Within the multivariate model of creativity, Robert Sternberg (2005) distinguished three types of processing phases in creative insight: (1) *selective encoding* that selects the important information, filtering out the irrelevant ones; (2) *selective combination* that keeps in mind significant information in order to combine it in a new point of view; and (3) *selective comparison* that links new information with old knowledge.

In the field of neurosciences, the investigation of insight is delicate, due to the difficulty to elicit many insight trials in a limited time period. The necessity of isolating the specific instant in which insight occurs in the mind, keeping monitored antecedent processing stages, seems also to be crucial. Despite these theoretical and operational constraints, a number of brain imaging studies have focused on the role of insight in creativity, revealing the neural correlates sustaining such a process. In order to clarify these findings, we take into account the specific information-processing stage involved in a particular convergent thinking task. In fact, consistent with the multivariate approach, differences between patterns of brain activation are highly associated with diverse types of processes required in the given problem-solving task. When participants were asked to restructure a problem in a new way, which is considered a key element in insight solutions, the involvement of the prefrontal cortex (PFC) was consistently observed (see Dietrich 2004 for a detailed review). For example, presenting participants with couples of incomplete sentences followed by different solutions, the highest activation in the lateral PFC was observed during insightful difficult solutions, compared to non-insight solutions (Qiu et al. 2010). Rearranging a problem into a new perspective as well as judging which insights are the correct ones during the whole process requires the contribution of higher cognitive functions, including sustained attention and memory retrieval, which are directly controlled by the prefrontal cortex activity. Some researchers stress the importance of temporoparietal regions in insightful problem solving (Bechtereva et al. 2004; Kounios et al. 2006; Starchenko et al. 2003), particularly the superior temporal gyrus (STG) in mediating semantic processing and facilitating the creation of remote associations (Jung-Beeman et al. 2004). The activation of bilateral temporal cortex seems to be also associated with the mental preparatory period before insight events, rather than non-insight mental preparation (Kounios et al. 2006). Comparing insight with the analytical search of solutions in the same remote associate task (RAT; a task requiring to find the word which is somehow associated with a triplet of words), heightened activation of the right anterior STG only for insight solutions was observed (Jung-Beeman et al. 2004). These results have been extended to other kinds of problem-solving tasks, such as anagram problems, demonstrating that evaluating insight problems, compared to search strategies, showed specific activation in the right ventral PFC (Aziz-Zadeh et al. 2009). In fact, it has been argued that whereas deliberate search strategies are principally controlled by the frontal lobes, spontaneous insight events are associated with the integrated activity of the frontal cortex, the temporal, occipital, and parietal areas (Dietrich

2004). Other brain regions seem also to be involved during insightful problem solving; for example, an activation of the right hippocampus during the "aha" experience when right answers to Japanese riddles were given has been demonstrated (Luo and Niki 2002). Instead, when participants were asked to be active researchers rather than passive receivers of correct solutions, results revealed the contribution of precuneus during the retrieval of successful prototype events, left inferior medial/frontal gyrus in forming new connections and disrupting mental sets, and inferior occipital gyrus and cerebellum during the reorganization of visual events and the distribution of attentional resources (Qiu et al. 2010).

Similarly, results emerging from EEG research demonstrate the multidimensional nature of the insight phenomenon. Even if insightful solutions occur suddenly and abruptly, EEG studies indicated that insight is not the product of a sudden process. On the contrary, as theorized by Sternberg (2005) the brain mechanisms underpinning insight are characterized by a specific temporal dynamic. Sankühler and Bhattacharya (2008) described well the EEG correlates under the insight phenomenon. Specifically, four phases in insightful convergent thinking have been identified, each characterized by different brain correlates. The first element of insight emerging from the analysis is the mental impasse, characterized by the activation of the gamma frequency band in the parieto-occipital brain regions. This activity has been explained in terms of an excessive attentive focus on inappropriate problem representations. In insight-like problems, the internal attentional demand is highly charged by unsuccessful solutions that must be stored in working memory (in order to avoid their repetition over time). Because working memory is limited, attention serves as a gatekeeper that, however, could potentially cause a mental impasse, because of an overload (Sankühler and Bhattacharya 2008). The second phase characterizing insight is a deeper understanding, which helps in identifying the correct solutions. Also in this phase, brain activity was associated with gamma activation in the parieto-occipital brain areas, however at lower frequency than in the previous phase. The lower gamma band activity in the temporoparietal regions appears therefore to be related to higher performance in insight problems. The following phase in the process requires a restructuring of the problem. This phase has been associated with an alpha band activity in the right prefrontal region. The prefrontal cortex is also highly associated with the planning of open-ended problems, and therefore the conscious restructuring of a problem. The final phase of the insight process is the suddenness of the solution, which, once again, showed a gamma frequency band activity in the parieto-occipital areas. This activity, which appears immediately before the solution response, has been associated with the conscious retrieval of the correct solutions from memory. The finding and production of a correct response was found in EEG research to be a complex process, involving a number of integrated cerebral processes, in line with Sternberg (2005).

Conative Factors

Creative Personality

The typical profile of highly creative individuals is to be socially undesirable, rebellious, introverted, or impulsive (see, e.g., “the dark side of creativity”; Cropley 2010). In extreme cases, creative people may suffer serious mental disorders. The general hypothesis is that creative people and psychotic patients share some cognitive processes, including preferential processing of competing sources over task-relevant information, disorganization of thought, generation of unusual, novel, and distant associations. Moreover, high levels of creativity have been associated with latent disinhibition (Carson et al. 2003; Fink et al. 2012), which is a key trait in psychopathology.

The link between creativity and a number of psychiatric disorders, such as schizophrenia, bipolarity, autism, and anorexia nervosa, has been suggested in a series of neuroscientific studies (e.g., Kyaga et al. 2011, 2013). At the behavioral level, a high level of creativity is positively associated with unusual experiences and impulsive non-conformity, which are two specific traits involved in schizotypy (Batey and Furnham 2008; Claridge and Blakey 2009). Similarly, it has been demonstrated that artist samples showed high level of schizotypy as well (Nettle 2006; Nelson and Rawlings 2010). At the neuroscientific level, creativity and schizotypy traits seem to show similarities in brain activity patterns, supporting the hypothesis that these two personality type profiles share similar cognitive processes. One of the first attempts to investigate this relationship comes from an fMRI study in which high schizotypal individuals were compared to low schizotypal subjects during the performance of an alternative uses (AU) task (Fink et al. 2014). Results indicated that the high-schizotypy group showed reduced deactivation of the right precuneus, which is critically involved in attending to environmental information (Corbetta et al. 2008). Likewise, more creative people showed weaker deactivation of the right parietal brain region and the precuneus, consistent with the general idea that similar cognitive processes may be involved in psychosis and creativity.

Creative people have also “positive” characteristics, comprising wide-ranging interests, desirability, self-confidence, or openness. The basic personality trait of openness to experience seems to play a crucial role in defining a creative profile. A recent study exploring the association between brain anatomy and creativity revealed that, compared to other personality factors (i.e., extraversion, conscientiousness, and agreeableness), openness to experience was the only personality trait of creative individuals that moderately mediated the association between the regional gray matter volume (rGMV) of the right posterior middle temporal gyrus (pMTG) and trait creativity. These results suggest that openness might play an essential role in modeling an individual’s trait creativity (Li et al. 2015).

Creativity, Emotion, and Motivation

In the context of creative cognition, the important role of *emotion and motivation* in modulating creative behavior has been stressed. Brain motivational systems are particularly relevant as creative individuals show greater baseline levels of arousal and stronger response to sensory stimulation (Martindale 1999). Moreover, high levels of motivation are associated with a proportionally high number of novel and useful ideas. Literature examining emotional and motivational influences on creativity has mainly focused on the impact of mood states of individuals on different aspects of creative performance (for a detailed review, see Baas et al. 2008). In particular, the beneficial role of positive mood on creative problem solving has been emphasized (Ashby and Isen 1999; Baas et al. 2008; see Isen 2000 for a review), with a greater number of responses in the AUT (Phillips et al. 2002), higher level of inhibition of dominant responses (van der Stigchel et al. 2011), more flexibility and greater attentive focus (Compton et al. 2004), and enhanced ability to exclude irrelevant information (Dreisbach and Goschke 2004). However, another line of research highlights that negative mood can have a facilitative influence on creativity (see Kaufmann 2003, for a review). For example, the frequency score on creative tasks can be enhanced by negative mood, particularly during tasks requiring concentration, detailed execution, divergent thinking, and analogical problem solving (Abele-Brehm 1992; Jausovec 1989; Kaufmann and Vosburg 1997). In fact, it seems that both positive and negative high arousal moods may enhance creative performance, compared to low arousal positive and negative moods (e.g., Agnoli et al. 2018a; De Dreu et al. 2008). The nature of these contradictory results in this field of research seems to stem from the difference of the explored emotional experience, as well as from the type of creative task used to measure creative performance.

One of the few neuroscientific studies in this field investigated whether the participant's performance to an AU task could be enhanced after previous cognitive and affective stimulation (compared to a control condition), focusing on EEG alpha changes. Specifically, creativity was stimulated via the exposure to other people's ideas (i.e., cognitive stimulation) and via the presentation of emotional sounds (i.e., affective stimulation). Similar to previous studies (e.g., Fink et al. 2009), results revealed that creative idea generation was associated with enhanced alpha synchronization in the prefrontal cortex and right hemisphere, and alpha desynchronization in left parietal and temporal brain regions. Compared to the control condition, both experimental stimulations (affective and cognitive) prompted stronger prefrontal alpha activity, and this was interpreted as reflecting enhanced internal awareness (Fink et al. 2011). In line with this view, an fMRI study demonstrated a facilitative effect of participant's high positive mood, compared to low positive mood, in solving problems with insight, as reflected in different patterns of brain activity during preparation periods preceding each task (Subramaniam et al. 2009). Overall, evidence suggests that the relationship between affect and creativity could be explained not only considering the influence of positive and/or negative moods, but also examining the level of general activation (i.e., arousal).

Environmental Factors

Domain Specificity

Among others, there are also contextual factors, expressed in the environment in which an individual lives, which contribute to the definition of creativity (Lubart et al. 2013). At the neuroscientific level, the influence of the context has been explored asking participants to perform more ecological creative tasks related to diverse symbolic domains, such as artistic, scientific, or other professional domains. In this sense, the domain setting may help us to better understand the contribution of environmental factors on creativity. An increasing number of fMRI studies used complex, “real-life” creative tasks with creativity-related samples (i.e., artists, scientists, musicians; see, e.g., Bhattacharya and Petsche 2005; Chávez-Eakle et al. 2007). The main advantages of this approach are to investigate the neural underpinnings of specialized creative cognition and to conserve the complexity and ecological validity of creative performance. In general, neuroimaging results revealed that different knowledge domains engaged a cooperation between different neural networks, including both controlled and spontaneous processes, consistent with the multiple creative styles idea proposed by Stenberg (2005). Although other domains have been widely investigated, including poetry (Liu et al. 2015) and visual art (Ellamil et al. 2012), most of the studies focused on the brain networks involved in musical improvisation. For example, one of the first fMRI studies compared improvisation and memory retrieval of a novel melody in a group of professional jazz musicians (Limb and Braun 2008). Results revealed that, compared to memory retrieval, improvisation engaged a distributed set of brain regions, including left inferior frontal gyrus (IFG), anterior cingulate cortex (ACC), and the medial prefrontal cortex (MPFC), with a deactivation in frontal areas, including the dorsolateral prefrontal cortex (DLPFC). These data were interpreted as reflecting internally driven mechanisms as well as disinhibition of conscious monitoring processes (Limb and Braun 2008; see also Bengtsson et al. 2007 for similar results). A similar experimental procedure was used with a group of professional freestyle rap artists, showing that vocal improvisation, compared to a simple memory retrieval, was related to the activation of supplementary motor area (SMA), dorsolateral premotor cortex (PMD), MPFC, and left IFG. Moreover, similar to Limb and Braun (2008), in this study a deactivation in DLPFC was observed (Liu et al. 2012). Overall, these findings suggest either activation or deactivation of brain networks associated with executive control mechanisms depending on the degree of cognitive control required during the improvised performance. Interestingly, with practice, some of these processes could be automatized in order to facilitate idea generation (Pressing 1988). Studies investigating the role of experience in improvisation showed deactivation of the right temporoparietal junction (TPJ) and other executive control brain regions in expert musicians (Berkowitz and Ansari 2010) and pianists (Pinho et al. 2014), compared to non-experts. The basic idea is that when expertise increases, processing demands should be minimized, and consequently attentional resources are free to focus on the overall performance monitoring. A deeper understanding of the role of experience in complex mental abilities was investigated in an EEG study in which a group of professional dancers, with high level of ballet expertise, was compared with a group of novices, with only a basic experience in ballet (Fink et al. 2009). Groups were required to perform different tasks in the dance domain that varied from high to low level of creative demands. EEG was used to compare alpha brain activity between professional dancers and novices during task performance. Results revealed that differences between these two groups emerged only when participants were asked to perform a creative task (i.e., mentally perform a new and original dance), showing a more right-hemispheric alpha synchronization in professional dancers compared to novices. According to the general alpha synchronization hypothesis (Sauseng et al. 2005; Klimesch et al. 2007), this result may be interpreted as reflecting a mechanism of inhibition (or suppression) of external bottom-up information and a more pronounced top-down activity. Overall, in line with the concept of multiple creativities (Stenberg 2005; Lubart et al. 2013), these results demonstrated the existence of different patterns of brain activity related to diverse groups of experts who are involved in diverse forms of contextualized creative domain-specific knowledge, including artistic and scientific backgrounds.

As theorized by the multivariate approach, domain specificity emerged in neuroscientific research as a central component in the definition of the creative process. This finding emerged from a number of studies which explored domain-specific creativity within specific knowledge domains (music, dance, etc.) proposing ad hoc methodologies to measure the specific creative behavior (e.g., Bhattacharya and Petsche 2005; Fink et al. 2009). However, notwithstanding the importance of the domain within the creative process, no neuroscientific study differentially explored brain dynamics between different knowledge domains. A first attempt to close this gap was made in the CREAM project, which compared and contrasted the brain dynamics in the scientific and artistic knowledge domains. Specifically, two groups of participants, representative of the scientific and the artistic domains of knowledge, were tested using an AUT task, in order to differentiate domain-specific brain dynamics during divergent thinking. Preliminary data showed that during idea generation, alpha synchronization was observed over the right parietal electrodes, as expected according to the literature (Fink and Benedek 2014), but also alpha desynchronization was recorded by left temporoparietal electrodes. Interestingly, the two opposite response patterns seem to distinguish the two groups of participants. Indeed, the right-lateralized alpha synchronization was specific to the artistic domain group (resembling the results of a number of past studies performed in the artistic domain), whereas the left-lateralized alpha desynchronization was observed only in the scientific domain group. These preliminary results are particularly important because for the first time they highlight a difference in brain activities during idea generation between different expertise domains. Even if participants belonging to scientific and artistic domains did not differ in their behavioral response (no differences in the AUT originality scores emerged between the two domains), these results showed that the same performance seems to be supported by different brain dynamics in the two domains. Specifically, even if both groups of participants were characterized by a brain asymmetry in the alpha band in the temporoparietal region, a right synchronization characterized the artistic group, whereas a left desynchronization characterized the scientific group. These preliminary results seem therefore to suggest that the domain plays its role not only in the phenomenology of the creative behavior as suggested by the multivariate approach, but also in the dynamics of the brain activity associated with creative behavior.

Non-invasive Brain Stimulation and Neurofeedback

Initial Evidence

From an operational viewpoint, brain stimulation can be used as an instrument to modulate and discover different components of creativity. An interesting method that has gained approval in recent years is the transcranial direct current stimulation (tDCS), which allows an investigation and modulation of cognitive processes (Kadosh 2013; Priori 2003; Zmigrod et al. 2015) by applying direct currents in specific brain regions. Recently, some studies using tDCS have investigated whether people's performance in a specific creative task, the Compound Remote Associates (CRA), can be improved. In this task, participants were presented with three unrelated words and each word can form a multiple word or phrase with the fourth, sought-for word. Results revealed that anodal stimulation over the left DLPFC improves CRA performance compared to cathodal or sham stimulation over the same region, as well as compared to anodal stimulation over the right DLPFC (Cerruti and Schlaug 2009). Different results were found in another tDCS study that failed to reproduce the initial findings but showed that anodal stimulation over the left DLPFC during CRA problems enhanced solution recognition (Metuki et al. 2012). A recent study extended these results examining whether tDCS can increase both convergent and divergent thinking. Participants performed the CRA task measuring convergent thinking and the AUT assessing divergent thinking (Zmigrod et al. 2015). Findings revealed the involvement of the left DLPFC in both convergent and divergent tasks and a mediating role of the posterior parietal cortex in problem solving (Zmigrod et al. 2015). Overall, these results showed evidence for a key role of the left dorsolateral prefrontal cortex in performing the CRA task. However, findings in this research field appear mixed and incomplete, leaving open questions regarding the underlying processes of creative thinking.

Creativity Enhancement

Even if neuroscientific research has mainly focused on understanding the principal cerebral mechanisms that contribute to creative performance, a recent growing body of neuroscientific studies has proposed and tested new protocols to successfully increase creative performance. Among the different tested methodologies, a technique that emerged as particularly suitable to the creative tasks is the neurofeedback training (NFT) procedure. Neurofeedback is a biofeedback modality that allows the user to change specific brain rhythms by means of an operant conditioning paradigm (Lopez-Larraz et al. 2012; Gruzelier 2014a; Marzbani et al. 2016). In other words, NFT enables users to exert internal control over the cortical rhythms recorded with EEG from the scalp. In this way, users are able to acquire self-control over specific brain activity patterns in order to implement these skills in daily-life situations (Gevensleben et al. 2009). NFT has been applied widely, because it is an easy, low-cost enjoyable way to modulate cognitive states in normal and pathological conditions (Marzbani et al. 2016). For instance, neurofeedback has been proposed as an enjoyable way to increase relaxation and cope with work-related stress (van Boxtel et al. 2012) or as a practical method to improve attention performance (Egner and Gruzelier 2004), memory abilities (Guez et al. 2015), executive functions (Hosseini et al. 2016), or other affective and cognitive functions (Gruzelier 2014a).

A few studies tested the use of the NFT procedure to increase creative performance. Even if research revealed interesting and promising results, this technique is normally used to efficiently train and modulate a state of relaxation, because in this state creative potential could be best expressed. Gruzelier and collaborators demonstrated in particular the efficacy of increasing relaxation though alpha/theta or alpha training to enhance creativity in the artistic domain, especially in musicians (Gruzelier 2014b; Gruzelier et al. 2014a; Egner and Gruzelier 2004). Because few attempt has been made to train participants to actively take control over a brain state which is directly involved in creative cognition as opposed to a more general well-being state such as relaxation, the CREAM project tested recently a new NFT protocol (Agnoli et al. 2018b). This protocol was developed specifically to enhance creative potential by monitoring the EEG signal over the right parietal region and providing visual feedback when the activity in this region increased. As previously described, EEG activity in this region represents a reliable marker of the cognitive processes that are specific for creative cognition and in particular for divergent thinking (Benedek et al. 2014). Specifically, a large body of evidence based on EEG recordings linked divergent thinking to brain oscillations. Among these, as already indicated, the alpha band (8–12 Hz) emerged as particularly important to understand the contribution of different processes (e.g., memory retrieval, top-down executive control, mental imagination) to creative production in divergent thinking (Fink and Benedek 2014). However, other types of rhythms, normally characterizing the EEG signal, such as the theta (4–7 Hz), the beta (15–25 Hz) and the gamma (>30 Hz) rhythms, have been investigated as well to disentangle the neuronal processes involved in creative cognition (Dietrich and Kanso 2010; Sandkuhler and Bhattacharya 2008). Interestingly, many of these studies have reported an asymmetric brain activity associated with creativity, often characterized by an increase in the right parietal cortex.

The CREAM NFT procedure resulted in a very intuitive feedback mechanism in which a video composed of different unrelated scenarios advanced if the participant's alpha or beta power in the right parietal region was 30% above the level of the alpha or beta activity recorded in the same area during an initial baseline. The effectiveness of the procedure was tested using a control group, which received the same visual stimulation, except that this feedback was not linked to participant's brain activity. Results showed that the CREAM neurofeedback procedure appears to be able to increase creative potential using three short neurofeedback sessions lasting 8 min each and performed in the same day. Creative potential was measured through originality and fluency scores derived from an Alternative Uses Task performed before the start of the training and repeated after each NFT session. EEG results highlighted in particular a constant increase of beta power in the experimental group compared to the control group during the three neurofeedback sessions, which was particularly evident in the right parietal area. Specifically, it seems that the NFT was effective only in the group that actually received feedback on the beta activity (experimental group), and that it was effective only in the region of interest that controlled the feedback (right parietal area). Moreover, results showed that both originality and fluency increased during the three NFT sessions in comparison to the baseline level. This result was significant only in the experimental condition, whereas in the control condition a general decrease or a lower increase rate of both originality and fluency was found (Agnoli et al. 2018b).

Overall these findings seem to suggest that by training active control on the synchronization of the brain activity in the right parietal region, an increase in divergent thinking performance can be obtained. On the basis of these results, we can suggest that certain components of the creative process may be trained using neuroscientific training procedures. Even if these findings refer only to divergent thinking, a challenge for future research is to understand both which components of the multivariate approach can be enhanced through neuroscience and what effect training a single component could have on the entire process.

Conclusions

This chapter has highlighted the utility of reflecting on the creative brain using a wide theoretical lens offered by the multivariate approach (Sternberg and Lubart 1995; Lubart et al. 2015). The multidimensional nature of the creative process is conceptualized as the interaction between "person-centered" factors, such as cognitive abilities, motivational drives, and personality traits, as well as "contextual influences" derived from the environment. The interactive combination of these factors makes the operationalization of creative thinking in a neuroscientific perspective quite difficult, or at least non-unique. However, from a quantitative viewpoint, the creative process can be measured in terms of productions, which reflect the creative potential of an individual as well as the conditions in which he/she came to operate. Numerous experimental studies have assessed brain activity (by means of EEG, fMRI, rCBF; or MRS) during the execution of different experimental tasks in controlled settings, expanding our knowledge about the possible mechanisms underlying creative behavior. Even though a significant heterogeneity of findings across studies of creative cognition emerged from the scientific literature, a coherent picture can be extracted, along the lines we proposed. Different modalities of creative thinking (such as divergent versus convergent thinking) are associated with functionally different brain activity patterns, according to the multivariate approach to creativity. The viewpoint presented in this chapter should motivate investigators belonging to cognitive, psychometric, and neuroscientific fields to incorporate the study of creativity into a more comprehensive multidimensional approach, encouraging conciliating methodologies and replications. The multivariate approach adopted here offers in particular a coherent theoretical grounding to frame the scattered results derived from the neuroscientific literature on creativity. In this chapter, the theoretical claims characterizing this approach have been shown to find support in neuroscientific studies.

Moreover, this theoretical framework opens further research avenues to explore the creative behavior reflected in the brain. An example would be exploring the relationship between different components defining creative behavior, in particular examining the hypothesized mutual compensation between components. How this hypothesis may find support in the brain functioning during a creative task is a challenging question for future research. Analyzing brain connectivity might, for example, provide interesting insights on the interaction between brain regions subsuming different components of creativity.

Much more effort is, however, needed to achieve a deeper understanding of the in vivo experience of creative behavior that will be challenged by the exploration of brain activity in response to more complex, real-life creativity tasks, taking place in rich environments. It should indeed be highlighted that the human brain is fundamentally a social brain. The emerging social cognitive neuroscience field (Adolphs 2003; Melloni et al. 2014) is revealing some of the basic neuronal mechanisms supporting social cognition, that is, how individuals think about themselves in relation to others. This evidence may shed new light on the neural correlates underlying the social aspects of creativity, and their relation to learning. A question for the future would be to use these recent neuroscientific findings to explore the creative brain in order to improve teaching and learning of creativity in educational environments.

Fascinating implications may also arise from the interdisciplinary field of cultural neuroscience (Chiao and Blizinsky 2016) applied to creativity research. Future studies might examine the nature of the human cultural diversity underlying creativity. Such complex behavior results from a dynamic interaction of biology and culture, and it would be stimulating to investigate how cultural values, opinions, and beliefs of different populations shape the creative human brain and, vice versa, how the human brain gives rise to disparate creative cultural capacities.

Future research might also explore whether creativity can be enhanced efficiently through ad hoc cognitive stimulation or specific neurofeedback training, and investigate more deeply how these intervention effects are reflected into the brain. Following the multivariate approach, we could propose to develop protocols to train specific components of creativity. This could generate, for example, a "multidimensional neurofeedback training," which could act on specific weaknesses following the results emerging from the profiling of individual creativity (Lubart et al. 2013).

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The Neuroscience of Creative Idea Generation

Mathias Benedek

Abstract Creative idea generation is the source of amazing novel insights and original products, which enrich everyday life and represent valuable contributions to arts and sciences. But how does the brain produce creative ideas? This question has been addressed in cognitive neuroscience research by measuring the brain activation during creative idea generation using different techniques such as EEG and MRI. This chapter introduces some of the key findings in this field: What is the functional role of alpha activity during creative thought? What brain activation is associated with the generation of novel ideas? How do large-scale brain networks interact during creative performance? These findings are integrated into a neurocognitive process model (RISE), which proposes that retrieval, integration/simulation and evaluation represent central, distinguishable neurocognitive processes underlying creative idea generation.

The Neuroscientific Investigation of Creative Idea Generation

Human creativity and innovation rely on our capacity to generate creative ideas. But how does the brain produce creative thought? The investigation of creative idea generation has a long tradition in cognitive research, and more recently, it has also been addressed by the cognitive neurosciences. Relevant research goes back to the study of divergent thinking, which represents the production of different ideas to open-ended problems (Guilford 1950, 1967). A good example is the alternate uses tasks, which asks for creative uses of everyday objects (e.g. "What can a brick be used for?"). Divergent thinking tasks have no single correct solution, but instead

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there are many possible solutions that vary in their originality. Divergent thinking thus is essentially another name for creative idea generation, and divergent thinking tasks are included in many psychometric tests of creative potential such as the Torrance Test of Creative Thinking (Torrance 1974), or the Évaluation du Potentiel Créatif (Lubart et al. 2013; see also Mastria et al., this volume). The performance in divergent thinking tasks can be scored in different ways including measures of the fluency and creativity of ideas. Divergent thinking fluency can be simply assessed by the number of ideas that were generated in a given time. The creativity of ideas is often evaluated by judges or sometimes inferred from the idea's infrequency (Benedek et al. 2013; Kaufman et al. 2008; Silvia et al. 2008). Together, creativity and fluency in divergent thinking tasks reflect a person's cognitive potential to produce many creative ideas, which is a relevant predictor of real-life creative achievement (Jauk et al. 2014; Plucker 1999).

Divergent thinking tasks have also been commonly adopted in the neuroscientific investigation of creative idea generation. However, while psychometric assessments of creative potential use divergent thinking tasks of several minutes, this is not feasible in neuroscience research, which requires large numbers of short trials in order to identify reliable brain processes (Abraham 2013). This issue can be addressed in two ways: one method is to assess self-paced idea generation over several minutes and ask participants to indicate when they have an idea (e.g. via button press), and then analyse the observed brain activation right before the occurrence of ideas (Fink et al. 2007). Another way is to use much shorter idea generation tasks of about 10–20 s that capture the brain activation associated with the production of single ideas in separate tasks (e.g. Fink et al. 2009a). In any case, neuroscience studies on creative idea generation require a temporal separation of time periods related to creative thought and the actual response of ideas in order to avoid artifacts caused by movement or motor-related activation (Abraham et al. 2012). The brain activation during creative idea generation can then be contrasted to that observed during other tasks involving lower creative demands. For example, comparing the brain activation during the generation of creative object uses with the generation of common object uses should reveal brain processes that are specific to creative thought.

So far, neuroscientific studies on creativity have employed a large range of creative tasks including verbal and figural insight problems, creative story generation, creative drawing, or musical improvisation, and brain activation has been measured with many methods including electroencephalography (EEG), magnetic resonance imaging (MRI), positron emission tomography (PET) or single photon emission computed tomography (SPECT). It soon became clear that it is difficult to identify consistent results across these very different tasks and methods (Arden et al. 2010; Dietrich and Kanso 2010). However, more recent reviews that focus on creative idea generation and specific methods such as EEG or MRI revealed first consistent patterns of brain activation (Fink and Benedek 2014; Sawyer 2011; Gonen-Yaacovi et al. 2013; Wu et al. 2015). In the following, I will present some of the main findings on the brain mechanisms underlying creative idea generation as obtained by the most common neuroimaging methods, EEG and MRI.

EEG Research on Creative Idea Generation

Many studies have used EEG to examine the brain activation related to individual differences in creativity and the process of creative idea generation. Most of this research focused on the role of EEG alpha activity, which represents the cortical oscillatory activity in the range of 8–13 Hz. Martindale and colleagues were among the first to show that creative people exhibit higher EEG alpha activity than less creative people (e.g. Martindale and Hines 1975). Moreover, they found that alpha activity is higher during story generation as compared to the less creative task of story elaboration (i.e. writing down the story; Martindale and Hasenfus 1978). By now, these findings have been replicated several times and findings suggest that EEG alpha activity is sensitive to creativity in various ways. First, relevant research suggests that EEG alpha power during task performance increases with creativity-related task demands (Fink et al. 2007; Jauk et al. 2012; Jaušovec 1997; Martindale and Hasenfus 1978). Second, alpha activity is higher during the generation of more as compared to less original ideas (Fink and Neubauer 2006; Grabner et al. 2007; Schwab et al. 2014). Third, alpha activity is higher in more versus less creative people, especially during creative idea generation (Fink et al. 2009a, b; Jaušovec 2000; Martindale and Hines 1975; Martindale and Hasenfus 1978). Forth, EEG alpha activity was shown to be increased after completing a creativity training (Benedek et al. 2006; Fink et al. 2006) and even after short creativity-enhancing interventions (Fink et al. 2011). Finally, EEG alpha varies as a function of the stage in the creative process during creative idea generation (Jaarsveld et al. 2015; Schwab et al. 2014). These EEG alpha effects are consistently observed at frontal brain regions and parietal regions of the right hemisphere (Fink and Benedek 2013, 2014).

The presented findings suggest a robust relationship between EEG alpha activity and creative idea generation (i.e. divergent thinking), but what is the functional meaning of alpha activity during creative thought? Early conceptions of alpha activity viewed it as indicator of reduced information processing or cortical idling (Pfurtscheller et al. 1996). Following this notion, the creativity–alpha relationship was originally thought to reflect a state of low cortical arousal, defocused attention (Martindale 1999; Mendelssohn 1976), or "hypofrontality" (Dietrich 2003). Today, this interpretation would be conceived as too simplistic, because increasing evidence suggests that alpha activity is actually related to active information processing (Palva and Palva 2007). For example, studies using memory and imagination tasks reported that alpha power was highest during conditions of highest task demands (Cooper et al. 2003; Jensen et al. 2002; Klimesch et al. 1999). Furthermore, frontal EEG alpha activity was shown to correspond to increases in frontal brain activity in terms of the blood–oxygen-level-dependent response when the same divergent thinking tasks are performed in the MRI scanner (Fink et al. 2009a). Recent interpretations of alpha activity rather link it to attentional demands (Jensen et al. 2012) as well as controlled memory retrieval (Klimesch 2012). For example, Ray and Cole (1985) described a study where they recorded EEG while having participants work on a number of tasks that either required the intake and processing of external information (e.g. paper folding task) or to focus on internal information processing (e.g. an imaginary walk or mental arithmetic). Alpha activity was found to be consistently higher during the latter "intake rejection" tasks than during the "sensory-intake" tasks. The authors concluded that alpha activity is related to the attentional focus, with alpha activity being higher during states of internally directed as compared to externally directed attention.

One EEG study intended to disentangle to what extent EEG alpha activity during creative idea generation is actually due to specific creativity-related processes or rather due to attentional demands (Benedek et al. 2011). To this end, this study contrasted divergent thinking with convergent thinking (i.e. tasks with single correct solutions), and additionally manipulated the attentional focus (external vs. internal) within tasks. In each trial, a four-letter word was presented (e.g. "POST") and participants had either to create an original four-word sentence (divergent thinking) or to find a correct anagram solution (convergent thinking). The attentional focus was additionally manipulated by allowing the processing of the stimulus word in only half of the trials (low internal processing condition), whereas in the other half of trials the stimulus was masked after half a second and thus had to be kept in mind (high internal processing condition). The analyses revealed that alpha activity was higher in both tasks when they were performed under high internal processing demands. In contrast, divergent and convergent thinking tasks hardly differed in alpha activity besides a tendency towards increased alpha in right parietal regions during the divergent thinking tasks. The findings thus supported the notion that increased alpha activity during idea generation is essentially due to high internal attention demands.

Interestingly, this study did not observe a clear task effect in terms of higher alpha activity during divergent thinking as compared to convergent thinking, although this had been a consistent finding in previous research. This discrepancy might be explained by the specific nature of the divergent thinking task selected in this study (i.e. four-word sentences) to allow a close matching with the convergent thinking task. Generating four-word sentences involves the consideration and manipulation of four unrelated letters and thus likely relies on the continuous processing of external information to ease working memory—it hence can be considered as a *sensory-intake* task. In contrast, most divergent thinking tasks involve processing of just a single semantic concept (e.g. "brick"), which does not require the continuous processing of the stimulus—these tasks could be termed *sensory-independence* tasks. In other words, alpha activity may not only be increased when an internal attention focus is enforced by stimulus masking, but also if the task does not require the processing of an external stimulus even though it is presented. This notion was tested in another similar EEG study that again used the four-word sentences task (i.e. a sensory-intake task), but contrasted it with the alternate uses task, a more typical divergent thinking task that is assumed to be largely independent from sensory processing (Benedek et al. 2014d). The results of this study showed that the high internal processing condition (i.e. stimulus masking) led to increased alpha activity only in the sensory-intake task, but not in the sensory-independence task. Moreover, alpha activity was generally higher in the sensory-independence task (i.e. the alternate uses task) than in the sensory-intake task (i.e. four-word sentences task). In other words, alpha activity was increased in those three conditions that involved sustained internal attention, and this alpha effect was most pronounced in parietal regions of the right hemisphere.

Together, these studies corroborate the view that increases of EEG alpha activity reflect mental states with an internal focus of attention. Further relevant evidence comes from alpha connectivity studies on working memory showing that internal manipulation processes are associated with functional alpha coupling between prefrontal and occipital regions, which was interpreted in terms of cognitive control exerted over visual brain regions (Sauseng et al. 2005). EEG alpha activity thus may represent a neuronal mechanism to shield ongoing internal processes from potentially distracting external interference. Since creative idea generation commonly relies on imagination rather than processing of external stimuli (Abraham 2016), EEG alpha activity may play an especially important role for creative thinking by shielding those inner representations and mental images (Benedek 2018; Fink and Benedek 2014).

MRI Research on Creative Idea Generation

Besides EEG research, the brain activation related to creative idea generation has also been extensively studied by means of functional magnetic resonance imaging (fMRI). fMRI provides higher spatial resolution than EEG and hence is beneficial for the identification of relevant anatomical brain regions. One of the first studies in this field measured brain activation during four divergent thinking tasks including the generation of alternate object uses, object characteristics, name inventions and word endings (Fink et al. 2009a). In each task, participants were asked to think of ideas for 20 s and vocalize their response in subsequent response periods. All these idea generation tasks generally involved brain activation in the left inferior frontal gyrus and in parietal and occipital regions lateralized to the left hemisphere. To extract the brain activation specific to creative thought, the alternate uses task was contrasted to the object characteristics task ("generate typical characteristics of common objects"), because the latter requires thinking of typical rather than creative responses. This contrast revealed that the alternate uses generation specifically involves higher brain activation in the left posterior inferior parietal cortex (i.e. left angular gyrus), but relatively lower activation in the right inferior parietal cortex (right angular gyrus and supramarginal gyrus). Several other studies used a similar design and observed largely similar results (Chrysikou and Thompson-Schill 2011; Fink et al. 2014a; Kleibeuker et al. 2013). For example, Abraham et al. (2012) reported activation of the left angular gyrus when contrasting the alternate uses task with a working memory task, and activation of the left inferior parietal cortex was observed when contrasting the alternate uses task with an object identification task. The angular gyrus is thought to be implicated in semantic integration processes

(Binder et al. 2009), which could be relevant for combining unrelated concepts towards original ideas.

The alternate uses task is a popular task in neuroscience research, because it is a well-tested task in cognitive research of creativity. One study examined the strategies involved in the alternate uses task and found that many ideas reported in the course of the task are actually recalled from memory rather than newly generated (Gilhooly et al. 2007). For example, thinking of creative uses of a car tire may trigger the familiar memory of a car tire used as a swing. While the recall of original uses from memory is a useful strategy, only the generation of novel ideas can be conceived as a truly creative act, because it involves the creation of new representations that have not been in one's mind before. One fMRI study capitalized on this issue by contrasting the brain activation of newly created versus recalled ideas (Benedek et al. 2014a). Participants were asked to perform 15 alternate uses tasks in the scanner for one minute each. Responses were recorded and, after the fMRI session, classified by the participants as being newly created or recalled during the experiment. The rather long task duration combined with a self-paced response mode ensured that reasonable amounts of novel and recalled ideas were available from all participants. The study revealed that creative idea generation was generally related to activation of the inferior frontal gyrus, superior frontal gyrus and precentral regions of the left hemisphere. More interestingly, the generation of new ideas as compared to old ideas was related to higher activation of the left inferior parietal cortex mainly involving the supramarginal gyrus. Finally, this study reported that activation in the left dorsal prefrontal cortex linearly increased with increasing creativity of ideas, which was interpreted in terms of higher executive involvement facilitating the retrieval of relevant unrelated concepts and the suppression of common, uncreative responses. The left supramarginal gyrus appears to be particularly sensitive to the generation of novel ideas (Benedek et al. 2014b; Fink et al. 2010, 2014b; Kleibeuker et al. 2013). Moreover, this region was associated with increased task performance following a three-week creativity training (Fink et al. 2015). The inferior parietal cortex (including supramarginal gyrus and angular gyrus) is involved in episodic memory retrieval together with regions such as the medial temporal lobe and prefrontal structures (e.g. Cabeza et al. 2008; Wagner et al. 2005). Research in the field of future thinking suggests that the inferior parietal cortex is a core structure that integrates information from our past to construct and simulate possible future events (Schacter et al. 2007, 2012). This notion is conceptually similar to common theories of creative idea generation, assuming that an idea originates from the novel recombination of relevant knowledge (e.g. Koestler 1964; Mednick 1962).

Another fMRI study investigated brain activation during generation of creative metaphors (Benedek et al. 2014a). Metaphors use unrelated concepts as vehicles to express or emphasize certain characteristics of another concept (Glucksberg 2001, 2003). For example, the metaphor "music is medicine" refers to the common conceptual category that "something is healing". Generating a metaphor hence requires finding unrelated concepts that serve to illustrate a property of interest. While neuroscientific research has thoroughly studied the brain correlates related to metaphor comprehension (Rapp et al. 2012; Vartanian 2012), so far little is known on how the brain actually produces original metaphors. Therefore, this study compared metaphor generation to the generation of synonyms, thus contrasting the production of figurative versus non-figurative language. In each trial, a cue indicated whether a metaphor or a synonym should be generated, followed by a brief sentence with an adjective in brackets, e.g. “The lamp is (glaring)”. Participants then had 10 s to think of a creative metaphor or an adequate synonym, before vocalizing the response in the subsequent response period. Whole-brain analyses revealed that metaphor production was associated with higher activation (as compared to synonyms production) of the left angular gyrus extending to the left middle temporal gyrus. Further activations related to metaphor generation were observed in the posterior cingulate cortex and precuneus, left lingual gyrus, bilateral parahippocampal gyrus and lingual gyrus and right cerebellum and dorsomedial prefrontal cortex. An additional parametric analysis showed that brain activity increased with the rated creativity of metaphors in the left dorsomedial prefrontal cortex and in a cluster located in the right middle temporal gyrus. Lesion studies showed that damage to this prefrontal region causes patients to fail generating responses from a larger set of possibilities (Robinson et al. 1998). Therefore, the dorsomedial prefrontal cortex is considered relevant for goal-directed semantic retrieval and the production of speech beyond set phrases (Binder et al. 2009).

While cognitive functions are often attributed to isolated brain regions, recent research suggests that the brain is actually organized into large-scale brain networks. These networks reflect the intrinsic coupling of distributed brain regions during rest and cognitive activity (e.g. Bressler and Menon 2010; Yeo et al. 2011). The brain regions observed during creative idea generation can be mostly attributed to two large-scale brain networks, the cognitive control network (CCN) and the default mode network (DMN; Gonen-Yaacovi et al. 2013; Jung et al. 2013; Zabelina and Andrews-Hannah, 2016). The CCN (similar conceptualizations also refer to the executive control network or the fronto-parietal control network) encompasses extended regions of the dorsolateral and ventrolateral prefrontal cortex as well as parts of the superior parietal cortex, and it is involved in cognitive tasks requiring sustained top-down, executive control. The DMN is composed of midline regions such as the medial prefrontal cortex and the posterior cingulate cortex and of the posterior part of the inferior parietal cortex. It is typically implicated in self-generated thought, which can be spontaneous as in mind-wandering or goal-directed as in mental navigation (Andrews-Hannah et al. 2014; Fox et al. 2015; Spreng et al. 2009). Given the different nature of the CCN and the DMN, it may not be surprising that these two networks are commonly found to be anti-correlated, meaning that tasks showing increased CCN activation also involve reduced activation of the DMN (Fox et al. 2005). However, in creative cognition tasks, we commonly find brain regions from both networks activated. Moreover, analyses of the functional brain connectivity revealed that CCN and DMN regions do not act in isolation but actually show increased coupling during many forms of creative cognition including divergent thinking (Beaty et al. 2015), poetry composition (Liu et al. 2015) and piano improvisation (Pinho et al. 2016).

Considering that the CCN is associated with controlled, evaluative thought and the DMN is associated with generative, constructive thought, this activation pattern suggests that generative and evaluative processes cooperate during creative thought (Beaty et al. 2016; Jung et al. 2013).

The presented fMRI studies are just a few examples of relevant research on the brain processes underlying creative idea generation. Many more studies exist that focused on creative idea generation in the visual domain (e.g. Aziz-Zadeh et al. 2013; Ellamil et al. 2012) or specific creative activities like story generation (Howard-Jones et al. 2005; Shah et al. 2013) and musical improvisation (Beaty 2015). Yet another approach is to examine what structural properties of the brain are associated with individual differences in creative potential. For example, higher divergent thinking ability was found to be related to higher grey matter density in clusters involving the right cuneus and the right precuneus (Fink et al. 2014a; Jauk et al. 2015) and in regions associated with the dopaminergic system (Takeuchi et al. 2010a). Moreover, divergent thinking ability has also been linked to white matter integrity (Jung et al. 2010; Takeuchi et al. 2010b) and white matter connectivity (Ryman et al. 2014), and these relationships appear to be moderated by gender (Ryman et al. 2014; Takeuchi et al. 2017). Future research in this field is challenged to demonstrate how functional and structural correlates of creative idea generation relate to each other (e.g. Bendetowicz et al. 2017).

Considering the presented fMRI evidence on creative idea generation, a few consistent findings can be observed, as also highlighted by recent meta-analyses in this field (Gonen-Yaacovi et al. 2013; Wu et al. 2015). Above all, relevant brain networks tend to be lateralized to the left hemisphere, which opposes the popular notion that creativity is specifically associated with the right hemisphere. These left-lateralized regions specifically include the left ventrolateral prefrontal cortex (especially inferior frontal gyrus), the left inferior parietal cortex (angular gyrus and supramarginal gyrus) and regions in the dorsolateral and dorsomedial prefrontal cortex. A closer description of the presumed functional meaning of these regions for creative idea generation is provided in the next section.

A Neurocognitive Process Model of Creative Idea Generation: RISE

The ultimate goal of neuroscientific investigations of creative idea generation is not just to map relevant brain regions, but, of course, to infer insights on the cognitive processes involved in creative thought. As for any high-level mental activity, it should generally be possible to understand creative idea generation in terms of specific cognitive functions such as attention and memory processes. Therefore, this final section attempts to outline a process model of creative idea generation that integrates available evidence from cognitive and neuroscience research. Considering the available theoretical and empirical literature, I propose that creative idea

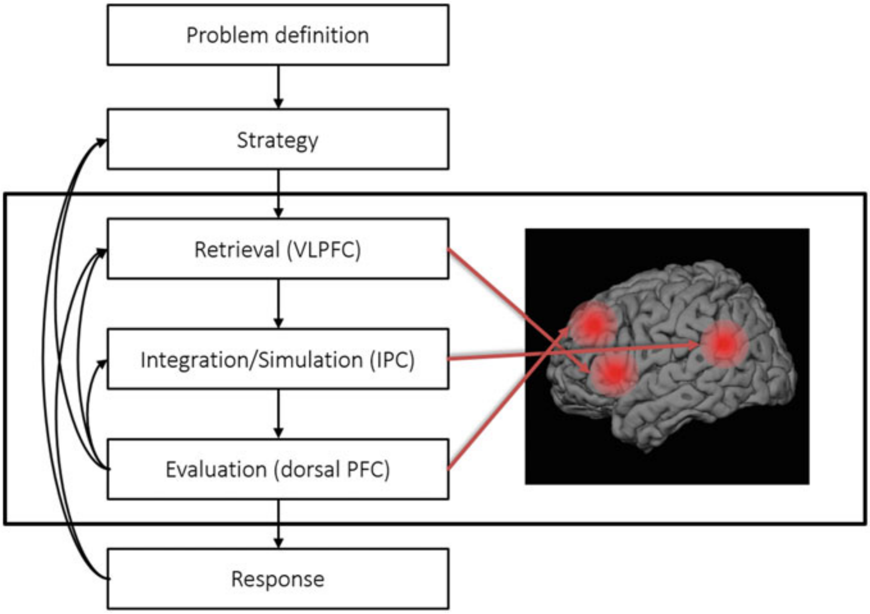

Fig. 1 Schematic depiction of the RISE process model of creative idea generation. The core processes include retrieval, integration/mental simulation and evaluation, which can be linked to brain activation in the ventrolateral prefrontal cortex (VLPFC), inferior parietal cortex (IPC) and dorsal parts of the prefrontal cortex (dPFC), respectively

generation can essentially be viewed as an open-ended, multiply-constrained search and integration process (cf. Smith et al. 2013). In brief, creative idea generation requires an initial *problem definition* that informs the adoption of a *strategy* for idea generation. This strategy guides iterative engagements of the *retrieval* of potentially relevant concepts, followed by *integration* and *simulation* processes to construct novel representations. Finally, an *evaluation* of prospective ideas takes place to decide whether they meet the task goals and can be reported (see Fig. 1). According to this model, creative idea generation encompasses discriminable cognitive processes that run consecutively and partially iteratively. In this process model, the first stages of problem definition and devising a strategy are not specific to creative idea generation but common for any form of complex problem-solving task. The more specific processes of how creative ideas arise thus involve iterative employments of retrieval, integration/mental simulation and evaluation, which can be recapped by the acronym RISE. I will now briefly describe the theoretical foundation of this model, illustrate it with an example, and then describe the presumed neural foundations of the involved cognitive processes.

The proposed model incorporates assumptions from other well-known models on creative cognition. First of all, it strongly relates to the associative account of creativity put forward by Mednick (1962) and Koestler (1964), who postulated that a creative idea results from the forging of novel combinations or “bisociations” between remotely associated concepts. The generation of novel representations thus requires the search for relevant unrelated concepts and a subsequent associative combination. This notion found empirical support in studies on associative abilities showing that dissociative abilities (i.e. retrieve unrelated concepts) and associative combination abilities independently predict creative potential (Benedek et al. 2012). The RISE model further presumes that these generative processes (retrieval and integration/simulation) interact with evaluative processes. An interplay between generation and evaluation is consistent with other accounts on creative thought referring to the interaction between divergent and convergent thinking (Cropley 2006), between blind variation and selective retention (Campbell 1960; Simonton 2011), or between generation and exploration phases as in the *Geneplore* model (Finke 1996).

As an example, consider that we look for creative uses of a car tire. In an initial problem definition process, we need to identify relevant task goals, which include the task-specific goal to find uses for a car tire, and the task-general goal that responses should be creative, which may be further specified as novel and effective (Diedrich et al. 2015; Runco and Jaeger 2012). These task goals inform the selection of a task strategy and are further reviewed during the evaluation process. A common initial strategy is to recall known original uses for the object (e.g. use it as a swing), but a more effective strategy would be to consider characteristic properties of the object and to examine how these properties could be used in a different context (Gilhooly et al. 2007). Following this strategy, properties of a car tire (i.e. it is round, flexible, dark) are used as cues in a multiply-constrained memory search. This retrieval process may trigger a first association of a floating tire, and a subsequent mental simulation may confirm that it roughly fits a body’s girth. A subsequent evaluation, however, may reveal that such an idea may be considered novel but also ineffective, as it will not swim well. This evaluation leads to the rejection of this idea and reroutes back to the retrieval of further shape-related concepts. Further retrieval based on the size and shape of a car tire may then evoke the association of a lampshade. Attempts to integrate the concepts of a lamp shade and a car tire may involve mental simulations of how to tinker a stylish lampshade from a car tire. A subsequent evaluation of this idea might come to the conclusion that this idea meets the imposed criteria (i.e. being novel and effective) and should be reported. This example illustrates how retrieval, integration/simulation and evaluation processes may interact during creative idea generation.

How do these specific cognitive processes link to the observed brain activation patterns? The most consistent brain regions involved in creative idea generation include the ventrolateral prefrontal cortex on the left inferior frontal gyrus, the left inferior parietal cortex (especially supramarginal gyrus and angular gyrus) and dorsomedial and dorsolateral prefrontal cortex. I propose that these regions can be roughly associated with specific RISE processes as outlined above. In brief, ventrolateral prefrontal cortex activity might reflect the process of controlled retrieval, left inferior parietal cortex activity may reflect semantic integration and simulation processes, and dorsal prefrontal cortex activity may be involved in the evaluation and selection process (see Fig. 1).

An extended involvement of the left inferior frontal gyrus has been observed during virtually all divergent thinking tasks, especially when considering contrasts with low-level baselines or shared activations between different idea generation tasks, including tasks that do not focus on creativity but more generally on broad retrieval (Chrysikou and Thompson-Schill 2011; Benedek et al. 2014b, 2016; Fink et al. 2009a). It is well documented that the left inferior frontal gyrus is involved in controlled semantic retrieval and more generally in semantic processing (Badre et al. 2005; Binder et al. 2009). Especially the anterior part of the inferior frontal gyrus (Brodmann's area 47) has been commonly implicated in executive aspects of semantic processing such as directing semantic search or comparing semantic concepts in working memory (Bookheimer 2002). The consistent inferior frontal gyrus involvement in creative idea generation thus may reflect controlled search and recall processes supporting the retrieval of relevant but reasonably remote concepts, which introduce novelty and can be used to forge new associative combinations.

Regions of the left inferior parietal cortex, especially the supramarginal gyrus and angular gyrus, are consistently observed when contrasting tasks of higher versus lower creative task demands. While the left angular gyrus was more strongly involved in the generation of creative metaphors versus synonyms and creative object uses versus anagrams (Benedek et al. 2014a, 2016), the involvement of the left supramarginal gyrus is particularly evident when focusing on novelty in idea generation (Benedek et al. 2014b; Fink et al. 2010, 2014b; Kleibeuker et al. 2013; Kröger et al. 2012). These inferior parietal regions are situated between sensory-motor systems and are commonly seen as supramodal integration zones where modal information converges and is integrated (Binder et al. 2009; Binder and Desai 2011). Moreover, the inferior parietal cortex contributes to episodic simulations, i.e. constructive mental simulations, based on episodic memory retrieval (Schacter et al. 2007, 2012). As such, the left inferior parietal cortex seems to play an important role in creative idea generation by integrating relevant concepts into coherent novel representations and adjusting them in mental simulations.

Dorsal parts of the prefrontal cortex have been observed in parametric analyses focusing on the creativity of ideas (Benedek et al. 2014a, b), which indicates that this prefrontal region is particularly relevant for the generation of highly creative ideas. Lesion studies showed that damage to the dorsomedial prefrontal cortex results in impairments of the invention of self-generated novel responses and poor performance when a large set of responses is possible (Robinson et al. 1998). Moreover, the evaluation of the appropriateness aspect of ideas and the evaluation of self-produced illustrations have been related to increased activation of regions in the dorsal prefrontal cortex (Ellamil et al. 2012; Kröger et al. 2012). Together, this evidence suggests that dorsal parts of the prefrontal cortex are particularly relevant for the evaluation and selection process in creative idea generation.

The RISE model proposes that retrieval, integration/simulation and evaluation processes take place during creative idea generation in a highly iterative and interactive fashion. This notion is supported by recent functional connectivity studies on creativity, which demonstrate increased coupling between large-scale brain networks associated with generative and evaluative processes in creative cognition. Specifically, as mentioned before, the default mode network (including the posterior inferior parietal cortex) and the cognitive control network (including the inferior frontal gyrus and anterior inferior parietal cortex) were found to show increased coupling during different forms of creative cognition (Beaty et al. 2016; Jung et al. 2013). The proposed interaction between frontal and parietal regions also seems to share some similarities with the Parieto-Frontal Integration Theory of intelligence (Jung and Haier 2007), which assumes that frontal regions act on abstracted sensory information in the parietal cortex. Recent research indicates that intelligence and creativity are in fact not so different as both rely on similar executive mechanisms as well as overlapping brain structures (Benedek et al. 2014c; Jauk et al. 2015; Silvia 2015). As a notable difference, however, creative idea generation builds on self-generated content rather than sensory information.

Finally, one of the most consistent neuroscientific findings related to creative idea generation is the observation of increased EEG alpha activity especially at posterior regions of the right hemisphere (Fink and Benedek 2013, 2014). Experimental studies were able to attribute this alpha effect to sustained internally focused attention (Benedek et al. 2011, 2014d). Creative idea generation processes such as retrieval, semantic integration, mental simulation and evaluation obviously require that attention is directed to internal self-generated content, whereas external stimuli are mostly irrelevant or can even be distracting. For example, when we generate mental images in the mind's eye, it may be crucial to shield them from interfering visual stimulation. This notion obtained further support in a recent fMRI study, which showed that sustained internally directed attention involves massively reduced activity in visual networks, and increased functional connectivity between visual networks and the right supramarginal gyrus (which roughly corresponds to the observed peak of EEG alpha activity during creative thinking). These findings suggest that the right supramarginal gyrus may be involved in the active suppression of visual information processing (Benedek et al. 2016). Moreover, EEG alpha activity could represent an important cortical mechanism for the maintenance of sustained internally focused attention, and thereby facilitate long and demanding search and integration processes during creative idea generation.

This chapter attempted to give an overview of the most consistent findings in brain research on creative idea generation. The available evidence from cognitive and neuroscience research was condensed into a neurocognitive process model of creative idea generation, which identifies discriminable cognitive processes and their neural foundations. Such a model does not claim to be complete or correct in all respects, but it rather aims to make implicit assumptions explicit so they can be tested and extended by future research. Following this path of theory-driven, empirical research, we will be able to increasingly demystify the concept of creativity and ultimately understand it as an "extraordinary result of ordinary processes" (Sternberg and Lubart 1996; p. 681).

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Investigating Creativity from a Semantic Network Perspective

Yoed N. Kenett

Abstract Semantic memory plays a role in the creative process, either as an integral component or as the basis upon which executive functions operate on. Yet, due to the challenge of representing semantic memory, the relationship between semantic memory and creativity has not been thoroughly investigated. In recent years, computational network science tools are increasingly being applied at the cognitive level to examine language and memory systems. Network science is based on mathematical graph theory, providing quantitative methods to investigate complex systems as networks. Here, a series of semantic network studies aimed at investigating different facets of creativity in low- and high-creative individuals will be reviewed. These studies include representing their structure of semantic memory (both at the group and individual level), simulating uncontrolled search processes over their semantic memory, examining the relation of semantic memory structure to creative achievement and fluid intelligence, and relating flexibility of thought to the robustness of their semantic networks to attack. Finally, a general theory relating semantic memory structure to typical and atypical semantic processing will be presented and its relation to individual differences in creativity will be discussed. These studies demonstrate how the role of semantic memory in creativity can be investigated via quantitative measures of connectivity, distance, and structure of semantic networks. Thus, the application of network science tools to study creativity provides a quantitative and direct investigation of theories on creativity. Importantly, network science offers powerful tools in quantitatively studying different facets of high-level cognitive constructs such as creativity.

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Introduction

The neurocognitive research of creativity is making progress in examining the contribution of various cognitive processes and capacities, such as executive functions (working memory, fluid intelligence, switching), personality traits (openness to experience), attention, inhibition, and episodic memory to creativity (Benedek et al. 2014; Beaty et al. 2016b; Madore et al. 2015; Zabelina et al. 2015; Radel et al. 2015). Several classic and more recent theories on creativity acknowledge the contribution of connecting weakly related or further apart concepts in memory in the creative process (Schilling 2005; Beaty et al. 2014; Benedek et al. 2012b; Mednick 1962; Smith and Ward 2012). Yet, due to the challenge of representing semantic memory, the relationship between semantic memory and creativity has not been thoroughly investigated. This chapter reviews recent computational attempts that apply network science methodologies to represent semantic memory structure and relate it to different facets of creative ability. Such attempts aim at directly examining the role of semantic memory structure in the creative process, based on the various theories of the creative process.

Current theories on creativity either emphasize the importance of bottom-up processes, top-down processes, or a dynamic shift between bottom-up and top-down processes in creativity. The bottom-up, associative theory of creativity argues that individual differences in semantic memory structure influence creative thought in a bottom-up manner (Kenett et al. 2014; Schilling 2005; Rossman and Fink 2010; Gruszka and Neçka 2002; Mednick 1962; Kenett 2018). It goes back to Mednick's (1962) theory, which assumes that creative individuals are characterized by "flat" (numerous and weakly related associations to a given concept) rather than "steep" (few, strong associations to a given concept) hierarchies in semantic memory. Rossmann and Fink (2010) concluded that creative individuals may have more links in their semantic memory and can activate remote associative relations faster than less creative individuals.

The top-down, executive theory of creativity argues for the importance of top-down cognitive control in the creative process, such as fluid intelligence, retrieval ability, and specific executive functions (Benedek et al. 2014; Groborz and Neçka 2003; Beaty and Silvia 2012; Nusbaum and Silvia 2011; Jauk et al. 2014; Lee and Therriault 2013; Silvia 2015; Martindale 1995; Mendelsohn 1976). According to this view, cognitive control supports creativity via top-down mechanisms that enable more effective memory retrieval and strategy implementation.

The dual process theories of creativity formalize the creative process based on its two main components—novelty and applicability—and argue for a dynamic shift between these two components (Sowden et al. 2014; Barr et al. 2014; Simonton 2013, 2015). Based on Campbell's (1960) evolutionary theory on creativity, Simonton proposed that creativity is a result of blind variation and selective retention theory (Simonton 2013). This theory views creativity from an evolutionary perspective, involving "blind" generation of exploratory ideas and a selection criterion that retains only relevant ideas (Simonton 2010). Gabora et al. proposed that creativity involves a neurally plausible contextual shifting of focus between an associative mode of thought and an analytical mode of thought, contingent on task demands (Gabora 2010; Sowden et al. 2014).

In all of these theories, semantic memory is a key component (Abraham and Bubic 2015). Semantic memory is the system of human memory that stores concepts and facts, regardless of time or context (McRae and Jones 2013). However, the way in which semantic memory is organized into categories and subcategories remains an open question (Jones et al. 2015). Recent theories on semantic memory consider it as a dynamic memory system, contingent on context (e.g., task demands), and individual differences (e.g., creativity) that allow the flexible and generative use of language (Yee and Thompson-Schill 2016). However, despite several computational models that have been proposed to represent it (Jones et al. 2015), the specific nature of semantic memory remains an open issue in cognitive research (McRae and Jones 2013).

In regard to creativity, semantic memory is either directly related to creative ability via its structural properties (Mednick 1962; Sowden et al. 2014; Simonton 2013), or as the basis upon which executive functions operate on (Mendelsohn 1976; Benedek et al. 2014). Thus, semantic memory structure plays an important role in the creative process. Recently, computational network science methodologies have been applied at the cognitive level to study language and memory (Baronchelli et al. 2013; Borge-Holthoefer and Arenas 2010; Karuza et al. 2016). These efforts provide a unique opportunity to quantitatively examine the role of semantic memory structure in creativity. Indeed, a few studies have been conducted to this end. This chapter will review various applications of network science to quantitatively examine different facets of creativity.

The structure of this chapter will be in the following way: First, the application of network science at the cognitive level and the main measures used to this end will be introduced. Next, the strength of applying network science at the cognitive level to study different facets of the creative process will be illustrated. Specifically, this chapter will focus on the following applications: examining the relation between individual differences in creativity and semantic memory structure; examining the relation between executive functions and fluid intelligence, and individual differences in creativity; examining cognitive search processes as related to individual differences in creativity; and finally, examining flexibility of thought as related to individual semantic networks. These issues will demonstrate the feasibility and strength of applying network science methodologies in the study of high-level cognition such as creativity. Next, a general theory proposing a continuum of semantic memory structure and how it relates to typical and clinical populations, including individual differences in creativity will be presented. Finally, the chapter will conclude with a general overview and a discussion on future milestones that cognitive network research must achieve to advance the research of creativity.

Network Science in Cognitive Science—A Brief Introduction

Classic cognitive theory proposed that semantic memory is represented as a network, with nodes representing concepts and links representing semantic similarity (Collins and Loftus 1975). A growing body of research applies network science tools at the cognitive level to investigate the network structure of language and memory (Baronchelli et al. 2013; Karuza et al. 2016; Borge-Holthoefer and Arenas 2010; De Deyne et al. 2016b), examining more fine-grained issues such as language development (Steyvers and Tenenbaum 2005; Hills et al. 2009), second language structure (Brysbaert et al. 2014; Borodkin et al. 2016), and memory retrieval (Vitevitch et al. 2012, 2014, 2016). Of the various network models developed in network science theory, the network model that has been widely used to examine complex systems is the small-world network model (SWN; Milgram 1967; Watts and Strogatz 1998). A SWN is a network characterized by both high local connectivity and short global distances between nodes, allowing for efficient spread of activation. This network type is known as a "small-world" network because every node in the network is relatively close to other nodes. Analyses of different languages have consistently shown how different linguistic systems exhibit SWN characteristics (De Deyne and Storms 2008; Borge-Holthoefer and Arenas 2010; Arbesman et al. 2010). These SWN characteristics are now considered fundamental characteristics of linguistic systems, which allow for efficient and quick retrieval in linguistic information (Borge-Holthoefer and Arenas 2010).

Two main characteristics of SWN are the networks clustering coefficient (CC) and its average shortest path length (ASPL). The CC refers to the probability that two neighbors of a node will themselves be neighbors (i.e., a neighbor is a node *i* that is connected through an edge to node *j*). The ASPL refers to the average shortest number of steps needed to be taken between any pair of nodes. A SWN is characterized by having a high CC and a short ASPL. An additional measure, (S), quantifies the "small-world-ness" of a specific network (Humphries and Gurney 2008) by computing the ratio between the CC and the ASPL, and it reflects the extent to which a network is "small-worlded" (a value greater than one indicates that the network is "small-worlded"). The measures presented so far examine the global characteristics of a network, or what is also known as the macroscopic level of the network (Baronchelli et al. 2013; De Deyne et al. 2016b). The two other levels of network analysis are its mesoscopic level, which focuses on the properties of sub-parts of the network, and its microscopic level, which focuses on the properties of specific nodes or edges of the network.

At the mesoscopic level, research is focusing on network community structure through the analysis of modularity. A network's modularity, (Q), examines how a complex system, comprised of many nodes and edges, breaks apart (or partitions) into smaller sub-networks (Fortunato 2010; Newman 2006). The modularity measure is a statistical measure that quantifies how much a network partitions into subcommunities. The larger the modularity measure, the more the network is comprised of sub-networks (Newman 2006). The notion of modularity is extensively investigated at the neural brain organization level to examine neuronal connectivity and functional networks (Meunier et al. 2010; Bullmore and Sporns 2012; Hilgetag and Hütt 2014). Such research has consistently shown how modularity of neural networks breaks down according to the progression of several different psychopathologies (Stam 2014; van Straaten and Stam 2013). However, limited amount of research has been conducted using this quantitative measure in the study of semantic memory structure (Kenett et al. 2016b; Siew 2013; see also Shai et al. 2015).

At the microscopic level, network analysis examines different properties of nodes and edges, mainly through centrality measures (Papo et al. 2014; Brandes et al. 2016; Koschützki et al. 2005). *Closeness centrality* measures the mean shortest paths from a node to all other nodes (local ASPL; Newman 2010). *Betweenness centrality* measures how often a node is used in the shortest path between two other nodes (Freeman 1977). *Word impact centrality* examines the effect of a node on the ASPL of the network (Kenett et al. 2011). Finally, *key-players* (Vitevitch and Castro 2015) identifies nodes that when removed result in the breakdown of the network to several smaller components.

How can semantic networks be constructed? While an ample body of work analyzes textual corpora to represent semantic memory structure (e.g., Steyvers et al. 2004; Thompson and Kello 2014), here we will focus only on behavioral tasks which represent semantic memory structure based on data collected from participants. To date, the extent to which textual corpora-based approaches represent semantic memory, compared to behavioral-based approaches, is still debated (De Deyne et al. 2016c; Mandera et al. 2015, 2017; Kenett et al. 2017). Two dominant approaches to construct semantic networks from behavioral tasks are via semantic fluency and free association tasks. *Semantic fluency* is a classic neuropsychological measure (Ardila et al. 2006). In this task, participants are required to generate in a short amount of time (usually 60 s) category members of a specific category (i.e., *name all the animals you can think of*). While standard behavioral measures of this task have been developed (Troyer 2000), they have also been criticized for their subjectivity (Body and Muskett 2012). In the last few years, different computational approaches have been proposed to represent semantic fluency networks (Goñi et al. 2011; Lerner et al. 2009; Kenett et al. 2013). *Free associations* are methods based on participants freely generating associative responses (De Deyne et al. 2016b). Current network approaches using free associations use a continuous free association paradigm, where participants are asked to generate either three, five, or as many associative responses they can think of in one minute to a cue word (De Deyne and Storms 2008; Hahn 2008; Kenett et al. 2011). Based on these responses, the semantic networks of the cue words are represented.

Network Science and Creativity

Over the past few years, neurocognitive studies examined the relation between semantic memory structure and creativity (Rossman and Fink 2010; Green 2016; Abraham 2014; Beaty et al. 2014; Hass 2016a, b; Bendetowicz et al. 2017; Wu et al. 2016). This was greatly facilitated by advancements in quantifying semantic distance (Kenett 2018). In parallel to these neurocognitive efforts, a network science perspective is gradually being applied to quantitatively examine the relation of semantic memory structure as related to individual differences in creativity. These applications include the investigation of the relation of the structure of semantic memory to individual differences of creativity (Kenett et al. 2014; Benedek et al. 2017), the relation of semantic memory structure to cognitive search in low and high creative individuals (Kenett and Austerweil 2016), the relation of semantic memory structure to fluid intelligence and creative achievement (Kenett et al. 2016a), and the relation of semantic memory structure to flexibility of thought in low and high creative individuals (Kenett et al. 2018). These applications will be reviewed below, to demonstrate the feasibility of applying network science at the cognitive level in the research of creativity.

Semantic Memory Structure and Individual Differences in Creativity

The most direct relation between the structure of semantic memory and individual differences in creativity was proposed by Mednick (1962). According to his theory, low and high creative individuals differ in their structure of semantic memory, to which he referred as "associative hierarchies" (Mednick 1962). However, the notion of "associative hierarchies" was ambiguously defined and over the years both supporting and contradicting evidence for his theory have been presented (for a review see Benedek and Neubauer 2013). The controversies surrounding Mednick's theory are mainly due to the challenge of modeling and representing semantic memory, which could allow examining Mednick's theory.

In the past several years, there has been a growing amount of computational studies applying neural network modeling examining the relation between semantic memory and creativity (Doumit et al. 2013; Marupaka et al. 2012; Kajić et al. 2017; Olteţeanu and Falomir 2015, 2016). For example, Marupaka et al. (2012) suggest flexible semantic combinations arise from small-world network dynamics as groups of co-active neural units—mechanisms that may support semantic processing during creative cognition (Marupaka et al. 2012). The basic assumptions of this model are that all thought is homogeneous, combinatorial, and associative, which converge with Mednick's (1962) theory of creativity. At the core of this model lies the idea of a neural semantic network, concepts in semantic memory are somehow organized together and this structure allows spontaneous thought to occur (for more details; see Marupaka et al. 2012). The authors examine various types of network models which account for different organization of semantic memory and conclude that the best model to describe semantic memory is the SWN model. Doumit, Marupaka, and Minai (2013) applied this model to analyze the writings of prominent poets (i.e., Dylan Thomas) and writers (i.e., F. Scott Fitzgerald), by extracting their associative networks based on their textual corpora which contain a varying degree of creative language (Doumit et al. 2013). This was done to investigate whether their neural network model can account for the difference in associative networks of "more creative" poetic texts versus "less creative," more structured, prosaic texts. The authors show that the "more creative" poet corpora exhibited a "flatter" associative distribution than the "less creative" prose corpora (see Doumit et al. 2013). Nevertheless, their work was preliminary and requires further investigation. While these models contribute and advance the research on modeling semantic memory and how it may relate to creativity, they are models and simulation based. Furthermore, they focus on specific creative tasks and do not account for any possible differences in semantic memory structure as related to individual differences in creative ability. Currently, two studies have applied network science methodologies to examine this relation, both at the group level (Kenett et al. 2014) and at the individual level (Benedek et al. 2017).

Kenett et al. (2014) applied network science methods to directly investigate Mednick's (1962) notion of the structural difference between individuals. First, the authors administered a battery of creativity tests (remote association task, a battery of divergent thinking tasks, and a metaphor comprehension task) on a large sample of individuals. They then applied a statistical decision tree approach to classify their participants into low and high creative individuals. Since the authors focused on semantic creativity, they considered their groups as low semantic creative (LSC) and high semantic creative (HSC) individuals (Kenett et al. 2014). Next, the authors applied a network science method based on free associations to represent the semantic memory network structure of 96 cue words in LSC and HSC individuals. This analysis revealed that the semantic memory network of the HSC individuals is less rigid than that of the LSC individuals (Fig. 1): The semantic network of the HSC individuals had a lower ASPL and Q values and a higher S value compared to the network of the LSC individuals (Kenett et al. 2014). The authors interpret the lower ASPL and Q as facilitating more efficient spread of information within the semantic network of the HSC individuals, which can lead to enhanced ability in connecting remote associations (see also Kenett et al. 2016b; Siew 2013, 2016). These findings provide empirical network evidence for Mednick's theory by showing that high creative individuals have a more flexible semantic network structure, which may allow for more efficient retrieval strategies when generating free associations (e.g., shorter distances between words and lower modularity).

However, the work of Kenett et al. (2014) aggregated individuals into groups of low and high creative individuals, thus possibly obscuring true individual differences in semantic memory structure as related to creativity. Thus, an examination of the relation of semantic networks and creativity at the individual level is needed.

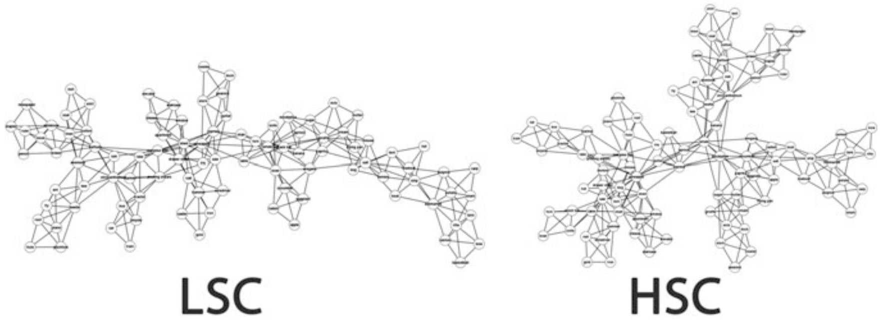

Fig. 1 A 2D visualization of the LSC and HSC semantic networks. Nodes are the 96 cue words transcribed into English. The links between nodes represent an unweighted, undirected connection between nodes. Illustration was adapted from Kenett et al. (2014)

Such methods are currently being slowly developed and are usually based on repetitive data collection from an individual (Morais et al. 2013; Zemla et al. 2016; De Deyne et al. 2016a). For example, Morais et al. (2013) have used an iterative associative "snowball" sample approach, where an individual generates an associative response to a cue word, and then a following associative response to the initial response and such onwards. However, this approach is extremely time-demanding (between thirty to sixty consecutive days of data collection per participant). More recently, Zemla et al. (2016) developed a method to estimate an individuals' semantic network based on a repetitive semantic fluency task. Their method is based on a computational probabilistic inference method and extends it to incorporate inter-item response times (Zemla et al. 2016). However, none of these methods have so far been applied to examine individual differences in creativity.

Benedek et al. developed a different approach to represent individual semantic networks based on semantic relatedness judgment ratings and related these individual semantic networks to individual differences in creative ability (Benedek et al. 2017). Their approach constructs individual semantic networks based on semantic relatedness judgments: The strength of semantic relatedness between a pair of words judged by a participant is considered a proxy of the semantic network connectivity and distance between these two words in their individual semantic network (Benedek et al. 2017; Kenett et al. 2017). Participants judged the semantic relatedness strength to all possible combinations of 28 cue words to construct their individual semantic network for these 28 cue words. These 28 cue words were composed of seven different semantic categories, with four cue words in each category. The authors predicted to find strong within category relatedness judgments and weak to none between category relatedness judgments. Furthermore, the participants were assessed for creative ability, fluid intelligence, and broad retrieval abilities. To minimize spurious relations between cue words in the individual semantic networks, three different filtering methods were applied: A threshold criterion based on a fixed edge number, based on fixed minimum relatedness, and by analyzing unfiltered weighted undirected networks. Network measures were computed from each of these three thresholded networks and related to the behavioral measures (Benedek et al. 2017).

Considering the "fixed minimum relatedness" method, creativity was positively correlated with CC and negatively with ASPL, which replicates the group-based network findings by Kenett et al. (2014). Furthermore, the correlation between Q and creativity exhibited an expected negative trend. For the other filtered networks, the authors only found a trend where more fluent people have semantic networks with shorter ASPL. This notion was further evidenced by a small positive correlation between fluency and average semantic relatedness judgments. This finding is in line with previous work showing that more creative people perceive stronger semantic relationships between more weakly connected concepts (Rossman and Fink 2010).

In sum, network science methodologies are slowly being applied to elucidate the relation of semantic memory structure and creativity both at the group (Kenett et al. 2014) and individual (Benedek et al. 2017) levels. While further research is needed to replicate and expand these initial findings, network science enables such a quantitative research.

A Quantitative Examination of the Bottom-Up and Top-Down Accounts of Creativity

These growing amount of studies highlight the importance of semantic memory structure and semantic distance in the creative process. However, the different theories on creativity (bottom-up, top-down, dual processes) attribute different importance to the role of semantic memory structure (bottom-up) as opposed to executive processes (top-down) in creativity (Beaty et al. 2014). Beaty et al. (2014) examined the involvement of bottom-up and top-down accounts to creative ability. The authors applied latent semantic analysis (Landauer and Dumais 1997) to compute semantic distance values of responses generated by participants during semantic fluency tasks to specific target words. Average semantic distance was considered as an index of semantic memory structure (Beaty et al. 2014). This measure, along with several measures of cognitive ability, was used to examine the contribution of both bottom-up and top-down processes in creative ability (i.e., divergent thinking (DT)). The authors found joint effects of average semantic distance and executive abilities, namely broad retrieval ability and fluid intelligence, on the fluency and creativity of DT responses.

The findings of Beaty et al. (2014) suggest the contribution of both bottom-up, associative structure and top-down, executive functions to creative thought (see also Forthmann et al. 2016). However, how do bottom-up and top-down processes interact and contribute to the creative process? Network science can provide a quantitative approach to examine the contributions of both of these processes in two means: First, by representing semantic networks and relating these networks to creative ability and executive processes. Second, by modeling search processes over semantic memory as related to individual differences in creativity.

Kenett et al. (2016a) examined the relation of fluid intelligence, creative ability, and semantic memory structure. The authors predicted that according to the bottom-up account of creativity, high creative individuals will exhibit in general a less structured semantic memory network, independent of their intelligence scores. According to the top-down account of creativity, however, the authors predicted that high intelligence individuals will exhibit a more structured semantic network, independent of their creativity scores. Thus, contrasting the semantic memory networks of groups varying in creativity and intelligence may provide quantitative support for either of the two accounts of the creative process. Participants completed a semantic verbal fluency task (name as many items as possible from a category, e.g., animals) and were divided into four groups based on their performance on intelligence and creativity measures. The semantic network representation of the animal category was compared for all groups. These results revealed that intelligence and creativity are differentially related to semantic memory structure: Intelligence was more related to structural properties (higher ASPL and Q values) and creativity was more related to flexible properties (higher S value). Further, this study found that the semantic network of the high creative, high intelligence group has both properties (Fig. 2).

Thus, while Beaty et al. (2014) found general mutual contributions of bottom-up and top-down processes in creativity, the findings of Kenett et al. (2016a) further contribute to understanding the roles of both of these processes by relating them to

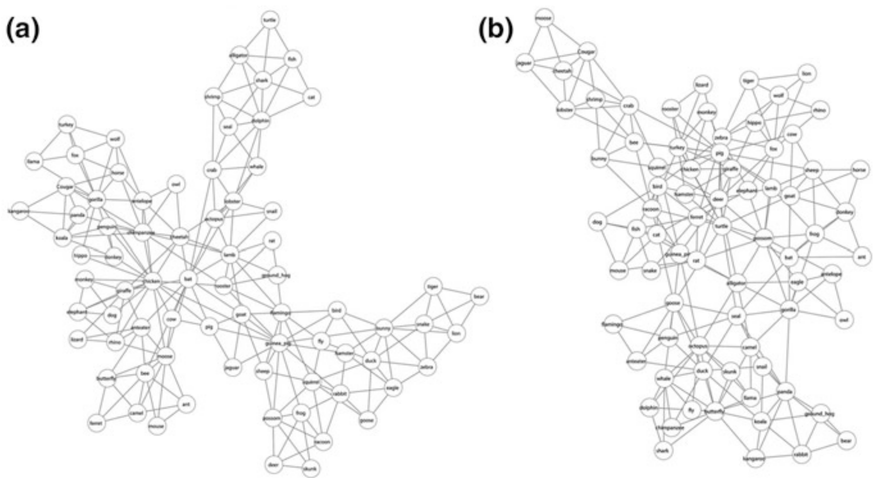

Fig. 2 A 2D visualization of the low creativity, low intelligence group (**a**) and the high creativity, high intelligence group (**b**) semantic networks. Nodes represent animal names and the links between nodes represent an unweighted, undirected connection between nodes. Illustration was adapted from Kenett et al. (2016a)

specific effects on semantic memory structure. Similarly, in their study on individual semantic networks and individual differences in creative ability, Benedek et al. (2017) also examined the relation of different facets of intelligence (fluid intelligence and broad retrieval abilities) and creativity. The authors found an effect of broad retrieval abilities predicting individual differences in creativity, which was independent of the network measures which were examined (Benedek et al. 2017). These findings provide further support for the independent contributions of both bottom-up and top-down processes to creativity.

What do these findings indicate regarding the roles of bottom-up and top-down processes in creativity? On the one hand, a more flexible semantic memory network with shorter average path length and higher clustering may facilitate the spreading of activation to more easily reach remotely related concepts (Kenett and Austerweil 2016) and contribute to the creation of novel combinations. On the other hand, a more structured semantic memory network may contribute to more efficient switches across modules (Nusbaum and Silvia 2011; Unsworth et al. 2011). This structure may contribute to overcoming conventional solutions and thus facilitate the effective evaluation and selection of relevant concepts (Benedek et al. 2012a). This perspective is in line with dual process theories of creativity (Sowden et al. 2014) and specifically to theories on the differential role of attention during generation and evaluation of creative ideas (Martindale 1995; Groborz and Neçka 2003). Current theory on creativity views such opposing and controlling forces as "controlled chaos" (Bilder and Knudsen 2014; Kaufman 2014). This notion of creativity as "controlled chaos" and how it can be examined from a cognitive network perspective will be discussed toward the end of this chapter.

Creative Search Processes over a Semantic Memory Network

According to associative theory of the creative process, the structure of semantic memory in high creative individuals allows them to connect between more remote concepts in memory (Mednick 1962). Thus, computational models of semantic memory structure and semantic distance can be applied to examine this search process and how it relates to individual differences in creativity (Kenett 2018). One such application is to examine semantic distances in DT tasks (Runco and Acar 2012). In DT, participants generate responses to verbal or figural cues, which are scored for their fluency and originality or novelty. A few studies have examined the relation of DT responses to semantic distance, under the assumption that the more creative a DT response is, the farthest its semantic distance from the original response is (Acar and Runco 2014; Beketayev and Runco 2016; Hass 2016a, b; Harbison and Haarmann 2014). Hass quantified conceptual expansion (forming novel exemplars of a concept) in a DT task by measuring the latent semantic analysis scores of the first five DT responses participants generated to different objects (Hass 2016a, b). These studies show how in general, as serial orders of the DT responses increased, their semantic distance latent semantic analysis score increased (Hass 2016b). However, these studies only examine the output of the search process that results in DT responses. What might be the cognitive process that lies at the basis of the retrieval of creative ideas and can it be quantitatively modeled?

Such a process might be based on the spreading activation mechanism (Collins and Loftus 1975). According to the spreading activation, once a concept is activated in memory, information “spreads” from it to all directly connected concepts and so forth (Collins and Loftus 1975). This information quickly decays over time and space (Den-Heyer and Briand 1986). Network research has indicated that a semantic network with lower Q and ASPL facilitates spread of activation over the network (Kenett et al. 2014, 2016b; Siew 2016). Computationally, spreading activation can be implemented as a random walk over a network (De Deyne et al. 2016b). Starting at a particular node, a random walk selects an outbound edge with a probability proportional to the edge’s weight and moves across it. As this process progresses, it explores more nodes in the network. Analogous to how spreading activation decays over a network, the probability that a walk moves from one node to another decay in their distance. Thus, the probability of moving from one node to another in a small number of steps captures their similarity.

Recent research has explored how random walk models can capture memory retrieval (Abbott et al. 2015; Capitán et al. 2012; Griffiths et al. 2007) and performance in creative tasks which require cognitive search, such as the remote association task (Bourgin et al. 2014; Smith et al. 2013; Smith and Vul 2015; Gupta et al. 2012). In the remote association task (Mednick 1962), participants are presented with a triplet of seemingly unrelated cue words (e.g., *Cottage*, *Swiss*, *Cake*) and are required to find a fourth single target word that is separately related to each of the cue words (*Cheese*; Bowden and Jung-Beeman 2003). Smith et al. (2013) view the remote association task as a multiple constraint problems, in which each cue word indicates a different attribute of the target word. Solving such a multiple constrained problem requires a two-stage process: First, a search for a possible solution is conducted and then this candidate solution is tested against all of the constraints of the problem to rate the acceptability of the solution (Smith et al. 2013). They found that participants solve remote association task stimuli first by selecting a set of possible answers constrained by a single cue word at a time. Furthermore, the authors show how prior candidate answers directly affect the following guesses, suggesting an associatively connected directed search, which is in agreement with the spreading activation model (Collins and Loftus 1975).

These studies investigated how well a random walk over semantic memory captures general performance on cognitive search and creative tasks. However, they have not examined whether differences in creative ability can be understood in terms of the same random walk process on different semantic memory structures. Recently, Kenett and Austerweil (2016) directly addressed this issue by simulating and comparing random walk models on the semantic networks of low and high creative individuals (Kenett and Austerweil 2016). The authors hypothesized that the structure of the semantic network of high creative individuals enables them to use simple search processes that reach further and to weaker connected concepts, than low creative individuals. To test this hypothesis, the authors conducted random walk simulations on the semantic networks of the LSC and HSC individuals, collected by Kenett et al. (2014). To conduct a random walk simulation over the two networks, the authors first computed a transition probability matrix: The probability of a walk to transition from a specific node to any other nodes connected to it. Next, they choose a similar starting node on both networks to initiate the walk. Finally, the authors initiated walks with varying number of steps of walks (10–200 steps) through 10,000 simulations.

The authors computed two “creative” measures based on the random walk simulations: The amount of unique visited nodes by the walk, as a measure of the breadth of the search, and the similarity between initial and final visited node, as a measure of the distance between connected concepts. To control for confound effects of the amount of unique visited nodes on the similarity measure, the authors also computed the similarity score between the initial node and a unique visited node after a fixed, truncated amount of unique visited nodes (e.g., similarity score between the initial node and the fifth unique visited node; see Kenett and Austerweil 2016). For each number of steps in the walks examined, the authors computed each of the two measures and examined the difference between the averaged measures of the two groups. A positive/negative difference score indicated that the HSC/LSC group had a bigger value than the LSC/HSC group. In line with the associative theory of creativity, the authors found that a random walk visits more unique nodes and that the similarity strength between initial and final nodes visited by the walk is weaker for walks over the HSC network than the LSC network (Fig. 3). Thus, individual differences in thought processes between LSC and HSC individuals can be produced by an uncontrolled search process on differing semantic networks, providing support for the associative theory of creativity (Mednick 1962).

The findings of Kenett and Austerweil (2016) demonstrate how search processes in low and high creative individuals can be examined via random walk simulations

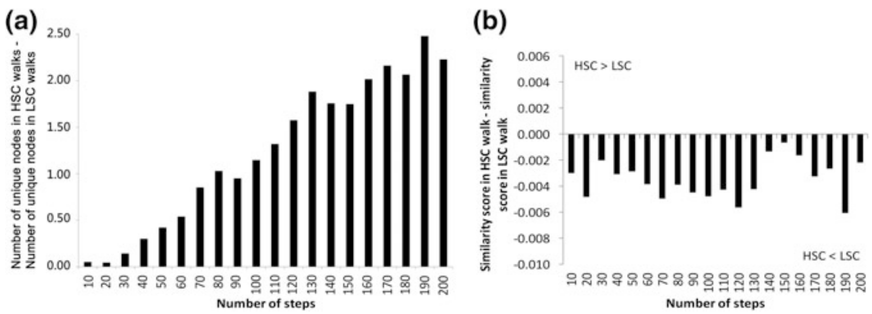

Fig. 3 Difference score between HSC and LSC groups (HSC-LSC) in amount of unique visited nodes (**a**) and similarity between initial and truncated final visited node (**b**). X-axis—number of steps in the walk; Y-axis—difference score. Illustration was adapted from Kenett and Austerweil (2016)

and how the walk over the semantic network of high creative individuals reaches farther and weaker concepts in their semantic network. The study of Kenett and Austerweil (2016) adds to the previous applications of random walk models to examine creative tasks such as the remote association task (Bourgin et al. 2014; Smith et al. 2013). These efforts demonstrate the strength of such models in examining cognitive search processes related to individual differences in creativity.

Quantifying Flexibility of Thought in Creativity

A defining feature of creativity is flexibility, the ability to create and use new mental categories and concepts to reorganize our experiences (Nijstad et al. 2010; Mednick 1962). Flexibility in creativity has been related to originality of ideas and the ability to break apart from mental fixations (Smith and Ward 2012). According to the associative theory of creativity, high creative individuals have a more flexible semantic memory structure, which facilitates their ability to "search" through their memory and connect weakly related concepts together (Mednick 1962). However, currently flexibility in creativity is studied only through indirect behavioral means (Benedek et al. 2014; Pan and Yu 2016; Chrysikou et al. 2016).

In an attempt to examine insight from a semantic network perspective, Schilling (2005) proposed that insight arises from a dynamical restructuring of semantic memory structure, which is unlike incremental learning. According to her theory, all prominent theories on the process of insight incorporate unexpected connections within or across semantic memory structure, by either creating new links between nodes or by finding "shortcuts" in the network (Schilling 2005). According to this unique theory, this restructuring leads to a rapid cascade of changes in the network, an effect that is in line with network theory research (Cohen and Havlin 2010; Barabási 2016). Consistent with this theory, Durso et al. (1994) applied a theoretical network research and demonstrated that insight can be verified as a restructuring that occurs when participants note similarity between concepts that had previously appeared unrelated. Thus, flexible restructuring of a semantic network is related to insight. How can the more general flexible nature of semantic memory in high creative individuals, as posited by creativity theory, be examined?

This issue was examined by Kenett et al., who used percolation theory to "attack" the semantic networks of LSC and HSC individuals, and examined the robustness of the semantic networks to these attacks as a quantitative measure of cognitive flexibility (Kenett et al. 2018). Percolation theory examines the robustness of complex networks under targeted attacks or random failures (Cohen and Havlin 2010; Newman 2010). This is achieved by examining the effect of removing nodes or links from a network, and how that removal affects the giant component (the largest connected group of nodes) in the network (Saberi 2015; Cohen and Havlin 2010). As a result of such a removal process, groups of nodes disconnect from the network. The groups that separate from the network are the network percolation components, and the remaining group of nodes is the giant component in the network. The robustness of a network is its ability to withstand such failures and targeted attacks, evident in relative little effect on the giant component of the network.

Kenett et al. (2018) quantify cognitive flexibility as the robustness of semantic network to attack, based on the assumption that the higher the robustness of a semantic network to attack, the higher its flexibility. Thus, in accordance with the associative theory of creativity, the authors predicted that the semantic network of high creative individuals will be more robust than that of low creative individuals. To examine this hypothesis, the authors conducted a network percolation analysis on the semantic networks of LSC and HSC individuals, data previously collected by Kenett et al. (2014). This was performed by using percolation theory to remove links with increasing link strengths and examining how this affects the robustness of the semantic networks of the LSC and HSC groups. Such degradation of links is also grounded in cognitive theory on memory phenomena such as dementia and retrieval failures (Burke et al. 1991; Borge-Holthoefer et al. 2011).

The study of Kenett et al. (2018) sheds further light on the difference in network structure between the two groups, by examining how they break apart. The authors show how the semantic network of HSC individuals is more robust to network percolation, as indicated by a slower breaking of their network (Fig. 4). Importantly, the authors show how the difference in robustness between the two groups is uniquely related to differences in the structure of their semantic networks. Specifically, the authors found that the mechanism that differentiates the robustness between the two networks lies in the HSC network having stronger links that connect between different components in their network than the LSC network. This difference between the two groups may facilitate spread of activation in the HSC network, an important aspect of the creative process (Nijstad et al. 2010; Mednick 1962), and provide a stronger "glue" in the network to resist such attacks.

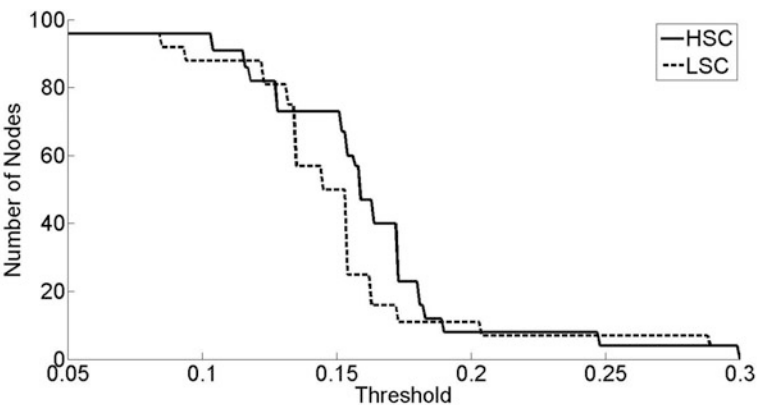

Fig. 4 Percolation analysis of the empirical networks of the LSC and HSC networks. X-axis—varying threshold of link strength that are removed (all links equal or smaller then); Y-axis—number of nodes. Illustration was adapted from Kenett et al. (2018)

Taken together, Kenett et al. (2018) quantify flexibility of thought as robustness of semantic networks to network percolation and show how the semantic network of HSC individuals is more robust to network percolation. The mechanism that facilitates this higher robustness of the HSC network (stronger interlinks) plays an important role in individual differences in creativity: It facilitates spread of activation between components in the network, thus allowing to "break free" from a component in the network and leading to novel combinations. This is directly related to theory on the effect of modularity on cognitive networks (Siew 2013, 2016; Kenett et al. 2014, 2016b).

Semantic Memory Structure and Individual Differences in Creativity—A Continuum

Finally, the differences in network measures related to individual differences in creativity can be related to a more general theory on the relation of semantic memory structure and typical and clinical populations (Faust and Kenett 2014). This general cognitive theory is based on the integrative explanation for the psychological state of well-being, put forward by Siegel (2010). According to his theory, emotional well-being is a state of integrative balance, easily disrupted by deviation either toward too little arousal, a state of rigidity, or excessive arousal, a state of chaos (Siegel 2010). Thus, mental illness can be defined as a shift from a state of integration either to a rigid extreme or to a chaotic extreme.

Based on Siegel's theory, Faust and Kenett (2014) proposed a continuum of varying semantic memory structures that constrain cognitive processes, such as retrieval from semantic memory (Fig. 5). At one extreme of this continuum is rigid networks, which are minimally connected (i.e., each node in such a network is only connected to one other node). Activation decays as it spreads through more links, which results in repetitive retrieval because only a few nodes close to the source will be activated enough to be retrieved. Rigid networks are characteristic of the semantic memory structure of individuals with autism spectrum disorders (Kenett et al. 2016b). At the other extreme is chaotic networks, which are highly connected. This results in disorganized retrieval because many nodes are activated from a single source. Chaotic networks are characteristic of the semantic memory structure of individuals with schizophrenia (Lee et al. under review). According to our theory, semantic retrieval in typical individuals is achieved via a balance between rigid and chaotic network structure. This balance allows both conventional (ordered) and flexible (chaotic) language processing (Faust and Kenett 2014).

In regard to individual differences in creative ability, as an individuals' semantic memory structure is more rigid, it is less creative, reaching in extreme cases the point of a pathological state. In contrast, as their semantic memory structure is more chaotic, it is more creative, yet in extreme cases it may result in a pathological state. This proposal is supported by research showing how persons with autism exhibit

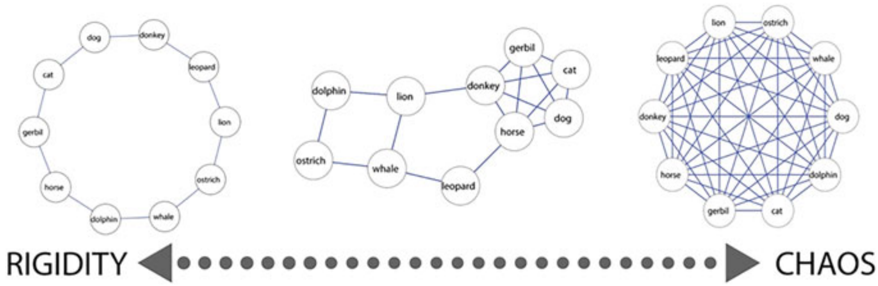

Fig. 5 An illustration of the semantic continuum. Ten nodes are presented varying in connectivity ranging from a rigid organization (left), to a chaotic organization (right). In between, these two extremes are networks with a balance between rigid and chaotic structure (center). Illustration was adapted from Faust and Kenett (2014)

difficulty in creativity tasks (Craig and Baron-Cohen 1999; Turner 1999). In regard to the other extreme of this continuum, research has found correlations between creativity and schizotypal personality traits (Kaufman and Paul 2014) and also that persons with schizophrenia exhibit atypical processing of metaphoric expressions (Zeev-Wolf et al. 2015). Our results are further related to the shared vulnerabilities model of creativity and psychopathology (Carson 2011, 2014). This model proposes that creativity and psychopathology share a genetic factor that is expressed as either creativity or psychopathology depending on an interaction between cognitive vulnerabilities (latent inhibition, novelty seeking, and neural hyper-connectivity) and protective factors (high IQ, cognitive, and flexibility). This model proposes that protective factors related to top-down control, in the form of high IQ, coupled with chaotic thought processes, exhibited with lowered latent inhibition, are related to higher level of creativity (Carson 2014; Kéri 2011). This prediction can be quantified in network science terms of Q and ASPL, as indicators of structure, and S, as indicator of chaos.

Thus, creativity can be considered as "controlled chaos" (Bilder and Knudsen 2014) and continuous levels of creative ability can be grounded in such a semantic memory structure continuum. Finally, this theory demonstrates the power of applying network science at the cognitive level, which allows comparing different groups, ranging from typical to clinical, on matched quantitative measures.

Conclusions

This chapter reviewed current studies that apply network science methodologies at the cognitive level to quantitatively examine different facets of the creative process. The contribution of semantic memory structure to the creative process by facilitating search, retrieval, and manipulation of concepts that generate novel and applicable ideas is strongly rooted in the various theories of the creative process (Mednick 1962; Benedek et al. 2014; Sowden et al. 2014). The application of network science at the cognitive level to study creativity is transforming the field: By allowing directly examining how semantic memory structure relates to individual differences in creativity; by grounding different facets of the creative process into quantitative, testable measures; and by expanding and empirically investigating different theories on the creative process. While cognitive network research on creativity is currently very initial, it has already demonstrated its potential in further elucidating the multifaceted nature of creativity and in the more general study of high-level cognition.

What milestones are required to achieve in the application of network science at the cognitive level in order to revolutionize the research of high-level cognition? First, relevant statistical methods need to be developed in order to statistically compare across empirical cognitive networks (Moreno and Neville 2013). Such methods are required when conducting empirical network research to determine whether two (or more) networks are significantly different from each other or not (null hypothesis). This lack of network comparison hypothesis testing is mainly due to difficulties in estimating or collecting a large sample of empirical networks and scarcity of statistical methods to compare between networks (see Moreno and Neville 2013). Currently, the statistical approaches applied to compare empirical cognitive networks are either via simulation of random networks (Borodkin et al. 2016) or via bootstrapping approaches (Efron 1979) to generate large distributions of network measures (as an example; see Kenett et al. 2016b).

Another milestone that must be reached is the development of methodologies to represent individual semantic networks. While currently a few such approaches exist, they are either extremely time demanding (Morais et al. 2013), being developed (Zemla et al. 2016), or are currently applied to examine small networks (Benedek et al. 2017). Creative ability widely varies across individuals. Thus, only the development of efficient methods to represent large-scale individual networks can advance the relation of semantic memory network measures to individual differences in creativity (De Deyne et al. 2016b).

A further milestone that must be reached is the development of methods to study dynamical cognitive networks. Semantic memory is increasingly considered dynamic, contingent on context, and variable between individuals (Yee and Thompson-Schill 2016). However, current methods to represent semantic networks are static in the sense that they analyze networks at one-time point and do not address dynamic shifting of these networks. While dynamic network tools are being developed to analyze brain networks (Braun et al. 2015; Doron et al. 2012), applying such tools at the cognitive level remains a challenge. This is mainly due to issues in how to construct cognitive networks at different time points.

Finally, perhaps the biggest milestone of them all is developing network science methodologies to relate cognitive networks to brain networks. At the neurocognitive level, research has implicated dynamic coupling between a top-down, executive control brain network and a bottom-up, "default mode" brain network in the creative process (Beaty et al. 2015, 2016a). These findings at the brain level may relate to the findings at the cognitive level described above. Importantly, in the last several years there has been a significant increase in the application of network science at the brain level, known as network neuroscience (Medaglia et al. 2015a). Especially important to the study of creativity, network neuroscience tools are being developed to study neural flexibility (Medaglia et al. 2015b; Braun et al. 2015; Chai et al. 2016) and to examine the roles of specific brain regions in "controlling" the neural system (Gu et al. 2015; Medaglia et al. 2016). Thus, network science encapsulates a unique opportunity to quantitatively examine creativity across different levels of analysis.

In sum, network science is revolutionizing and transforming neurocognitive research of high-level cognition. Slowly, research applying network science at the cognitive level to quantitatively study the role of semantic memory in creativity is being conducted. This work allows examining classic theories on the role of semantic memory structure in the creative process, expanding and evolving these theories and grounding them in quantitative measures in the process.

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The Neuropsychological Aspects of Musical Creativity

Ana Luísa Pinho

Abstract Creativity emerges from the individual or collective intellect, in order to unfold the conundrum of life and give rise to meaningful deliberations for the attainment of a flourishing life. More specifically, creativity is commonly defined, within the framework of psychology, as an act or product that shall fulfill three main criteria: originality, unexpectedness, and usefulness. The cognitive science approach to creativity investigates the intellectual processes and representations concerned with the creative thinking. The methodologies of cognitive science, derived from the technological advancements of the past sixty years, have begun to adopt a more definitive and systemic perspective. Neuroscience has emerged, under this context, as the scientific study dedicated to explore the biological substrates of the nervous system, by utilizing a multitude of techniques such as neuroimaging. Cognitive neuroscience, in particular, studies the neural correlates of mental processes, and it constitutes the central approach herein adopted to examine musical creativity as a product of the human mind. In the present section, a definition plus historical evolvement of creativity are firstly provided together with an overview of its developments in psychometry. Secondly, a comprehensive description regarding the scientific advances about the topic, and within the field of cognitive neuroscience, is described according to: (1) the model on the four types of creativity and (2) the main categories of experimental designs implemented so far. Lastly, the latest advancements on the study of musical creativity, in particular musical improvisation, will be addressed under the neuroimaging framework.

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Creativity

Nature evolves from transformation and adaptation based on fundamental processes that constitute the driving force toward creation. Evolution thus relies upon constructive mechanisms that progressively disrupt the current settings and conceive new possibilities. With regard to the anthropological perspective, the nourishment of the curiosity sustained by fostering imagination arises as an innate modus vivendi to surpass self-nature. These are the underpinnings that have enabled humankind to conceptualize about creativity.

Origins and Concept

Creativity emerges from the individual or collective intellect in order to unfold the conundrum of life and give rise to meaningful deliberations for the attainment of a flourishing life. Nonetheless, the concept of creativity has itself changed across time as an endeavor to grasp its meaning for humanity.

Ancient pre-Greek civilizations had developed the concept of genius, which came attached to the idea of mystical powers of protection and good fortune. However, Greeks gradually changed the concept when it started to be associated with the Daemons. The idea of genius became mundane and intrinsically linked to individual's abilities and appetites.[1] Being a genius took thus a social value and, by the time of Aristotle, it was frequently associated with madness and frantic behaviors.[2] Romans additionally linked these ideas to exclusively male capacities (Albert and Runco 1999, pp. 17–18).

The research community agrees that the earliest concept of creativity in the Western world came from the biblical story of the creation, part of the Genesis, alluding to the idea of crafting on Earth under God's will. Some criticism was raised in the second century A.D. toward these interpretations but without marked success. In general, Western beliefs supported the idea that creativity could only happen by godlike intervention, while Eastern cultures emphasized the role played by the intervenients. Eastern philosophies defined creation as a process of discovery and mimicry, thus reflecting proneness to perceive natural cycles, harmony, regularity and balance[3] and (Albert and Runco 1999, p. 18).

[1]These attributes were not necessarily pejorative. They might be constructive as well as destructive.

[2]This idea was recovered, during nineteenth and early twentieth centuries, to name eccentric and erratic behaviors.

[3]As stated by Boorstin (1992), Eastern traditions were in favor that "the idea of the creation of something ex nihilo ("from nothing") had no place in a universe of the yin and yang." (Boorstin (1992).

The assumptions about creativity linked to the divine were not challenged for a long period. During the Middle Ages, special talents or unusual abilities were usually interpreted as delegations of an outside spirit (Albert and Runco 1999, p. 18).

Only in the Renaissance, transformative ideas around this topic had clearly manifested as a consequence of the early modern cultural approach. At this period, the outstanding attributes of great artists had started to be recognized as their own.

This rare chapter of the history of mankind brought out the power of discovery and the disruption of cultural and religious paradigms. Thence, when we examine the succeeding Age of Enlightenment's view in the eighteen century, we find two profoundly and intellectually new perspectives: reason and individualism. A new paradigm shift took place as a consequence of The Enlightenment's resistance towards religion's knowledgeability; Natural Science was thus taking shape as an institutionalized philosophy and methodology. Although not many changes related to ideas about creativity had occurred between the years of 1500 and 1700, a substantial amount of new contributions were of the utmost importance to foster the interest in research. It was around this period that science started to prevail as a role model of the Western thinking and, simultaneously, to develop instruments of discovery and models pertaining the physical world. This dramatic turn of events constituted for many scholars the beginning of a distinctive Western civilization embedded by Modernity (Albert and Runco 1999, pp. 18–20).

According to what has been described, creativity arises as a universal concept crossing many different academic fields, such as philosophy, technology, economics, anthropology, psychology and, more recently, cognitive science. And while a multitude of approaches have been used to study the creative phenomenon, most of the conceptual and definitional work has been conducted in psychology, more specifically, using psychometric methods—"the direct measurement of creativity and/or its perceived correlates in individuals" (Plucker and Renzulli 1999, p. 35). Although psychology became a formal discipline already in the late nineteenth century, creativity has only attracted considerable attention for the latter half of the twentieth century. In 1950, J. P. Guilford pointed out in his American Psychological Association Presidential Address the scarce amount of entries focused on creativity (less than 0.2%) in Psychological Abstracts up that date and, thus, more attention should be paid to this research topic (Sternberg and Lubart 1999, p. 3; Plucker and Renzulli 1999, p. 35).

A common and generic definition of a creative act, widely accepted among scholars, is that "Creativity is the ability to produce work that is both novel (i.e., original, unexpected) and appropriate (i.e., useful, adaptive concerning task constraints)" (Sternberg and Lubart 1999, p. 3). Even so, creativity is not only about the individual, when one takes the enterprise of achieving a fine solution, but also about the way society addresses new scientific findings, new movements in art, new inventions as well as new social programs.

Confluence Theories of Creativity

Several explicit theories from the past thirty years have proposed different approaches, each of them emphasizing different factors that must converge for creativity to occur (Sternberg and Lubart 1999, p. 10).

Amabile (1983) described creativity to be not solely associated with individual creative-relevant skills, but rather a confluence of creative proficiency, intrinsic motivation, domain-relevant knowledge, and suitable abilities. Grueber and his colleagues had proposed, in turn, an evolutionary system based on the interplay between individual's behavior and knowledge gradually acquired (Gruber 1981, 1988; Gruber and Davis 1988). On the other hand, Csikszentmihályi (1988, 1996) described creativity as a synergy between the individual, the field, and the cultural context, i.e., a subject transforms information on a specific topic, and potentially extends it, according to cognitive processes, personality traits, and motivation. Gardner (1993) suggested that the development of creative projects may arise from singular and critical situations (e.g., tension promoted by two competing fronts) or mild asynchronies between the individual and the external context (e.g., uncommon individual talent for a particular domain).

Finally, Sternberg and Lubart (1991, 1992, 1995, 1996) presented the investment theory of creativity, in which creativity springs up from the will and ability of "buy low and sell high". Such concept stands for the ideas which are not usually well-accepted from the beginning, yet they become of a great value due to the individual's transformative skills.

There are six paramount confluence resources that partake of the model[4]: (i) intellectual abilities, (ii) knowledge, (iii) styles of thinking, (iv) personality, (v) motivation, and (vi) environment (Sternberg and Lubart 1999, p. 11).

Three major categories of intellectual abilities can be distinguished: (a) the synthetic ability that conveys systematization for perceiving the whole-problem and thinking "out-of-the-box"; (b) the analytic ability that allows for pursuing what is useful from what is not; and (c) the practical–contextual ability that heightens the capacity to persuade others of the value of one's idea. Interestingly, the absence of factor(s) produces ineffectual results, like: (1) if only synthetic ability exists, the whole-context will not be properly addressed, since new ideas are not subjected to proper testing; (2) if only analytical ability exists, the thinking will turn to be powerfully critical but not creative; and (3) if only practical–context ability exists, the idea will be transmitted not because it worth some thought, but rather because it was well and powerfully presented (Sternberg and Lubart 1999, p. 11).

Knowledge also constitutes another important aspect to consider when we examine creativity and it is often called crystalized intelligence (Sternberg and O'Hara 1999, p. 256). It is a "double-edge sword" because one may find it necessary to advance beyond into the enterprise, yet knowledge can prevent creativity to occur by leading an individual to become entrenched.

[4]In agreement with the Investment Theory of Creativity (Sternberg and Lubart 1999, p. 11).

With regard to styles of thought, a self-deliberative style turns to be essential in the pursuit of creativity, i.e., the preference for thinking in new ways in respect to one's own choices. Yet, one may find appealing to think in novel ways, but such accomplishment requires analytical ability for the development of creative ideas (Sternberg and Lubart 1999, p. 11).

Personality also plays a major role regarding creative achievement and their contributing factors include: (I) self-efficacy and willingness to overcome obstacles; (II) take sensible risks; and (III) tolerate ambiguity. Particularly, "buying low and selling high" implies self-determination in the enterprise of breaking conventions and acting in creative ways (Sternberg and Lubart 1999, p. 11). Further, seminal work conducted by Dollinger et al. (2004) investigated the relation between creativity and the Big Five personality traits as measures extracted from a battery of tests on divergent thinking (see section "Creative Cognition"). No personality trait was found to be consistently correlated with creative personality apart from openness. Another representative study of personality and creativity by George and Zhou (2001) has even shown that levels of creative achievement were higher among open participants if they were given undefined tasks (Feist 2010, pp. 120–121).

Motivation is also recognized to be highly important for creativity, by influencing intrinsic task-focused disposition. Research in this topic (Amabile 1983) had revealed that truly creative people are those who show inwardly involvement and commitment to work, because they do love what they are doing, rather than seek potential reward (Sternberg and Lubart 1999, p. 11). In addition, Prabhu et al. (2008) have also shown that intrinsic motivation plays an important role as a mediator between openness and creativity (Feist 2010, p. 121).

Finally, and in contrast to the aforementioned factors focused on individual differences, environment is crucial for creative functioning. Because it is very difficult to reproduce creative environments, where spontaneous and typically non-observed behavior takes place, the formal tests of creativity measuring the ability or tendency to be creative outside the test situation are scarce and, often, questionable (Plucker and Renzulli 1999, p. 46; Nickerson 1999, p. 406). Simonton (1999) examined historiometric data,[5] based on inquiries performed by creative individuals. The factors identified were: (A) birth order, i.e., whether the individual is the first-, middle-, last-born, or only child[6]; (B) childhood trauma (e.g., parental loss); (C) family background, e.g. creativity is frequently linked to disturbances in the familiar setting; (D) education, mostly related to less conventional environments; (E) role models and mentors, who become sources of inspiration, contributing as a major driving force on the creative achievement of the pupil; (F) cultural factors, by enforcing discipline or aesthetical suasion; (G) social factors,

[5]Historiometric methods are drawn upon quantitative data extracted mostly from historical documents.

[6]Interestingly, it was shown that notable scientists are more likely to be firstborns than creative writers.

like social structure or demographic phenomena; and (H) political factors, e.g. critical contexts, such as war, may promote uneasy psychological states.

Creative Process

Several descriptions of the creative process were developed as an attempt to better explain the underlying psychological mechanism. The most widely accepted Western description involves four pivotal stages of progress: (i) preparation, (ii) incubation, (iii) illumination, and (iv) verification (Hadamard 1945; Poincaré 1921; Ribot 1921; Rossman 1931; Wallas 1926). Preparation relates to the preliminary analysis of the problem as well as the first endeavors to execute the task. Incubation might be associated with active unconscious work on the problem, automatic spreading of activation in memory, associative play or disregard of issues potentially irrelevant, and a subsequent mental rest. Illumination emerges afterward when a sudden but promising idea consciously arises. Finally, the creative idea is evaluated, developed, and refined during verification. Although the validity of this approach might be debatable, a certain consistency with introspective narratives by Western creators is still noticeable. Furthermore, an important and peculiar attribute that characterized undoubtedly the Western approach is its assertiveness toward cognitive problem solving and subsequent product-oriented definition of creativity. In fact, evidence for an alternative approach congruent with Eastern philosophies has been reported by Maduro (1976) in a study conducted on Indian painters. The outcomes seemed to indicate that the incubation process is rather implicated with "achievement of an internal identification with the subject matter of the painting" and illumination is, in turn, very much driven by personal-oriented motivations. Nevertheless, verification is still about social communication pursuing personal realizations, like in the Western model (Lubart 1999, pp. 341–342).

Creative Cognition

The cognitive approach to creativity investigates the intellectual processes and representations concerned with the creative functioning.

On the quest for an operationalization of creativity, divergent-thinking batteries have been largely used as behavioral models across many studies on creative cognition; such studies pertain to the investigation of mental functions involved during the creative process. Divergent-thinking tests are based on the extensive production of novel and meaningful responses by exploring many possible solutions. They contrast with standard tests of achievement and ability, which imply convergent thinking, since the latter essentially require only one correct answer. A peculiar characteristic ascribed to the test is the clear emphasis upon fluency, since it is seen as a key component while the creative process is still ongoing.

Psychometric tests to measure individual abilities in divergent thinking were firstly introduced by Guilford (1967), named the Structure of the Intellect divergent production tests. According to Guilford, creative people could be characterized by the capacity of quickly generate a multitude of novel and original ideas as well as to think in a flexible fashion (de Manzano 2010, p. 9). Nevertheless, it is important to notice that divergent thinking does not stand for creativity. It conveys instead the ability to enable creative thinking together with other confluence factors (see section "Confluence Theories of Creativity") (de Manzano 2010, p. 9).

Presently, the most advanced methodologies have adopted a more definitive perspective, when compared to earlier approaches, and experiments quite often take place in highly controlled environments. The human mind is herein defined as "a complex system that receives, stores, retrieves, transforms, and transmits information", i.e., an information-processing system (Stillings et al. 1998). Thus, considering the systemic dimension of this approach, the capacity for creative thought is perceived as a rule rather than a combination of exceptional subject-specific features. Thence, the underpinnings of the creative cognition approach, undertaken to investigate human creativity, follow the next list of claims: (i) The normative human cognition property is the set of generative abilities that furthers everyday cognitive activities, surpassing discrete stored experiences usually linked to "creative geniuses"[7]; (ii) the identified generative abilities are open to rigorous experimental examination; and (iii) creative accomplishments, from the most ordinary to the most extraordinary, are based on common mental processes presumably observable (Ward et al. 1999, pp. 189–190).

A general framework which attempts to systematize creative functioning is the Geneplore model, grounded in the creative cognition approach. According to this heuristic model, creativity can be explained as a two-step process: generative and exploratory. Generative processes reflect the variety of potentially creative ideas, named "the preinventive" structures (e.g., memory retrieval, formation and combination of the recalled memories, transfer of information from one domain to another, categorical reduction), whereas exploratory processes refer to the evaluation, interpretation, and employment of the selected preinvented structures. The model also includes constraints on the (final) product, which can be accomplished by imposing them anytime during generative and/or exploratory phase. This allows the model to become flexible to a wide selection of possibilities. After the exploratory phase is finished, the processes can operate in cycle, up to the moment when preinventive structures result in a final creative idea (Ward et al. 1999, pp. 191–193).

Research encompassing studies both in human subjects and computer simulations has increased over the past thirty years, as an attempt to extricate the complex mechanisms implicated in creativity. Multiple methods have thus emerged

[7]A corollary of this statement is that the few individuals, who demonstrate outstanding capacities, use cognitive processes very different from those employed by the majority of the people and, thus, methods of cognitive science are not suffice to characterize such processes (Hershman and Lieb 1988).

primarily in the fields of: (a) psychology, mostly addressing experimental studies focused in human behavior); (b) artificial intelligence, using computational models developed to simulate aspects of human performance; and (c) neuroscience, dedicated to study the biological substrates of the nervous system, addressing a multitude of techniques, such as neuroimaging (Thagard 2014). Cognitive Neuroscience is drawn upon theories combining methodologies from the three aforementioned fields, and it constitutes the central approach underlying the studies anent creativity, in particular musical creativity, that feature the upcoming sections.

The Neural Correlates of Creative Thinking

Under the framework of cognitive neuroscience, many studies, focused on the neural correlates underlying creativity, have appeared with increased frequence for the last fifteen years. The four predominant methodologies that have resulted in the most seminal, even though intriguing, findings are: electroencephalography (EEG), positron emission tomography (PET), transcranial magnetic stimulation (TMS), and functional magnetic resonance imaging (fMRI).

A theoretical account was proposed by Dietrich (2004) based on advances of the past twenty years mediated by the aforementioned techniques. It is intended to describe four types of creativity, each of them regulated by a distinct neural pathway. Creativity can then emerge through two information-processing modes: (1) deliberate, in which a conscious effort shall be sustained; and (2) spontaneous, in which the mental phenomenon arises unexpectedly. Such modes are in turn regulated by either cognitive or emotional structures. The current model thus delivers a unique characterization of four different aspects present during the creative act, as a result of the combination between the information-processing modes with the cognitive or emotional structures. However, it must be stressed that creative manifestations are never the pure form of one fundamental component, but the combination and interaction of several.

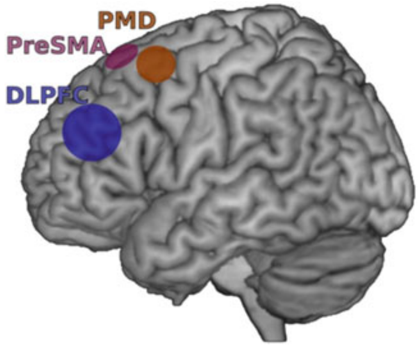
It is consensual that modulating behavior poses major challenges, as well as what concerns afterward to separation and analysis of its fundamental features. Besides, behavioral models are tested and studied normally under non-ecological contexts, which may introduce potential confounds. Hence, it is hard to assessing spontaneous behavior, due to constraints of the environment, in which experiments usually take place. As a result, seminal work on creativity relies, to a great extent, on experimental paradigms attempting to capture cognitive and deliberate mechanisms.

Functional regions in the prefrontal cortex, namely dorsal areas, are recognized to play an important role on the integration of highly processed information to allow for performance of cognitive functions, such as self-construct (Keenan et al. 2000; Vogeley et al. 2001). In particular, the dorsolateral prefrontal cortex (see Fig. 1) is above all connected to the temporal, occipital, and parietal cortices, which are in turn devoted to assemble and assimilate sensory information; subsequently, the output is directed from the dorsolateral prefrontal cortex toward the motor cortices. Many studies have shown the involvement of this region in general cognitive abilities, such as working memory, goal-directed attention, and temporal integration (Fuster 2000a; Posner 1994). Despite the primary role of dorsolateral prefrontal cortex in extrospective networks, further investigations have revealed a fundamental interplay of dorsolateral prefrontal cortex within introspective networks, specifically between medial regions of the prefrontal cortex such as the cingulate cortex and the ventromedial prefrontal cortex (Dietrich 2004). These structures have appeared to be typically involved in affective processing as well as conceptualization of complex emotions, like assessing significance of social contexts. Therefore, the dorsolateral prefrontal cortex integrates both emotional and cognitive information in order to attain appropriate behaviors, which are in turn mediated by the premotor and motor regions (Fuster 2000b).

Creative thinking falls within the scope of the aforementioned mechanisms and, notwithstanding the type of creative process generated, all four categories share, at the end, a common pathway featured by the dorsolateral prefrontal cortex (Dietrich 2004). Unsurprisingly, research has demonstrated the major role of the prefrontal cortex during the creative process, particularly when creativity is the result of deliberate control as opposed to spontaneous generation. Dietrich (2004) hypothesized that deliberate closed problem solving may show larger activation in the frontal areas, namely the dorsolateral prefrontal cortex, whereas solutions to open-ended problems may exhibit higher activity in the temporal, parietal, and occipital areas. Because these latter areas are primarily devoted to perception as well as long-term memory, it is argued that spontaneous insights may emerge from there. The frontal lobe is devoted instead to internalizing sophisticated mental abilities, such as abstract thinking, planning, working memory, and willed action (Sawyer 2011). Particularly, a systematic investigation of neural processes underlying free selection has been performed using PET and TMS by means of simpler behavioral models attempting to characterize willed action[8] (Jahanshahi and Frith 1998). These behavioral models include: (i) finger and hand movements (Deiber et al. 1991; Frith 2000; Lau et al. 2004; Playford et al. 1992); (ii) number generation (Jahanshahi et al. 2000). Further, contrasting pseudo-random generation of responses with stereotyped actions has also contributed for a better description of free selection. Several cortical regions were then identified, such as the dorsolateral prefrontal cortex, medial and lateral premotor areas, as well as the anterior cingulate cortex. This approach has thus allowed for an elegant analysis of the various aspects involved in free selection, such as attention to action, working memory, suppression of stereotype responses, and selection per se (Desmond et al. 1998; Lau et al. 2004; Nathaniel-James and Frith 2002).

[8]Willed actions can be described as self-generated behaviors, involving: (i) attention and conscious awareness; (ii) choice and control, and (iii) intentionality (Jahanshahi and Frith 1998). They thus fall within the class of behavioral models, which are pointed to be part of the creative act.

Fig. 1 Schematic representation of three major brain regions involved in the performance of musical improvisation: the dorsolateral prefrontal cortex (DLPFC), the dorsal premotor area (PMD), and the presupplementary motor area (PreSMA)



In summary, the dorsolateral prefrontal cortex is putatively involved in high-order executive functions, such as creative thinking. According to Dietrich (2004): "It further integrates already highly processed, formulated plans and strategies for appropriate behavior in a given situation, and instructs the adjacent motor cortices to execute its computational product." Thus, it is expected the dorsolateral prefrontal cortex, together with motor cortical regions, might be involved in conscious and deliberate creativity. Moreover, the superimposition of these highly complex structures allows for a dramatic increase in cognitive flexibility, furthering sophisticated cognitive processes required for creative thinking (Dietrich 2004).

Meta-analyses have extensively validated the role of the dorsolateral prefrontal cortex during the creative process. Results using coordinate-based meta-analysis in fMRI studies have shown the implication of this region along with the right anterior cingulate cortex, the posterior parietal cortex, left fusiform gyrus, and middle temporal gyrus during creative idea generation in the performance of divergent-thinking tasks (Wu et al. 2015). Particularly, free-generative tasks were associated with the frontoparietal network, comprising the dorsolateral prefrontal cortex and the inferior parietal area. In addition, the left dorsolateral prefrontal cortex was linked to free selection and update of semantic content in working-memory tasks (Gonen-Yaacovi et al. 2013).

According to Sawyer (2011), studies that yielded relevant contributions to the research of creativity can be grouped into five main categories of experimental paradigms: (i) creative insight; (ii) mind wandering and incubation; (iii) creative brains vs. non-creative brains; (iv) differences in expertise; and (v) musical improvisation. They will be addressed in detail over the next sections.

Creative Insight

Insight (aka Illumination, see section "Creative Process") relates with the moment when a sudden but promising solution to a open-ended problem consciously arises. It may also involve the redevelopment of an ongoing situation in a new, more efficient as well as more productive manner. Yet, it is clear that, in both cases, creative insights occur in consciousness, which is, in turn, controlled by working-memory processes sustained by the prefrontal cortex.

Many studies using either EEG or fMRI have contributed to clarify specificities associated with the mechanisms involved during insight, in order to fully characterize its neural correlates (Sawyer 2011). For instance, a general important question is whether insightful solutions recruit different cognitive machinery than ordinary problem solving or they are just a result of a purely subjective feeling of emotional intensity at the time of discovery. Jung-Beeman et al. (2004) conducted experiments by solving verbal problems that could lead to insight versus non-insight solutions. Although both cases shared a largely cortical network, the results showed distinct cognitive processes associated with "Eureka!" experiences, such as significant activity in the anterior superior temporal gyrus of the right hemisphere previously reported to be implicated in remote association tasks.

Mind Wandering and Incubation

As mentioned above, a creative idea often succeeds a stage of incubation. Previous studies have suggested possible descriptions for this phenomenon, like random subconscious recombination, spreading of activation or mental relaxation, and subsequent selective forgetting (see section "Creative Process"). Nevertheless, the exact nature of this process remains unclear. Brain imaging studies have recently sought for further explanations, by drawing analogies with mind wandering. The unintentional shift from a primary task to another, in which no personal goal lies within such behavior, is often described as mind wandering. It is thus argued that mind wandering may potentiate creative thoughts[9] (Baird et al. 2012; Salvi and Bowden 2016; Zedelius and Schooler 2016). Indeed, the default network[10] was already found to be active in tasks involved in passive sensoring processing, but, conversely, it showed less activity on tasks associated with high central executive demand. Accordingly, results from an fMRI investigation, performed by Manson et al. (2007), support the idea that the same areas involved in a default network are also implicated on high-incidence mind-wandering periods, introduced (in the context of this particular experiment) by extensive training of visuospatial working-memory tasks. In conclusion, the latest findings have suggested that these momentary episodes of mind wandering may reflect ongoing processes of "mini-incubation" that can further an insight and, thus, contribute to the awakening of the creative mind (Sawyer 2011).

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[9]We often assume that if we don't notice our thoughts they don't exist, (…) When we don't notice them is when we may be thinking most creatively."—Dr. Kalina Christoff, University of British Columbia, Vancouver (Hotz 2009).

[10]Brain system active in resting state but typically reduced during active conditions (Buckner et al. 2008). Interestingly, it also exhibits less activity during unconscious states (Andrews-Hanna et al. 2010).

Creative Brains Versus Non-creative Brains

Differences in neural activity between people who get greater scores on tests of creativity and people who score lower have also been explored. An early study, using EEG, Martindale and Hines (1975) found that high creative people showed higher levels of alpha wave activity,[11] while performing a test.[12] In contrast, people with lower scores had lower alpha wave activity. Another study, using PET, employed three different tasks with expected three different levels of cognitive recruitment in the frontal lobe. The tasks, listed next by ascending order of cognitive load, are: (i) automatic speech task (count aloud, starting with 1); (ii) word fluency task (i.e., say all words that come to mind, starting with the three specific letters); and (iii) a divergent-thinking task.[13] The results revealed that highly creative individuals exhibited greater levels of regional cerebral blood flow on both hemispheres during both word fluency task and divergent-thinking task in the anterior prefrontal cortex, whereas low-creative individuals showed a decrease of activity frontotemporal and anterior prefrontal areas in the left hemisphere when performing the same tasks. On the other hand, highly creative individuals had more increased activity in the aforementioned regions during the execution of the divergent-thinking task, when compared with the corresponding activity while performing the word fluency task. No differences in the activity level of both tasks were identified for low-creative individuals (Carlsson et al. 2000). In general, several studies have provided evidence that less creative people activate slightly less the right hemisphere, whereas high creative people exhibit patterns of bilateral activation. Results from a PET study undertaken by Chávez-Eakle (2007) also indicated bilaterally distributed patterns of activity, displaying greater prevalence in the right hemisphere for higher scorers on verbal creative tasks. Despite many studies, including the aforementioned as well as meta-analysis (Mihov et al. 2010), have reported right dominance of hemispheric specialization for creative thinking, one must not conclude that creativity "is placed in" the right hemisphere (Sawyer 2011). Indeed, Dietrich and Kanso (2010) reviewed the research findings about creativity and the main conclusion was that no other specific centers but frontal lobe at both hemispheres is always involved during creative process (Dietrich and Kanso 2010; Carlsson 2014, p. 59).

Differences in Expertise

Brain imaging studies have also explored differences due to extensive training. Regarding art training, EEG studies have indicated that well-mastered tasks

[11]Alpha waves (8–13 Hz) occur while awake, under relaxation and with eyes closed.

[12]The tests of creativity used in this study were the Alternate Uses Test and the Remote Associates Test.

[13]Brick Test.

typically correspond to greater coherence or synchronization across several cortical regions. For instance, Bhattacharya and Petsche (2005) found that MFA[14] students generally exhibited enhanced delta[15] band synchronization in the frontal regions upon performance of a mentally composing drawing, while non-artists exhibited short-range beta[16] and gamma[17] band synchronization. In addition, the study also revealed that artists had greater delta and alpha band synchronization with stronger effects in the right hemisphere, when compared with non-artists. Other studies involving chess players also demonstrated that professional players showed higher delta band coherence than amateurs, when trying to anticipate the next moves. The findings overall suggest amelioration of long-term visual memory efficacy due to task-specific training. With regard to dance training, Fink et al. (2009) concluded, in a research study using EEG, that professional dancers had enhanced alpha synchronization in the posterior division of the parietal regions when executing a creative test.[18] When professional dancers were directly compared with novices, greater alpha synchronization at the right hemisphere became visible while performing an improvisation imagery task. These studies assessing for expertise generally support the idea that neuroplasticity mechanisms may evolve across lifetime due to extensive practicing of the technique. Besides, there is considerable evidence that expertise is closely related to domain-specific creative performance and it may allow for retrieval of relevant information as well as recognition when a new idea is worthwhile. However, some researchers have pointed out the broad and comprehensive features of certain creative skills that can be acquired and applied in various and distinct problems and situations (Ward et al. 1999, pp. 207–208). According to Finke et al. (1992), “expert knowledge may be most useful when applied in conjunction with general principles for generating and exploring preinventive structures” (Ward et al. 1999, p. 208).

The neural correlates of musical improvisation and corresponding effects of expertise will be next addressed, in further detail, under the framework of musical creativity.

Musical Creativity

Creativity is typically perceived and acknowledged in terms of its final outcome, i.e., the creative product. Although no clear objective criteria have been established, novelty is usually taken as a distinctive characteristic that must be fulfilled in order

[14] Master of Fine Arts.

[15] Delta waves (0.5–5 Hz) occur during sleep.

[16] Beta waves (13–30 Hz) occur due to increased alertness and focused attention.

[17] Gamma waves (>30 Hz) are presumably implicated in creating the unity of conscious perception.

[18] Alternative Uses Test.

to produce a valuable creative product. Given the utilitarian perspective, a widely accepted normative to reach general consensus, one can claim that a creative product shall also contain some level of usefulness and appropriateness according to the social context. The social value of a creative product can thus be reflected in the visual arts, literature, scientific theories, technologic advancements as well as music (Nickerson 1999, p. 393). Musical creativity thus arises as a social practice that embodies and mediates the inner need of communication among individuals.

Investigating the neuropsychological mechanisms that underlie musical creativity involves the identification of suitable behavioral models. Possible aspects of these models include performing, listening, writing, and analyzing. Composition and improvisation can be described in terms of such aspects, and they have been generally considered to play a central role in research. They both account for the fundamental activity which is the "creation of new music." Yet, their practice is naturally very different. Composition draws upon revision, i.e., the chance to go back and forth over the process, whereas improvisation relates directly to performance in which the inwardly associated extemporaneous process is marked by irreversibility (Tafuri 2006, p. 138).

Musical performance provides a suitable behavioral model because it can be easily recognized and it enhances the ongoing progress of the task. It constitutes a platform for self-expression, since it is linked to the intrinsic and immediate interchangeability of different ideas. Particularly, musical improvisation involves a permanent exchange of ideas that are original, unpredictable, and emergent. As a consequence, it became one of the most accepted behavioral models for experimental paradigms in research.

Hence, the following section consists of a general overview of neuroimaging studies, as attempts to explore the cognitive mechanisms underlying musically improvised performance.

Musical Improvisation

The extensive work by Pressing (1988), within the scope of cognitive psychology, has revealed what it turns to be the most significant mental processes involved during extemporization. Fundamental conclusions, drawn from these studies, highlight the role of expertise, as an acquired skill that requires substantial amount of deliberate practicing. Moreover, such intensive training shall be domain-specific (Pressing 1988), plus guided by qualified instructors (Ericsson 2008). Deliberate training enables automation and, thus, the simultaneous engagement on memory retrieval, monitoring, motor control, and sensory plus perceptual encoding, among others (Pressing 1988; Beaty 2015). Together, they liberate fluency and real-time control over performance. Indeed, creativity in improvisation is not merely defined as a free-generative process of individual notes, but rather the interplay between different capabilities which allows for a successive development and rendering of prelearned musical structures. Therefore, extensive training permits rapid

Fig. 2 MR-compatible fiber-optic piano keyboard (LUMItouch, Inc.)

accessibility of musical patterns while richer structures are continuously associated and integrated into larger assemblies, leading to complex performances (Pressing 1988).

In line with these ideas, experimental paradigms have been developed as an attempt to study the topic through the use of neuroimaging techniques and, thus, progressive adaptations have been implemented in order to overcome constraints featuring the highly controlled settings inside of the laboratories. Further and according to what stated above, musical improvisation has been widely used as a valid behavioral model in many research topics and it has been particularly acquainted in many neuroimaging studies dedicated to investigate the neural correlates of musical creativity. Yet to the date, there were still few studies that have examined improvisation in terms of musical performance in adults. They are thus discussed next in more detail, following a chronological order.

The first of these studies refers to an fMRI experiment conducted by Bengtsson et al. (2007). Brain activity of eleven professional pianists was measured while the participants were improvising on the basis of a visually displayed melody and using a one octave magnetic resonance (MR)–compatible piano keyboard (see Fig. 2), as well as when the participants had to reproduce thereupon the previously improvised melody. In addition, the participants were also asked during neuroimaging data acquisition to perform free improvisation without memorizing the performance. The main findings were the result of a conjunction analysis between the contrasts "Improvise versus Reproduce" and "FreeImp (i.e. Free Improvisation) versus Rest". The brain regions found to be predominantly involved were the right dorsolateral prefrontal cortex, the bilateral rostral area of the dorsal premotor area, presupplementary motor area (see Fig. 1), left posterior superior temporal gyrus,[19] the right fusiform gyrus, and the bilateral middle occipital gyrus. Further, the presupplementary motor area was positively correlated with the degree of complexity of the improvisations. According to Bengtsson and colleagues, the key finding of the study was the significant activity found in the dorsolateral prefrontal cortex, since

[19]Close to the temporoparietal junction.

this region was previously reported to be involved in free selection, attention to action, working memory, and suppression of stereotype responses (see section "The Neural Correlates of Creative Thinking").

In Limb and Braun (2008), six professional jazz pianists were asked to perform an improvisation musical task in a MR–compatible piano keyboard with thirty-five full-size piano keyboard, while fMRI data of brain activity were collected. The tasks consisted of two types of conditions: an over-learned condition and an improvise condition. During over-learned conditions, the participants were asked either (i) to repeatedly play a one octave ascending or descending C major scale in quarter notes, or (ii) to improvise in quarter notes using a single octave C major scale. During improvise conditions, they were instructed either (i) to play a novel melody, which was previously memorized before the scanning, or (ii) improvised based on a given composition's chord structure. When contrasting improvisation to over-learned sequences, the results displayed a broad pattern of deactivation in the medial prefrontal cortex, medial portions of the dorsolateral prefrontal cortex, lateral orbital regions, the limbic and paralimbic regions, the basal ganglia, insula, and the temporoparietal junction (temporoparietal junction). The results are interesting and raise intriguing issues concerning improvisation. Yet, they shall be interpreted under the context of a case study due to the small sample size used and the fixed-effects analysis employed for the statistical inference. So, they represent possible implications rather than provide definite conclusions. In fact, the results regarding dorsolateral prefrontal cortex involvement lead to opposite interpretations when compared to the ones referring the earlier Bengtsson's study. One can speculate that effects due to improvisational skills might have determined the results on both studies. Improvisation constitutes an essential feature in jazz performance, whereas classical pianists might improvise less frequently. Further, one can also hypothesize about differences in complexity between the two experimental paradigms. Improvisation is less demanding when it is based on a scale or chord structure than a musical template provided with ornamentations[20] (Berkowitz 2010, pp. 6, 28 and 29). Besides that, activity elicited in the frontal lobe for classical pianists, namely in dorsolateral prefrontal cortex and presupplementary motor area,

[20]Heinrich Schenker theorized on the model of the two levels of musical formulas (or musical schemata, i.e., the archetypal patterns which define a musical style (Gjerdingen 1988, 2007)). Such model attempts to describe the structural basis of tonal improvisation. The first level relates to bass lines and their harmonic progressions (harmonic progressions can be defined as musical treatises presented in a systematic, simplified, and stylistic neutral fashion, such as a block of chords), whereas the second consists on perceiving such harmonic progressions idiomatically, i.e., through the use of melodic figures (Rink 1993). Pressing (1984) denominates the first level as referent. The referent is thus a structure of events in which improvisation can be crafted. Also, and according to Pressing's terminology, the second level represents the knowledge used to build the "musical surface" of the underlying referent. From the cognitive perspective, the referent allows for the internalization of certain features in musical language, so that they can be conceived with some degree of automaticity. On the other hand, conscious attention mechanisms regulate decision-making cognition on higher-level musical processes (e.g., relationships between events, form, and feel).

explains explicit processing of novel motor sequences, whereas jazz pianists seem to depend on regions for implicit routine and automated behavior relying on interactions among cortical regions and limbic structures (Doyon and Benali 2005). It shall also be noticed that the experimental design employed on Limb's study relates to over-learned tasks which generally constitutes a simple endeavor. This can probably explain the widespread patterns of deactivation during improvisation, resembling the default network associated with resting-state activity, which become usually less active upon engagement on cognitive tasks (de Manzano 2010). In fact, Manson et al. (2007) suggested that extensive training could lead to mind wandering, allowing people to daydream. It is thus a task characterized by passive sensory processing, typically described by activation of the default network (Manson et al. 2007). One could thus speculate that control conditions were triggering mind wandering as a preparatory process for the next improvisation conditions.

Berkowitz and Ansari (2008) studied twelve trained undergraduate pianists in an fMRI experiment using a five-key piano-like response device from C to G, only with white keys. The experimental paradigm consisted in a 2 × 2 factorial design where rhythmic and melodic motor sequence creation were examined both separately and together. Specifically, the tasks were classified in four kinds of conditions varying in melodic and rhythmic freedom. The main effect of melodic improvisation showed significant activity in rostral and anterior cingulate cortices, ventral and dorsal premotor cortices, supramarginal gyrus, and cerebellum. Deactivated regions relative to rest, displaying an increase deactivation with and increase of melodic freedom, were the superior and medial frontal gyri, posterior cingulate cortex, and angular gyrus. The main effect of rhythmic improvisation was identified on the anterior cingulate cortex, inferior frontal gyrus, dorsal premotor area, motor and somatosensory cortices. The pattern of deactivation, e.g. in medial frontal areas, comes into line with results from Limb and Braun (2008), suggesting deactivation of the default network during improvisation. There are, however, some issues that shall be addressed: (i) approximately 33% of the data, from the twelve subjects accounting for the analysis, were removed; (ii) conditions with melody constraint, where the participants were asked to play patterns, contained a free-choice element (free choice is cognitively implicated in improvisation) because they could play any of the predemonstrated patterns allowed for the experiment; (iii) metronome was only used during conditions with rhythm constraint and not for those related to improvisation, constituting a possible auditory confound (since it is not clear whether there might be interactions between regions involved in explicit auditory processing and regions involved in the creative process per se); and (iv) behavioral results show a main effect of melodic freedom on the variability assigned to the interval between two consecutive keystrokes as well as interaction between melodic freedom and rhythmic freedom on the variety of note combination, suggesting that the neurocognitive components controlling different aspects of rhythm and melody might have not been entirely isolated (de Manzano 2010).

Berkowitz and Ansari (2010) examined functional expertise-related differences between musicians and non-musicians during improvisation. The experimental paradigm was the same as the one employed in studies from the same authors described above (Berkowitz and Ansari 2008). The main finding was a deactivation during melodic improvisation in the right temporoparietal junction, whereas non-musicians exhibited no change in activity in this region. Nevertheless, there are few considerations that shall be pointed out. Behavioral results showed a three-way interaction of melodic freedom, rhythmic freedom, and group on the variability of note combination. This is a direct consequence from the interaction between melodic freedom and rhythmic freedom within the musicians group already identified in the previous study. The variability of note combination was slightly greater during melodic improvisation with rhythmic constraint than in melodic improvisation with rhythmic improvisation. One can speculate that this interaction is a consequence of the auditory stimulation from the metronome present during conditions with rhythmic constraint, to which the musicians are more sensible. Given this, one can argue whether there was a true behaviorally matched performance as claimed by the authors. On the other hand, similar levels of musical performance between musicians and non-musicians are most likely related to the dimension of the musical keyboard. Thus, the question about the ecological validity of the task may arise. Even if the results reflect cognitive mechanisms underlying behavior with improvisatory content, that does not necessarily represent musical improvisation to the full extent and, thus, creative decision-making per se. Very little is known about expertise-related neurocognitive processes involved in musical improvisation among trained musicians. It is, thus, necessary to isolate first and properly their specific components, in order to perform further endeavors on the investigation of functional differences between musicians and non-musicians during musical improvisation. Our study (Pinho et al. 2014) as well as Lopata et al. (2017), herein described, provide the first steps toward a better comprehension of the specific effects of training in musical creativity.

The neural correlates of musical improvisation and pseudo-random generation were also tackled by de Manzano and Ullén (2012b). Brain activity was measured in a group of professional classical pianists using fMRI, who performed musical improvisation of melodies in two generative tasks—pseudo-random sequence generation and musical improvisation—on a twelve-key/one octave MR-compatible piano keyboard (see Fig. 2). Three main findings are notable from this study. First, there was a considerable overlap between brain regions involved in the two generative tasks. These regions included the dorsolateral prefrontal cortex, dorsomedial prefrontal cortex, inferior frontal gyrus, anterior cingulate cortex, and presupplementary motor area. Secondly, the dorsolateral prefrontal cortex as well as other association areas in the dorsomedial prefrontal cortex and parietal cortex was more active during pseudo-random response generation than during musical improvisation; no areas were more active during musical improvisation than during pseudo-random generation. Thirdly, the size of the response space was parametrically manipulated, i.e., the number of allowed notes (pitches) in the generative tasks. For the reasons given above, dorsolateral prefrontal cortex activity was expected to be related to the size of the response space. However, this hypothesis could not be confirmed; no regions showed activity related to response space size.

These findings can be interpreted as follows. Firstly, it appears clear that there is a common core of regions, including the dorsolateral prefrontal cortex, that are involved in both pseudo-random generation and musical improvisation, and thus are likely to play domain-general functions in generative tasks. Secondly, the higher dorsolateral prefrontal cortex activity in pseudo-random generation may result from several reasons: (1) musical improvisation is an innately more natural behavior than pseudo-random generation; (2) that musical improvisation was more trained than pseudo-random generation; (3) spontaneous musical responses need to be suppressed during pseudo-random generation. Thirdly, the lack of a relation between dorsolateral prefrontal cortex activity and response space size may reflect that the three different response sets, used in this study, represented different musical modes. The smallest set consisted of two notes only; the middle set (six notes) were notes from an F major scale; and largest set (twelve notes) consisted of the complete chromatic scale. Accordingly, there may have been a possibility for the subject to use strategies, i.e., improvise in a certain mode or style, to shortcut the need to maintain a particular response set online during the improvisation.

The presupplementary motor area and lateral premotor regions have been proposed to be involved in sequential control and learning of spatial sequences, respectively. Thence, de Manzano and Ullén (2012a) suggested that these regions could also be implicated in controlling rhythmic and melodic aspects of the improvisation. Earlier studies of temporal and ordinal control of sequence performance sustained this hypothesis (Bengtsson et al. 2004; Schubotz and von Cramon 2001). The idea was thus tested in an fMRI experiment using a 2 × 2 factorial design where the rhythmic and melodic structures of musical samples were either unspecified or determined (i.e., notated) with need for improvisation.[21] The results confirmed the hypothesis. Main effect analyses reinforced the idea of the presupplementary motor area to be predominantly involved in rhythmic improvisation. The results also showed more activity in the dorsal premotor area during melodic improvisation.[22] Nevertheless, a substantial overlap between brain regions involved in rhythmic and melodic improvisation was identified, i.e., both presupplementary motor area and dorsal premotor area displayed an increased activity throughout all improvisation conditions. These results come into line with the findings of Berkowitz and Ansari (2008). In addition, a psychophysiological-interaction analysis (Friston et al. 1997) demonstrated that the correlation in activity between the presupplementary motor area and cerebellum was higher during rhythmic improvisation than during other conditions. The authors concluded that functional connectivity between premotor areas and other regions depends on the spatiotemporal demands of movement sequencing control.

[21]The MR-compatible piano keyboard was the same as the one used in the previous investigation by de Manzano and Ullén (2012b) (see Fig. 2).

[22]The presupplementary motor area was also significant activity in the main effect of melodic improvisation.

An fMRI study by Liu et al. (2012) has also investigated the neural correlates underlying lyrical improvisation. While in the scanner, participants were asked to sing, following a eight-bar musical background track and according to two possible musical styles: (1–Improvised) freestyle, improvised fashion; and (2–Conventional) ordinary performance based on the anticipated rehearsal of the lyrics. Results contrasting both conditions revealed strong effects on lateralization of brain function widespread across the left hemisphere for the improvisation period. They include the presupplementary motor area, dorsal premotor area, and inferior frontal gyrus, among others. In addition, the authors also reported decreased activation of the dorsolateral prefrontal cortex and increased activation of the medial prefrontal cortex.

We sought to investigate the specific neurocognitive effects derived from expertise in musical improvisation (Pinho et al. 2014). A natural question that arises is whether extensive training in such activity may induce neuroplasticity in the brain. Many of the observed correlates of general musical training reflect not only acquisition of highly specific sensorimotor skills but also cognitive abilities required for various aspects of musical expertise. However, no study has previously focused on the effects of training in musical improvisation. Brain activity was measured in a group of thirty-nine professional (both classical and jazz) pianists using fMRI. They performed free musical improvisation on an MR-compatible piano keyboard.[23] When contrasting the respective periods of improvisation versus resting-state, results revealed a significant negative association between improvisational training and activity in a number of cortical regions at the right hemisphere. Also, improvisational training was specifically associated with functional connectivity during musical improvisation, using the premotor and prefrontal regions as seed regions, and controlling for age and conventional piano practice. More experienced improvisers showed higher functional connectivity during improvisation between prefrontal, premotor, and motor regions of the frontal lobe. Furthermore, the results were shown not be confounded by more experienced improvisers, who could potentially produce more complex musical samples.

Donnay et al. (2014) have described the neural correlates underlying interactive generative musical improvisation between two expert jazz musicians. A two block designed paradigm was used to assess such interaction between subjects. The two paradigms differed in level of complexity; “Scale” was a highly constrained task of minimal complexity, whereas “jazz” represented a task with greater complexity and ecological validity. In Scale, there were two tasks: (1) both subjects play alternately a D Dorian scale in quarter notes or (2) they took turns improvising four-measure phrases. The jazz paradigm was also constituted by two different tasks: (3) both subjects played alternately four-measure segments of a novel jazz composition, which was memorized prior to scanning and (4) they improvised monophonically with no melodic and rhythmic restriction. For all experiments, one of the two

[23]The same equipment was used in previous investigations (see de Manzano and Ullén (2012a, b) and Fig. 2).

participants was laid in the scanner, while the second one was in the control room. Brain activity using fMRI was measured in eleven male musicians. The interactive tasks were based on alternate responses between both participants. The subject inside of the scanner was always the first one who started the task. Contrasting the improvise tasks with the memorized tasks, the results showed an intense bilateral activation in inferior frontal gyrus (corresponding left hemisphere area was placed in Broca's area), posterior superior temporal gyrus (corresponding left hemisphere area was placed in Wernicke's area), as well as in the presupplementary motor area. Deactivations during improvisation accounted for bilateral angular gyrus. General spontaneous musical exchange was associated with bilateral activation of the dorsolateral prefrontal cortex. The authors concluded that regions involved in syntax processing, usually assigned to linguistic semantic processing, are not domain-specific for language but rather domain-general for communication. Previous investigation from Limb and Braun (2008) revealed an extended deactivation over many areas, including the dorsolateral prefrontal cortex, when musicians were performing improvisational musical tasks. The present study, in line with other studies, showed completely opposite results. The authors of this study thus claimed that such deactivation described in Limb and Braun's findings was due to a presumably state of "flow," often reported by musicians while playing. The authors also concluded that the activation exhibited in the dorsolateral prefrontal cortex, on the latest results, is associated with conscious self-monitoring of behavior, due to the social context implied in the musical exchange paradigm. Indeed, dorsolateral prefrontal cortex was previously identified to be involved on selection of suitable response's set given the task on demand (Nathaniel-James and Frith 2002), suggesting a correlation between its activation and increased working-memory demands while musical exchange.

We also explored the contribution of the dorsolateral prefrontal cortex in creative cognition (Pinho et al. 2016). Different neuroimaging studies have shown so far seemingly paradoxical results regarding the implications of the dorsolateral prefrontal cortex in creative functioning. On one hand, dorsolateral prefrontal cortex has been argued to exert active control over free-generative tasks by inhibiting habitual responses, thus enabling more original output; on the other hand, a deactivation and concomitant decrease in monitoring and focused attention has been suggested to facilitate more spontaneous associations and novel insights. Here, the study highlights that creative cognition can be implemented in different ways given different circumstances. Two categories of behavioral conditions were specified in the experimental design to convey constraints either on the musical structure (set of pitches) or on the emotional expression (happiness or fear) of the improvisations. The results confirmed higher activity in the right dorsolateral prefrontal cortex, as well as in the parietal lobe and right dorsal premotor area, when contrasting structural conditions with emotional ones. These results suggest higher attentional effort and cognitive control when the participants had to conform to the structural constraints. Conversely, deactivations were identified for the emotional constraints in the same regions, plus other regions explicitly contributing to emotion processing. Overall, these findings come out in agreement with what previously described in section "The Neural Correlates of Creative Thinking" about the four-category model in creativity. All types of creativity share a common network involving the dorsolateral prefrontal cortex, regardless of the circuit that has triggered the creative insight. In addition, dorsolateral prefrontal cortex was found functionally connected with the frontoparietal network as well as the cerebellum during structural conditions and to various regions comprising the default network during emotional conditions.

Finally, an EEG study by Lopata et al. (2017) undertaken with experienced musicians have explored differences in neural responses between tasks with different levels of creative demands. The experimental design was composed by three main conditions characterized as follows: (1) passive listening of jazz melodies; (2) playing back the melody listened during condition (1); (3) imagining a self-improvisation performance; and (4) actual free improvisational performance. Overall, results exhibited greater alpha band activity in frontal areas during the free improvisational condition when compared with the remaining ones. Effects of expertise were also assessed, and they demonstrated higher activity in the same areas for those subjects with more improvisational training. Moreover, these results were affected by the quality of the performances,[24] as revealed by the correlations obtained between alpha EEG power and post hoc analysis of the behavioral data. It is worthy of note that such outcomes using EEG are in accordance with the fMRI counterparts (Pinho et al. 2014), since they both support evidence about ongoing plasticity effects due to improvisational training and their influence toward creative thinking.

In conclusion, differences between results suggest that musical improvisation is not restricted to a fixed set of regions but rather a network of interchangeably functional regions dependent on task- and context-specific domain. As a behavioral model to study creativity, it thus shares many specialized functional networks previously identified in, e.g., free selection or divergent-thinking tasks. Either extrospective or introspective networks have been, respectively, linked to creative behavior featuring deliberative-cognitive mechanisms or spontaneous-emotional ones, in line with the model proposed by Dietrich (2004) (see section "The Neural Correlates of Creative Thinking"). These mechanisms are not mutually exclusive and can pertain to the same high-cognitive process, involving creativity. Further investigation is essential to identify and isolate its fundamental neurocognitive components that may control distinct aspects. Besides, the employment of systematic procedures is crucial for the development of normative experimental designs, which can in turn mitigate idiosyncrasies relative to specific tasks (Saggar et al. 2016). Such practices may thus allow for concomitant reproducibility and

[24]The Musical Improvisation Questionnaire (Lopata et al. 2017) was used to assess the improvised performances. Qualified judges were asked to rate the records according to criteria which provide benchmarks for discriminant validity testing, such as technique or aesthetical appeal. This questionnaire was developed based on The Consensual Assessment Technique (Amabile 1982), which takes a broad definition of creativity to include aspects related to both performance and outcomes. By this way, the final scores are intended to translate the overall value of the creative behavior.

subsequent generalization toward the creation of a well-grounded ontology (Poldrack and Yarkoni 2016) covering this topic.

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Part II
Neurophysiology of Aesthetics (Zoï Kapoula)

Empirical Aesthetics: In Quest of a Clear Terminology and Valid Methodology

Claus-Christian Carbon

Abstract Empirical aesthetics is truly an emerging field of research. Besides the impressive generation and production, a great variety of empirical insights and a worldwide increasing and scientifically active community we face an obvious confusion of terminology and a lack of standard research methods to base our research on. The initial question to be addressed for researchers in the field of aesthetics is whether they aim to research aesthetics regarding art-related phenomena or whether they want to know how everyday phenomena are processed aesthetically. Additionally, we have to define what constructs like aesthetic appreciation and aesthetic experience really mean and how we can optimally operationalize and measure such constructs in terms of employed variables and research methodology. For instance, artworks can definitely be processed on basis of beauty aspects, but at least with contemporary art, beauty assessments do not reflect art-specific processing which is much more about elaboration, understanding and struggling for meaning. Only by clearly defining our main concepts and methodology, we will succeed in advancing the field of empirical aesthetics in the future. This chapter also sums up some methods for measuring phenomena associated with aesthetic experience, called the research method toolbox for capturing aesthetic experience. Such methods are particularly important to be employed in order to capture the dynamics going on while we experience something aesthetically.

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Aesthetics: Confusion of Terminology

In everyday life it is rather vague, how the term “aesthetics” is actually used and what people associate with it exactly. For most people aesthetics just means “beauty”, so for these people aesthetics is mostly linked to affective qualia, which are often universally defined. For others, aesthetics is linked with taste, especially as judgments of taste. Another party spontaneously thinks of the critical reflection on art, so aesthetics are related to very sophisticated and educated, cognitive qualia.

This high level of ambiguity in everyday terminology is reflected in scientific contexts of aesthetics as well. In fact, researchers mostly do not refer to a clear terminology—they talk of aesthetics in an unfocused, undefined and often non-theoretical way. As a consequence researchers often mean very different things when they research aesthetics, and in the end even within one research group and one researcher the terminology changes, sometimes even within one piece of research (e.g. aesthetic judgments = aesthetic preferences = aesthetic processing = optimal stimulation of the brain, see Leder et al. (2004)).

One major reason for this overall confusion is that nowadays research on aesthetics which is often signed by researchers devoted to empirical research does not refer to a clear theory behind or underlying their research. So-called empirical aesthetics or experimental aesthetics is a wide and heterogeneous research field emerging from psychological research of the mid-nineteenth century—most prominently represented by German philosopher, physicist and experimental psychologist Gustav Theodor Fechner. It was Fechner who established the field of experimental psychology as such by having developed a set of clearly defined experimental methods he comprised as psychophysics. The ground-breaking idea behind psychophysics was to systematically investigate the relationship between physical stimulation and its psychological sensation. Besides these historical achievements, Fechner did also left behind a rather burdensome legacy as psychophysics as a main tool to research aesthetics inevitably means to break up an aesthetic Gestalt into its components. To do this means to still falling back to a structuralistic, pre-Gestaltist view—we will clearly lose the Gestalt emerging from single components by such a procedure and research philosophy (see also Makin 2016). This means that most theoretical concerns refer to just loosely interconnected principles or findings based on such psychophysical studies. For instance, when we try to investigate the aesthetic success factor of a brilliant design, we should not independently analyse how local versus global shape, how material and texture and how colour aspects contribute to the overall aesthetic experience as these factors are never aesthetically independent from each other. We should also never forget that aesthetic experience is often based on multi-sensory qualities (Carbon 2016).

A further problem is that most aesthetic theories do not address true aesthetic qualities, e.g. being fascinated by the artwork, or showing deep impression on the beholder’s side, or feeling chills and thrills, as they only propose using very reductionist sets of variables—mostly, beauty (see Mallon et al. 2014; Redies 2014) or preference (see Palmer et al. 2013). It is quite interesting how rich, in contrast, the beholders' aesthetic word usage in everyday life is. In a study by Augustin et al. (2012), it was shown that this richness is also diverse when taking different aesthetic object areas and aesthetic domains into account.

Aesthetics: Lack of Methodology

To break up the aesthetic Gestalt into allegedly independent sub-components also means to lose the contact to what I call "aesthetic experience" in a narrow sense (Muth et al. in press, 2015): Experience is not reducible to single assessments or evaluations, mostly: ratings! Experience is characterized by deep involvement and by getting affected when being exposed to, for instance, an artwork. Experience also means to gain experience after having processed the artwork, to be in the best sense of the word "experienced"—thus, aesthetic experience changes our cognitive knowledge and our affective state. However, most research methods employed in current aesthetic research do not address aesthetic experience as such, but they often claim to do so.

The lack of understanding what aesthetic experience is really about can be seen in rather "static research methods"—methods which try to capture static properties of artworks. We could call these ideas also object-related approaches, because the main idea behind it is that an artwork can be divided and subdivided in several, ideally independent, objective aspects for which we can assess the respective subjective quality. And these objective qualities, as they are object-inherent, are stable or even static. The essential misunderstanding with this approach in the domain of art is that people, here: participants of our aesthetic studies interact with artworks, they experience something in regard to artworks, get insights and become experienced by artworks and debate with others through social interactions. All these phenomena are highly dynamic, so an artwork is always in a state of flux—at least as soon as an object is not a mere object any more but is genuinely processed as an artwork.

A Research Method Toolbox for Capturing Aesthetic Experience

In the following, I will present some ideas which we have followed over the last decade which yield experimental routines that try to capture dynamics of aesthetic experience. All the referred methods are just a slice of the research portfolio which we currently employ, but they paradigmatically show how different the time

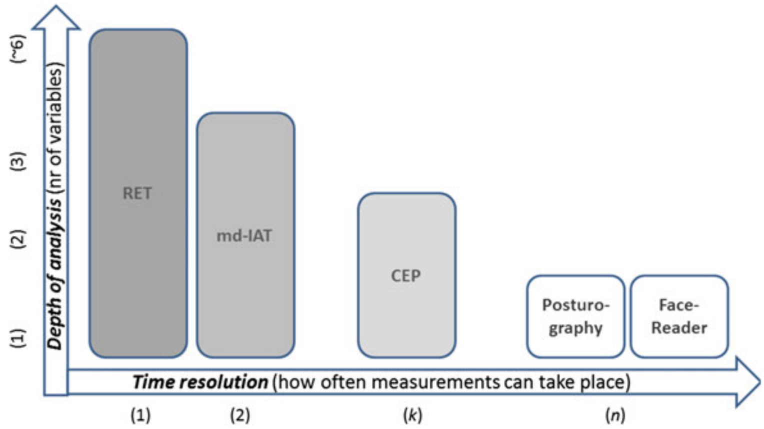

Fig. 1 System of different methods for capturing aesthetic experience according to three essential dimensions: (1) time resolution (x-axis), (2) depth of analysis (y-axis) and (3) invasiveness (the darker the background the higher the invasiveness of the employed method). Time resolution refers to the capability of how often the respective method can measure a specific variable. Depth of analysis refers to the number of variables that can be employed per measurement episode. Invasiveness means how strongly the measurement procedure changes the aesthetic experience itself. The different methods displayed here in acronyms (e.g. RET, md-IAT) are described in detail in the text as follows

resolutions of such methods can be, how different they are in terms of the depth of analysis and how strongly they differ in terms of invasiveness. Figure 1 illustrates this schema.

Repeated Evaluation Technique (RET)

When we enter an art gallery with artworks or artistic styles, we are not familiar with, we face a fundamental problem in validly measuring aesthetic appreciation but we gain a lot of insights in the dynamics of aesthetic experience. This argument is particularly true for all kinds of very uncommon, unknown and innovative pieces of art: We do not possess the adequate cognitive habits to understand and appreciate such material at first stance (Carbon 2015). Interestingly, our whole assessment, appreciation and experience might change very fast when getting more familiar with the artwork. Then, we are able to evaluate even very innovative material in a differentiated, complex and multifaceted way. After a while, we will reach a kind of temporary saturation and we experience the material quite coherently (Carbon 2011)—after a further while we often begin to rethink an artwork, mostly when these artworks show "Semantic Instability" (*SeIns*) (Muth and Carbon 2016), e.g. when these artworks show qualities linked with phenomena of ambiguity, indeterminacy or abstractness (Muth et al. in press; Pepperell 2011). We have found out

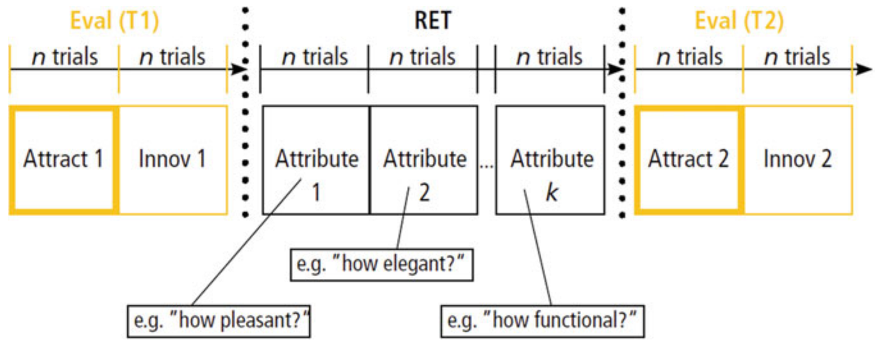

Fig. 2 Schema of the Repeated Evaluation Technique (RET) introduced by Carbon and Leder (2005). Graphic is adapted from the original figure published by Carbon and Leder (2007). *Eval* stands for evaluation phase (at time points T1 and T2); *Attract* is referring to the rating measure attractiveness, which is quite typical for testing in applied design-oriented fields of interest; in art-related contexts, mostly the variable interest or a variable linked with preference is used at Eval (T1) and Eval (T2), here innovativeness (Innov) is measured instead

that only after deep elaboration do people start assessing non-first glance qualities, the meaning or complex associations (Belke et al. 2015). To standardize such a familiarization process, we have developed a procedure called Repeated Evaluation Technique (RET) (Carbon and Leder 2005). Within a RET participants are forced to elaborate on the material via standardized routines where they have to reply to pre-defined sets of variables which cannot be answered without deeply processing the material (Craik 2002). The RET has been employed in a wide range of fields with very different dependent measures, accompanied by physiological measurement such as pupillometry and eye-tracking behaviour (Carbon et al. 2006) or electrodermal activity (Carbon et al. 2008)—where we revealed that RET enabled to amplify the signal-to-noise ratio for physiological measures besides those of rating measures. A schematic view on the RET can be retrieved from Fig. 2.

Multidimensional Implicit Association Test (md-IAT)

The next research method I will show has a comparable time resolution and depth of analysis like the RET, but is signified by lower invasiveness. The md-IAT shows an elegant possibility to address important research questions without explicitly asking the participants. Meanwhile, this routine is not very applicable to capture complex aesthetic experience but is limited to a very limited number of variables.

In fact, most aesthetic researchers rely on more or less explicit assessments, which are highly invasive and cognitively penetrable. This means that participants directly know which issues are of interest for the research, and they build up their own hypotheses about the research hypotheses employed by the researchers. The md-IAT is based on Greenwald and colleagues' IAT (Implicit Association Test) (Greenwald et al. 1998) which claims to measure "implicit associations" or even "attitudes" (Greenwald et al. 2003). Note that the IAT is not used in research without criticism, however; see, for instance, Fiedler and Bluemke (2005). The md-IAT is an extended IAT offering a multidimensional perspective (Gattol et al. 2011): it is capable of providing detailed information on the multifaceted nature of an artwork's associations, with reliable possibilities for measuring the viewer's attitudes towards the artwork. Due to its implicit nature, people's associations do not need to be conscious, a fact that is especially helpful when people are not aware of their associations, when they are not able to express them or when they are not willing to share them with the experimenter.

Main disadvantage of the md-IAT is the time you actually need to conduct a study: typically, you need at least several minutes with about 20–30 trials just for assessing one single target concept. This means that employing a full md-IAT for just one-time point needs about ≥ 20 min. Figure 3 shows an exemplary output of an md-IAT, here from the domain of brand versus logo versus product associations in the automotive field. Values on the x-axis show *D* measure means, a typical dependent variable used in the context of IAT research; D measures can be positive or negative—we can interpret these values as association strengths with a respective attribute; see for more details Fig. 3.

Continuous Evaluation Procedure (CEP)

The next research method shows a much better time resolution, but a lower depth of analysis than the two already referred methods RET and md-IAT; moreover, it is signified by relative low invasiveness. The Continuous Evaluation Procedure (CEP) is particularly interesting when we can define some very clear events going on, for instance, the start of a presentation or the event of an insight while watching an artwork, a so-called Aesthetic Aha-insight moment (Muth and Carbon 2013) where we characteristically feel pleasure afterwards (Muth et al. 2013). Typically, we let decide where "Aesthetic Aha"-insight moments occur in a separate run in the beginning, sometimes we also use data from a different sample of persons to minimize possible carry-over effects from initial insights to other variables which might be associated with aha moments or at least could be biased by ahas. Thus, the aha moments are identified by real persons based on own experiences; aha moments, although based on such personal processes, are, nevertheless, mostly very consistently assigned to certain episodes making the aha moments quite good anchors for psychologically important events.

The CEP research method borrows its terminology from the fact that the method is capable of continuously tracking the evaluation of a variable. If several CEPs are combined, we can even gain knowledge on several variables in parallel.

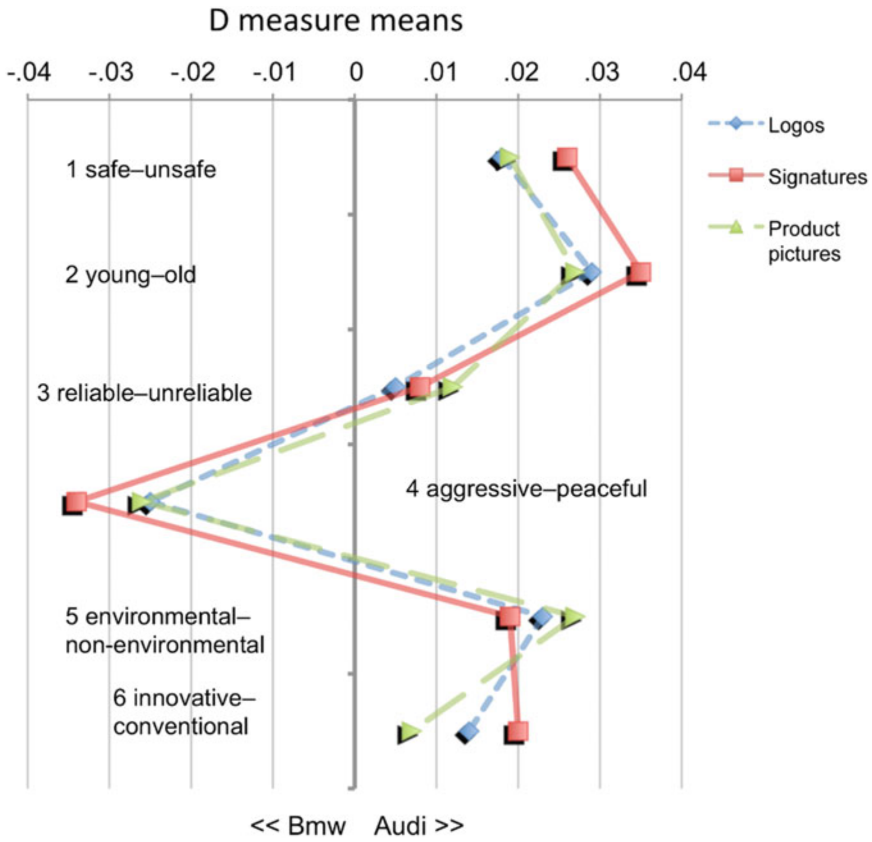

Fig. 3 A typical outcome of an md-IAT study, here from the automotive field: Three different layers of brand depictions were compared via an extensive md-IAT. All in all, six different target variables were defined (safety, youth, reliability, aggressiveness, environmental concerns and innovativeness). The higher D measure means are, the stronger the association of the respective variable—in the given example, we have defined positive D measure means as associations with Audi and negative D measure means as associations with BMW. Audi shows higher associations with all variables but aggressiveness (defined via the scale aggressive-peaceful). D measure can only interpreted in relation to a counterpart, here BMW; thus, the associations might change when Audi would have combined with another brand than BMW. Overall, at the time, when the study was employed, Audi seems to be a safer and younger and also to be a more environmentally oriented brand than BMW (Gattol et al. 2011)—at least for the participants tested in this seminal md-IAT study

The continuous assessment of the material is made possible by the utilization of an analogous lever which is employed as input device (Muth et al. 2015). The data output resembles typical continuous data outputs of EEG/MEG experiments, but the events are mostly not just onsets of presentations but aesthetically significant

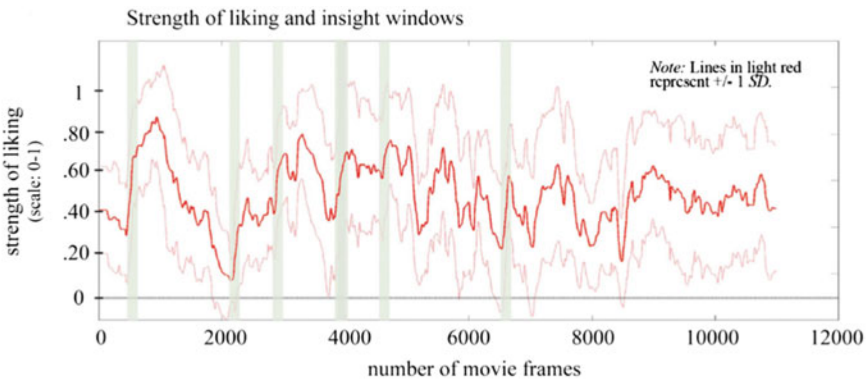

Fig. 4 Original data from Muth et al. (2015) with participants' assessed liking when exposed to an artistic movie by Claudia Muth (see details in Muth et al. 2015). Medium grey bars indicate aesthetic aha events which are always signified by an increase of assessed appreciation: these increases of appreciation can be observed just after such aesthetic aha moments have been occurred

events where something aesthetically happens in a participant. Accordingly, Fig. 4 shows liking data in relation to aesthetic aha events (Muth and Carbon 2013).

Emotional Footprint: Implicitly Measuring Body Sway

The next research method shows a fine-graded time resolution, but is restricted to one single variable which is mainly based on the theory of "Ur-Affekte" (ur-emotions) by Kafka (1950). Parrot (2010) has recently referred to Kafka's view on affects in terms of motoric responses and expanded on this perspective. Both authors interpret an object (e.g. an artwork) as an entity that shows clear affordances in the sense of the ecological perception theory introduced by Gibson (1979). Kafka classified these affordances within a 2-by-2 schema: first of all (A1) attraction (being attracted to an object) which Kafka calls "Ingestion" (e.g. greed), and (A2) aversion ("Ejektion", e.g. reluctance). Then on a second axis: (B1) fleeing from an object ("Rezession", e.g. if we are frightened), and (B2) moving towards an object/a subject ("Profusion", e.g. in the case of loving something or somebody). We successfully applied a posturographic device (see relevant research measuring aesthetically relevant behaviour with a posturography, Kapoula et al. 2011) to the theory of Kafka and Parrot which enables us to obtain data with a temporal resolution of 100 Hz at a high precision which is capable of detecting even very minor body sway.

The data relevant for measuring the *Ur-Affekte* is overlaid by compensatory activation of several muscle groups all over the body (Winter et al. 2003) and is additionally confounded with movement jitters. By employing higher-order

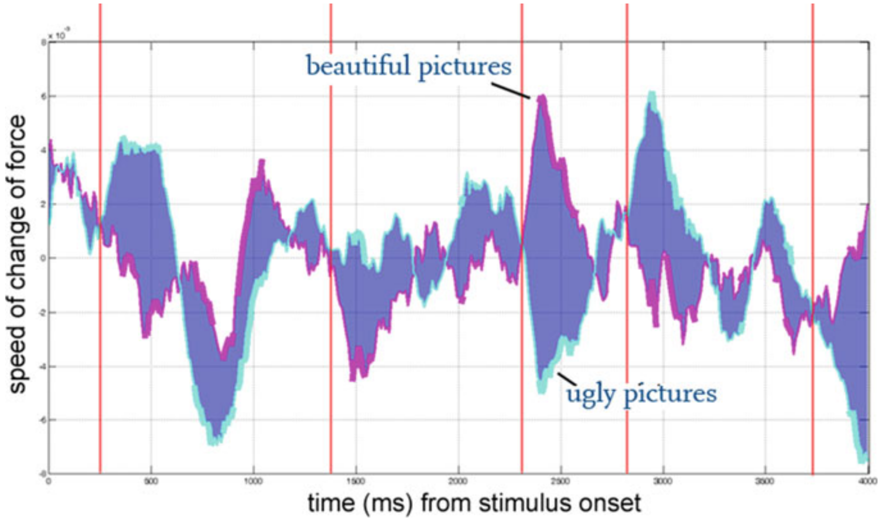

Fig. 5 Posturographic data in terms of speed of change of force (front minus back force sensors) for beautiful versus ugly pictures. The graph is based on the findings of Raab et al. (2012)

Fourier-transformations which are related to the ideal curves, we can analyse the fast and event-related motoric reactions apart from any harmonic oscillations. Such residuary motoric reactions seem to reflect the involuntary parts of attraction and aversion which we call "Emotional Footprint". Actually, the emotional footprint technique is capable of identifying simple but quite insightful affective reactions in a non-invasive way—see Fig. 5.

FaceReader: Capturing Emotional States

The next research method is similar to the emotional footprint as it belongs to a group of methods which are signified by low invasiveness. Meanwhile, this method shows a very fine-graded measurement of emotional states extracted from facial expressions. Since the early emotional theory by Darwin (1872) facial expressions played a very prominent role in the research of emotions (Frith 2009). Until very recently, "face reading" was extremely effortful and asked for qualified and highly trained specialists who were certified as FACS (de)coders (Ekman and Friesen 1975) making the entire procedure inefficient and costly (Donato et al. 1999). Nowadays, we can select out of a list of companies which offer face reading software products, for instance the Noldus FaceReader©. Only recently we have systematically tested FaceReader (Weth et al. 2015), a tool that is based on trained artificial neural networks operating on a statistical learning algorithm. Interestingly, this algorithm is modelled after biologically oriented neural networks.

A big advantage of a software product like FaceReader is the ease of use and the fast processing of vast numbers of videos and thus the analysis of a great number of experimental conditions and groups. Importantly, the to-be-analysed videos do not have to be based on very high quality either, in fact they can easily be recorded via built-in webcams. The greatest plus, however, is the spontaneous behaviour of the participants which can be captured. So reading the face of a beholder is one of the best ways to gain insights into the experience of this person. People are not requested any more "to stop and then resume" their experience—in fact such disturbing instructions are often the standard repertoire of many aesthetic research studies. Any kind of such an instruction would strongly endanger the possibility of feeling immersion and experiencing flow and thus could potentially prevent that real aesthetic experiences take place. Figure 6 illustrates typical data gained from a study on music appreciation tracked by FaceReader.

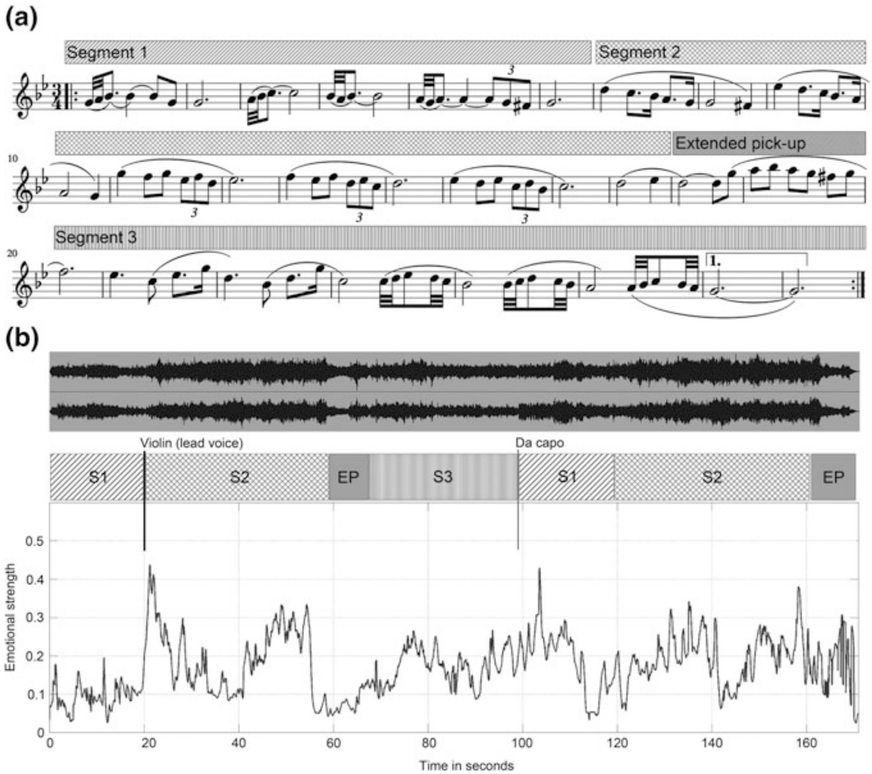

Fig. 6 Emotional strength related to the specific sections of a musical play. The figure originates from Weth et al. (2015)

Conclusion

The present paper aims to sensitize the reader to two problematic issues of current aesthetic research: First of all, current research attempts are mostly unconnected to each other, even within one research group or even across different studies of one single researcher—they mostly lack ideas to connect different results and to comprise them by a more general theory on aesthetics. One important reason might be the specific founding of the whole field of empirical aesthetics by Gustav Theodor Fechner approximately 150 years ago. Second, if we are really interested in deeper phenomena of aesthetic processing, mainly if we are interested in highly dynamic processes which we typically experience in real art contexts, we should use research methods which are by definition able to capture such dynamic phenomena. The present paper shows some recent developments in empirical aesthetics that might help to understand this emerging and fascinating field of research much better. Finally, employing a variety of research methods which are specifically selected or even developed to get insights into the real interesting aesthetic phenomena, for instance, feeling chills and thrills, experiencing wonder or awe, being impressed and overwhelmed, will help to get closer to what is really going on in the art gallery context besides overly controlled and artificial laboratory conditions (Carbon 2017; Muth et al. 2017).

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Design and Enfictionment Experiencing a Hybridizing Strategy in Architectural Prospects

Eglantine Bigot-Doll

Abstract This chapter questions and investigates the links that exist between the two now widespread fields of architectural design and fiction emerging in prospective academics and practices. In an academic situation, we here observed three productions of students in a master's degree program at the School of Architecture of Lyon, ENSAL, France. By creating a video tale, the produced projects bear a temporal dimension which re-introduces a linearity into a prospective strategy. Indeed, during the last decade, parametric and advanced tools for modeling in design stages (CAD/CAM) have injected a complexity which eluded the crystallization of forms in the conception timeline. That is why, as an experimental process aiming to generate singular cultural and technical habits in architecture, students were asked to produce a film, activating this way a creative dimension by maintaining a singular linearity in time *by fiction*. These fictions are integrated into our research as a *line of attack* raising rationality with a view to sharpen architectural materiality prospects. Such prospects follow the MAP-Aria laboratory studies on computation potentials in architectural design processes. The layout of a written chapter does not allow the presentation of samples of animated pictures. That is why, a large amount of screenshots were retrieved from the movies.

Introduction

Architectural stances in matters of design imply a heavy involvement of representation and creativity during the whole conception process. Whereas architecture deals with three-dimensional volumes, fiction, whether it is narrative and/or figurative, remains one- or two-dimensional, at most. Nevertheless, while observing architects describing their own production, we often identify the impact of images, analogies, or mythologies influencing the conception as narrations at different

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stages. We tried to set an academic situation with students of master in the School of Architecture of Lyon, ENSAL, France, aiming to observe the results of project development led through narrative strategies through video with a view to generate singularities in matters of aesthetics, functions, and constructive approaches. Firstly, we will define and clarify precisely the terms of language typologies between design and fiction. Secondly, through students' short films made during the semester of their degree program—just like it is now emerging as a new paradigm in many schools of architecture[1]—we will try to expose the interlaced lines in architectural design with a view to finally discuss the prospective relevance of such a conceptive approach. This research had been developed in accordance with the MAP-Aria laboratory investigations and follows on a previous article which investigated *Percepts and Parameters* in architectural design (Bigot-Doll 2017). Fabrice Cavaillé and Marian Janda actively participated in this research, respectively, as a video maker and a computational designer.

Design Versus Fiction

Design and fiction seem structurally dissimilar. Design—and architectural design a fortiori—is physical, whereas fiction seems syntactical. Architects are familiar with drawing, measurements, matter, and space, whereas fiction is linear and temporal. Though architectural design and fiction are different by nature, these two endeavors are connected by sensible practice[2] and aesthetic inclination which are intrinsically closer to art than an academic discipline. Narration and storytelling are part of conception by interlacing forms and contents of a project (Vitalis and Guéna 2017), and the selected video medium which mostly represents architecture via animated images of renderings, physical models, etc., retrieved from the project, inevitably generates fiction just by the chosen point of view, framing, etc.

With a view to investigate the effects of such paradigms into conception, fifteen students of a master's degree program in architecture at ENSAL (School of Architecture of Lyon, France) were asked during an entire autumn semester to generate a project which should accurately question architectural fields through a video tale as a tool for conception. What we mean by architectural fields is the set of essential components which, physically or not, embody our domain. Mainly, architects define them as space generating (as well as generated by) usages, matter, structure, percepts, and aesthetics. Architectural language is made up of shapes, as stated above. Narrative form is syntactical. However, both are representing part of a human thinking. As a certain kind of creative practice, this process is also led by

[1]Among the the most famous such as Sci-Ach, AA School, etc.

[2]APEL DSV, ARCHITECTURE + SCIENTIFICITY = ARCHITECTURICITY (Architecturicité in French), http://www.canal-u.tv/video/ensa_lyon/gilles_desevedavy_une_nouvelle_architecturicite.22713.

aesthetical empathy (Lemarquis 2014) and, in this capacity, belongs to the class of representations of the subtle (Cometti 2005).

In the literature and logics history, Lewis Carroll was the very first to explore the connection which lies between geometrics and fiction (Wilson 2008). *Through the looking-glass* (Carroll 1994) is an *"enfictionment"*[3] of a chess game programmed and implemented into a Euclidian fictional metaphor. Indeed, Carroll animates Alice according to each piece of chess translation. She moves, grows, and shrinks throughout the novel. It is programming, writing, and setting a spatial fiction. Just a decade later in 1884, Edwin Abbott *enfictionned* geometrics into the satirical novel *Flatland* (Abbott 2013). From these examples, and according to the assumed uncertain future which keeps questioning students on their architect's *devenir,*[4] we deliberately admit that our pedagogy, with a view to lead this research and to encourage the emergence of new and necessary outcomes, should include fiction as an essential rationality development strategy (Reboul 2009).

Whether we deal with narrative or graphico-physical representations, let us admit that the video medium is located just between these two categories. Video medium contains images revealing space animated in a narrative time. Our students will design a film and an architectural project in parallel, as two analog interlaced branches.

Projective Lines

Fiction as Practice[5]

Any practice is inscribed and subjected toward temporality whether it deals with architectural conception or not. And, the substantial difference standing between architecture and narrative fiction, as previously asserted, is "Space versus Time." However, François Roche, famous French architect and researcher "by practice," carries the necessity of a fictional *scenario* leading his productions as a contents catalyst (蓝青 2006) and integrates short films in some of his projects. Following this stance, practitioners claiming and/or experiencing fiction such as well-known Rem Koolhass or French artist–architect Didier Faustino got massive in the last decades, whereas the traditional scheme of conception process as taught in traditional studios of architecture remains linear and prerogatives rationality applying a tough procedure which could be roughly defined as the following: spontaneously drafting, drawing according to the guidelines, making it strictly fit, and exporting for construction. The investigated position in this paper proposes to explore emerging prospects through fiction with a view to generate singular habits. These

[3]As an encapsulation implementing information from one formal syntactical nature to another.

[4]Echoes Deleuzian devenir autre could be literally translated « a becoming other » .

[5]R&Sie (pronounce "heresy", hérésie in French), Roche F, http://www.new-territories.com/.

habits are located on a social level, just as much as on a physical and structural level.

In line with these paradigms, as pivotal performers in architectural design, we today witness the robotics eruption. Robots happen to be compared to physical characters in architecture conception and fabrication (CAD/CAM). The architects Fabio Gramazio and Mathias Kohler in ETH Zürich were some of the very first to inject robots in their own architectural prospects (Gramazio et al. 2008). Likewise, François Roche and Stephan Henrich consciously and constantly personify robots in operative *scenarii* (Roche and Lacadée 2014; Picon 2014) creating in this way a singular and figurative epistemology toward fiction and embodiment of architectural design according to Antoine Picon, and more generally, tools enhance imagination.

In our research, as we do not own robots, students can use 3D printers, laser cutter, and computers. Therefore, they can (almost) easily, instrumented with affordable 3D modelers and parametric software, produce dynamic conception thanks to programing and implement virtual to physical using CAD/CAM basic tools. Such apparatuses imply lots of iterative loops during conception stages. Strategies in matter of parametric design bear the particularity to constantly postpone the crystallization of shapes. Contemporary architectural design is definitely no more linear. Therefore, our approach intends to maintain an assumed out of focus line thanks to fiction. This fiction is carried by a film.

We will here present three sets of chronological screenshots retrieved from the students' films. The first one, *La Source* (Source 2015), is a reflection toward a future shortage of drinkable water in towns. The second film, *Flying Loft* (Flying 2015), still positions its *scenario* in a dark future where people could communicate their humor only thanks to pigeons carrying an *emotional ether*, from one dovecote shelter to another. Finally, *La Coujina Filante* (2015), an urban associative kitchen, will briefly resume and conclude on the *liminal* links existing between the fiction and the project produced which questions existent habits versus projected places.

La Source, firstly written as a novel, questions the function of public urban sources. "*Will this place be a sanctuary? Will it be battlefield?*" The film shows aesthetical blue-tinted images. From the very start of the semester to the final project, the color kept leading the film. Ink on hands, unbreathable air, blue sky, etc., the blue atmosphere combined with a "white to blue" tint brought the story to a layered and foldable architectural apparatus frugally delivering drinkable water balloons. In the film, the balloons are shown directly in the fridge, operating a narrative ellipsis from the metaphor to a projected new habit (Figs. 1 and 2).

The beginning of *Flying Loft* has the same structure. We are immersed in a fictional future. This future is, however, very close to our everyday life. The video is filmed in the school at Vaulx-en-Velin in a classroom. The two characters interpret a pessimistic scene in which everyone can possibly fire the colleague at the next table via the Internet connection representing and criticizing unemployment, social solitude versus over connectivity. After his dismissal, the main character blows an ether in an origami container (Figs. 3, 4 and 5), while a strange shape is shrinking from an ice cube.

Fig. 1 Video screenshots 1/4 retrieved from *La Source*, Aaogyk

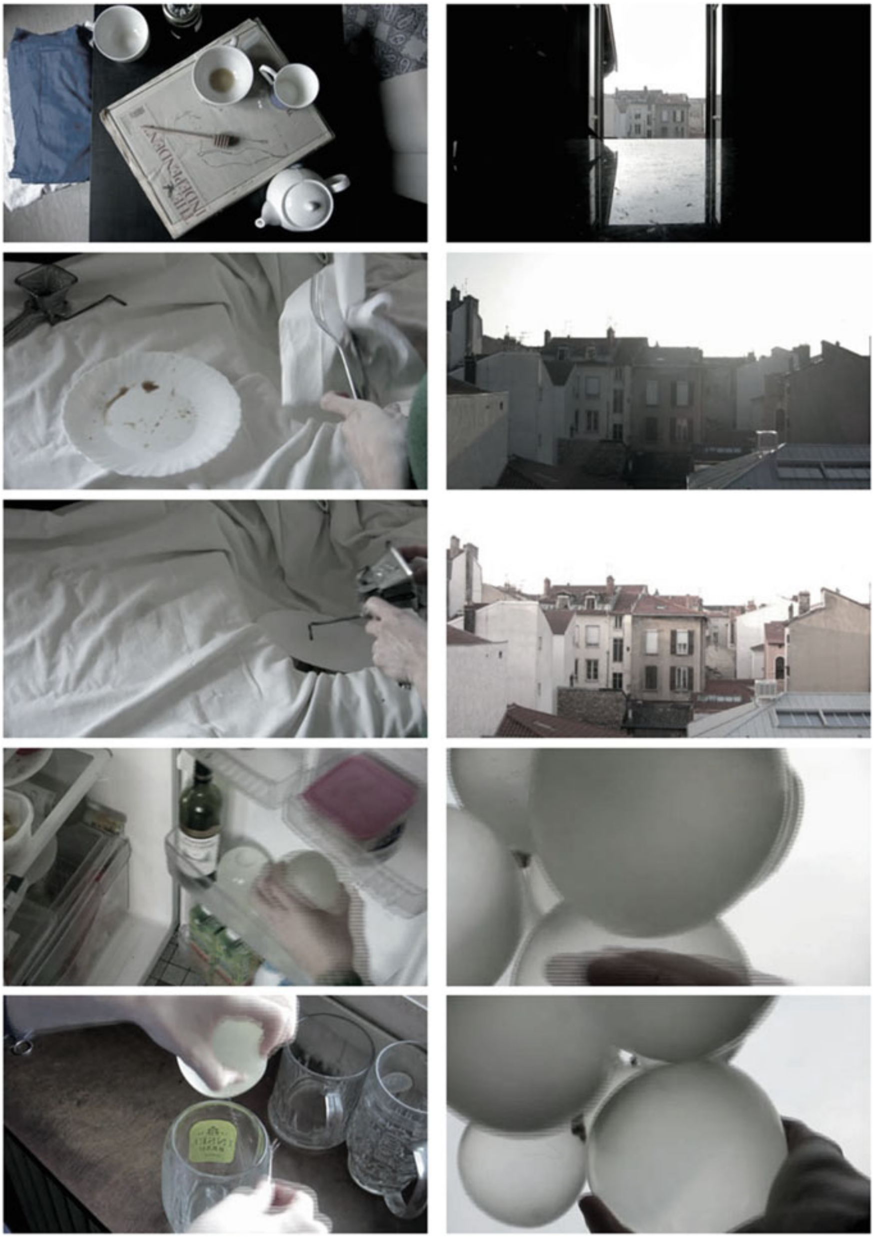

Fig. 2 Video screenshots 2/4 retrieved from *La Source*, Aaogyk

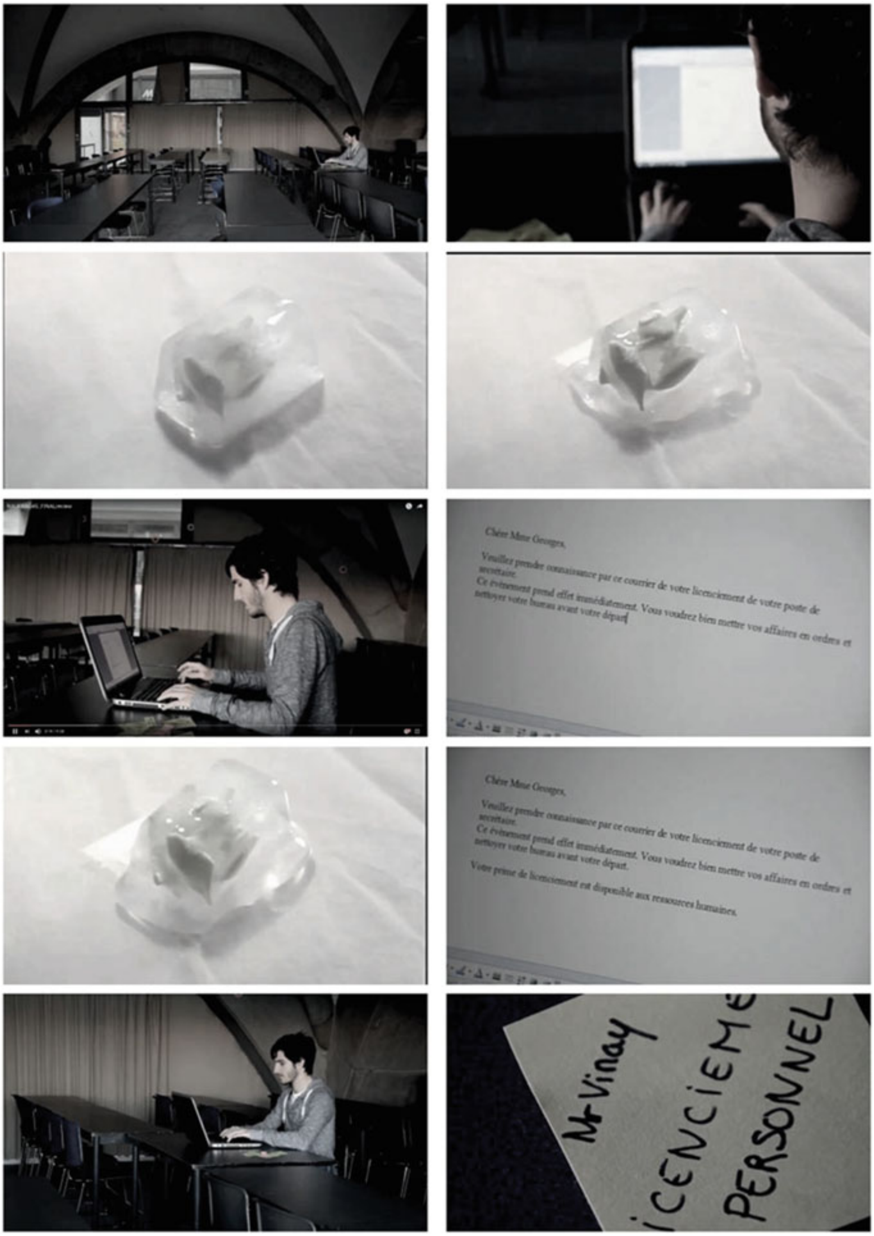

Fig. 3 Video screenshots 1/3 retrieved from *Flying Loft*, Naufrages

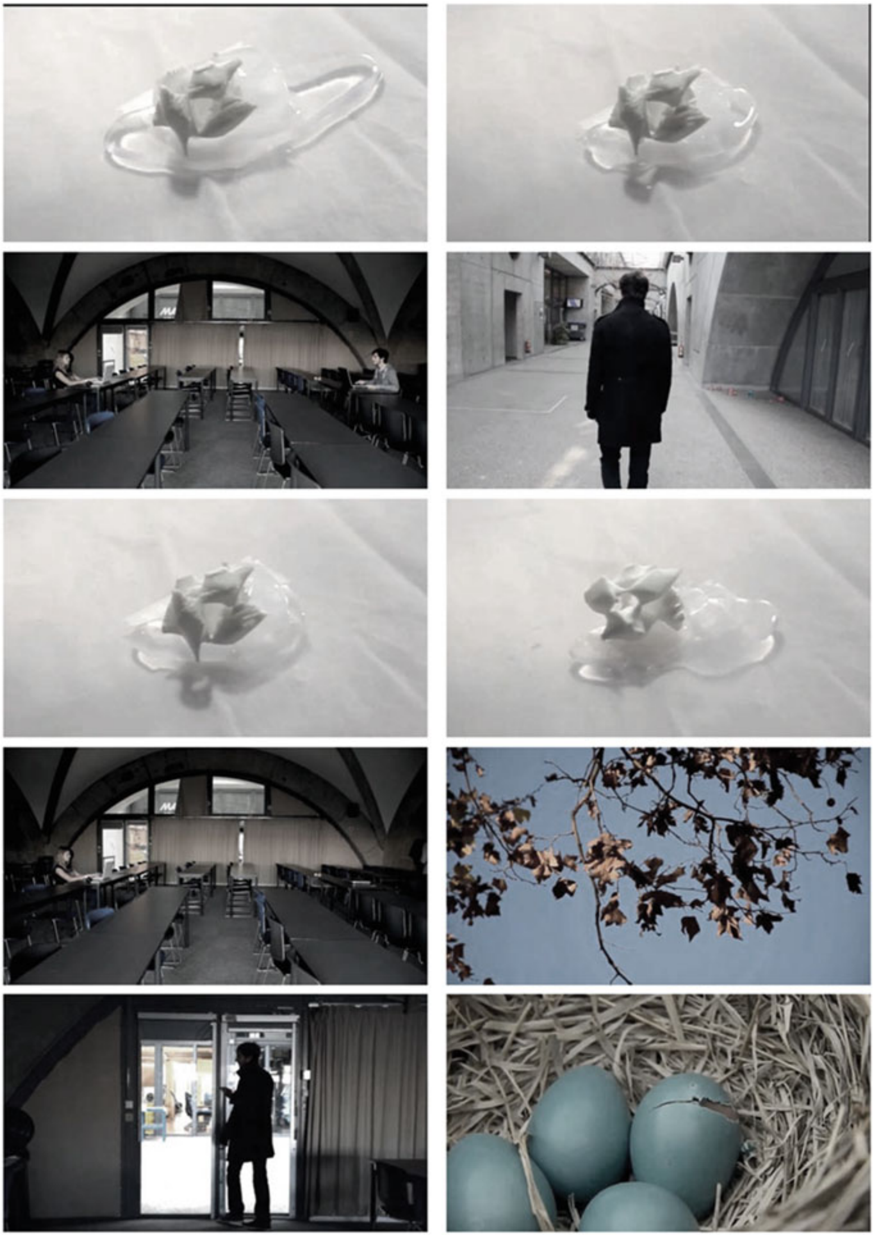

Fig. 4 Video screenshots 2/3 retrieved from *Flying Loft*, Naufrages

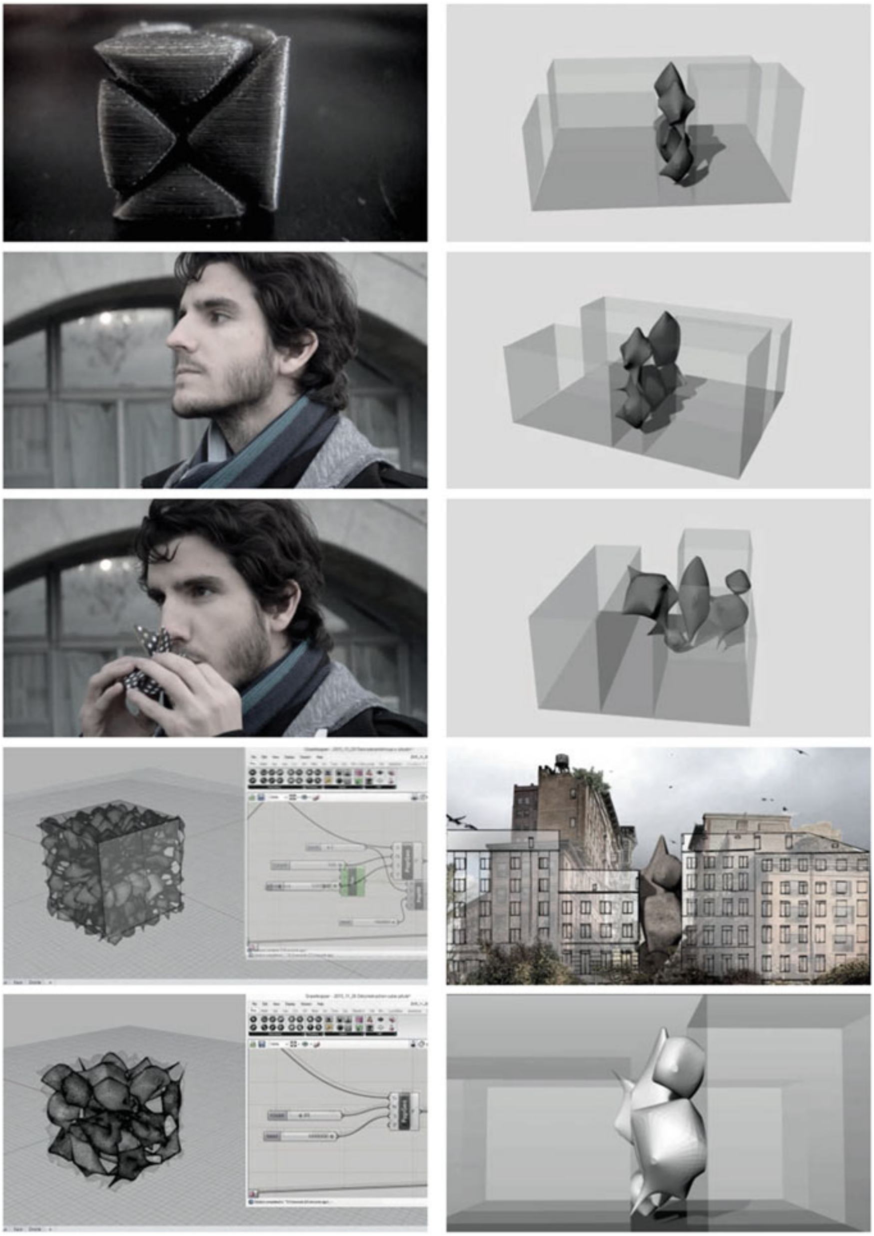

Fig. 5 Video screenshots 3/3 retrieved from *Flying Loft*, Naufrages

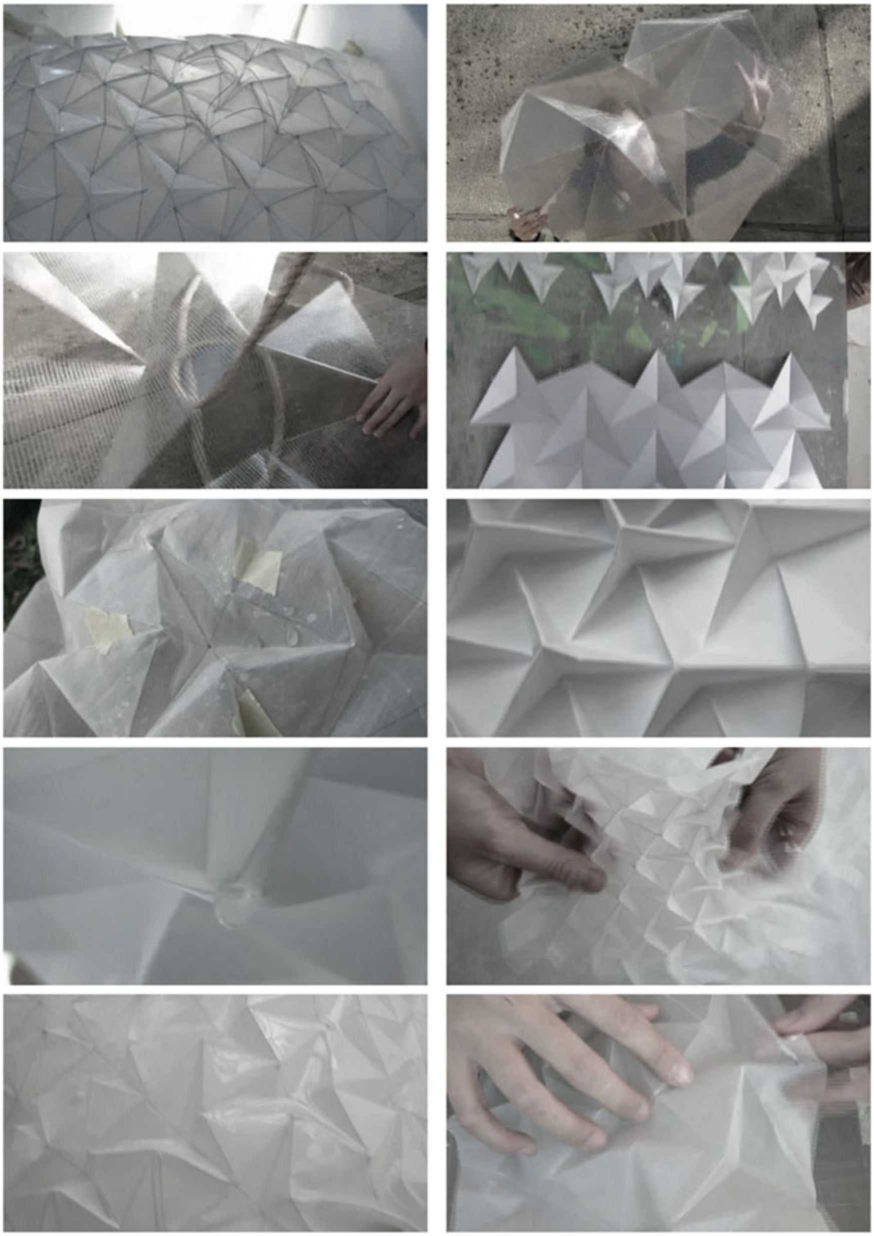

Fig. 6 Video screenshots 3/4 retrieved from *La Source*, Aaogyk

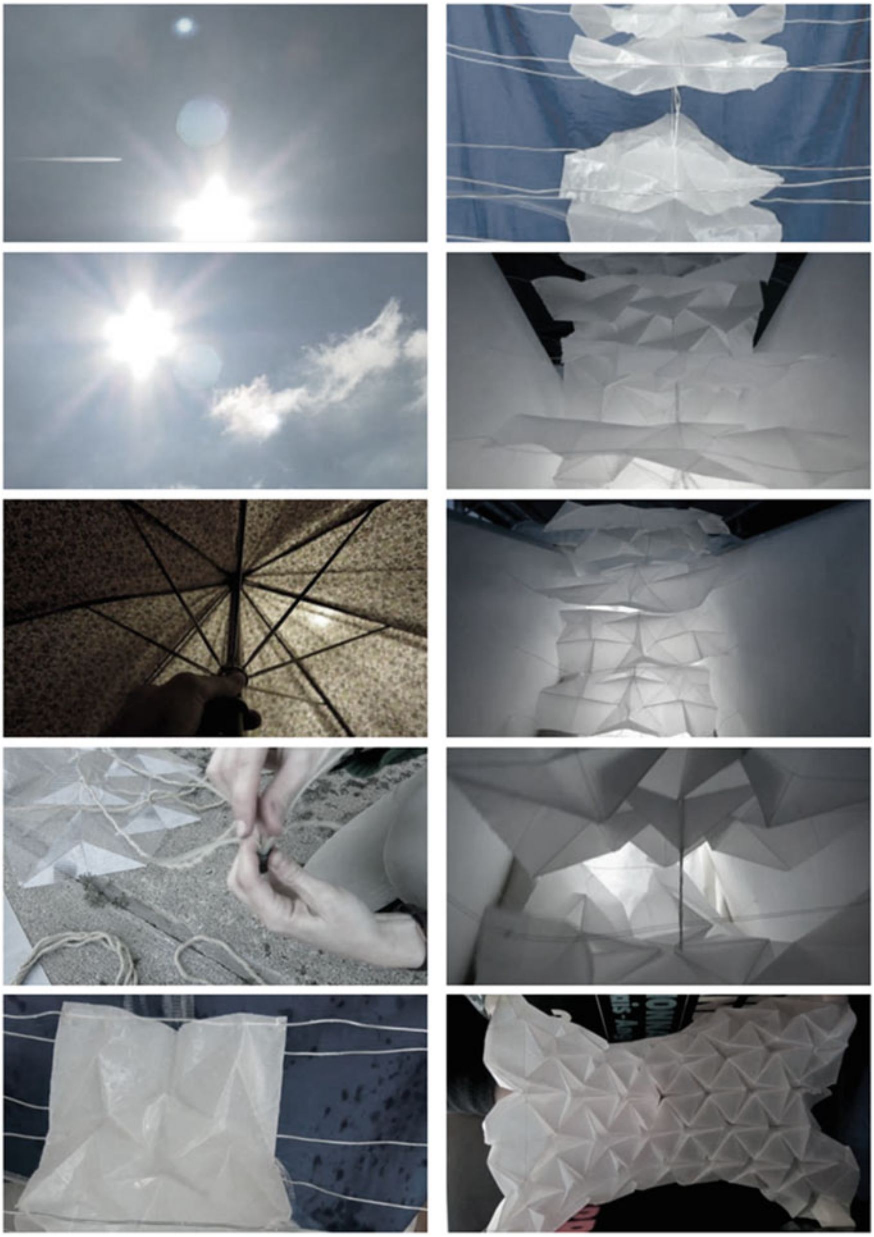

Fig. 7 Video screenshots 4/4 retrieved from *La Source*, Aaogyk

Both of these *scenarii* can be compared to Chris Marker's movie, *La Jetée* (Marker 1962) as an assumed shared reference. The similitudes belong to the subtle promiscuity from the real life we all know. From these fragments punctured from reality, an interpretation of a close future is emitted. Indeed, Chris Marker shows real black and white pictures of completed disasters to *enfictionnate* the Third World War. The moviemaker invents a close fictional future using fragments retrieved from reality, questioning in this way the liminal frontier between tangible certainties and prospective diversions. This is precisely the bypass we are assumed to generate and observe in a prospective architectural design process.

We now clearly see the line described by the film and its links between reality and fiction. Combining narration and images, the movies created by students are bringing architectural responses on a practical level but also on an epistemological point of view in which language and form, concepts and objects (Foucault 1966) as ingredients for a Foucauldian architecture of *other spaces* (Foucault 1967) are called.

Prospective Fabric

Form follows ~~FUN~~FICtion[6]

… And fiction raises rationality as previously quoted from Anne Reboul's researches. In this regard, let us try to evaluate the potentials of such a design strategy in terms of creativity generating new pedagogical outcomes and practical skills for students, as well as for practitioner architects. Indeed, comparing students' films to the resulting projects accurately questions the creative connections generated in terms of cognition on one hand, and the stakes in matter of operative architectural conception, on the other hand. Form by geometry, materiality, or structure is the most visible results, but functions, habits, and social schemes seem here as relevant as design.

As a fabric, the conception stage is fed by the movie operative narration. The emitted *scenarii* act as a [sub]conscious projective thread. Interlacing the curly projective line of design and the linear vertebral fiction by the film, this fabric creates singularities by analogy. Jean-Pierre Chupin, French architect researcher in Canada, legitimates analogy as a crucial cognitive scheme in terms of an architectural conception stage. As homologies mimic objects, analogies borrow the

[6]From Louis Sullivan's *fff* modernist adagio: "form follows function." This sentence had been appealed by several architects (Bernard Tschumi, Michel Denès), artists, graphists, etc.

intrinsic structure of forms and concepts (Chupin 2007). In this regard, the fiction [as an object] generates an analog link with the project. This knitted combination is what we assume to name the *prospective fabric* (Bort 2013).

La Source sets a narrative and figurative landscape, whereas, in a second part, the fiction is relayed by the work-in-progress stage showing a consequent amount of physical models injected "in real-time" into the *scenario* (Figs. 6 and 7). Just as in *Flying Loft*, we are no longer able to strictly distinguish story and project. In the *Naufragés'* work, an object is, almost subliminally, inserted in a shrinking ice cube. The project is properly shown in the second part of the film (Fig. 5).

On the contrary, *La Coujina Filante* sets a situation extracted from students' life, namely a meal (Fig. 8). In this way, it is [not] a *"real fiction"* as long as the couscous baking scene is a fragment extracted from a moment of life. These three young women are sharing something true, and the project emerging is questioning the everyday habit of "cooking for," "cooking with." What is the typology of a kitchen, how could it become an *other space* by a form research? Compared to *La Source* and *Flying Loft*, *La Coujina Filante*, in the same vein, inserts the project in the second part of the movie (Fig. 9), but in this case, contrary to the two other examples, their project weaves a fiction by injecting the unreal in the optimistic everyday life scene. The architectural materiality generated from the movies in these three projects is fabricating high-tech conceptions, using advanced tools in terms of CAD/CAM, with a view to operate a general return to low-tech in a global care of contemporary habits in a society which is constantly threatened by lack of resources, whether they are physical or social.

Architectural *fabric by shunt* operates loops in time and space. In terms of fiction, Jorge Luis Borges when he wrote *The Circular Ruins* (Borges 2014) already intended to inject temporal loops into narration just as Quentin Tarantino's movie *Pulp Fiction* (Tarantino 1994). Here, by weaving the two disciplines carried by architecture and fiction by film, we produce a complexity by adding physical space and materiality dimensions. We here clearly identify the hiatus which lives along such a hybridization. The students took advantage of the uncertainties created by a blurry situation with a view to generate architectural prospects on a fabrication level, trying to rationally reconsider our way of living in our shifting society: collecting water in towns, sharing humors avoiding Internet networks, sharing physiological needs considering percepts and affects by embodying singular *scenarii* liberated from traditional right-angled volumes.

Fig. 8 Video screenshots retrieved from *Coujina Filante*, Raw

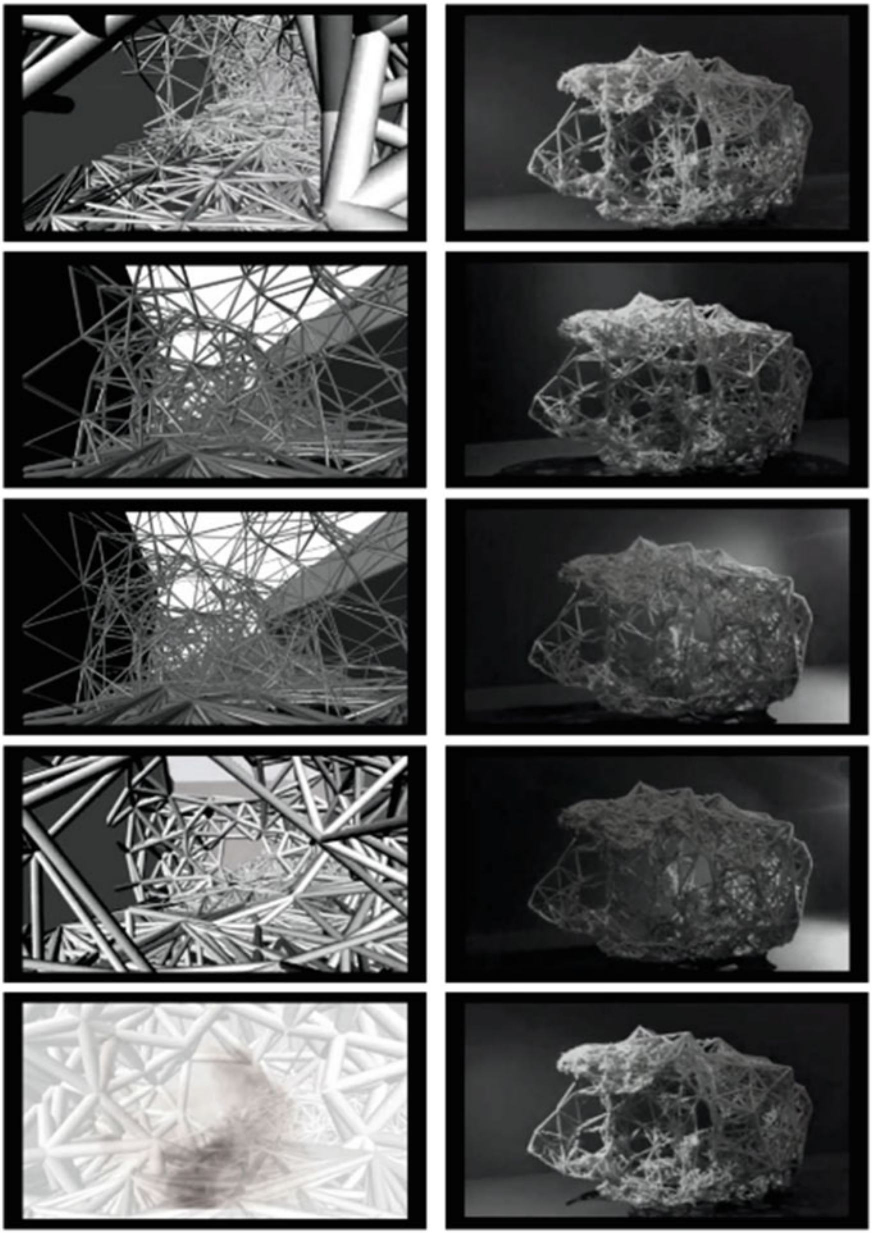

Fig. 9 Video screenshots retrieved from *Coujina Filante*, Raw

Conclusion

Whether the film is ignited by a color, constructed on ellipsis, analogies, or metaphors, the whole students' production is obviously motivated by the ambition to generate new aesthetics. Jacques Rancière, beyond the concept of aesthetical subconscious (Rancière 2001), shares the theory that aesthetics creates politics, and reciprocally (Rancière 2000). In our research, we express an epistemology based on new cultural habits and construction techniques. And, whereas the artists' and architects' empathy toward matter is already well identified (Braun et al. 2015), the dynamic incorporated by time develops closer from what Gilles Deleuze calls art and style by interlacing fields using analogies and metaphors. A new aesthetics creator generates new styles by producing original syntaxes from his own language. About Proust and *In Search of Lost Time*, Deleuze says (Deleuze 2014):

> *The interiority of time is declined in its dis-measurement.*

Using the video medium as crucial pivot, we here sought to explore the gap remaining between this Deleuzian dis-measurement for new aesthetics and habits versus architects' well-known Dürer's Underweysung der Messung (Dürer 1525), the craftsman technical tools prescribed for fabrication which we still practice today.

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Performative Gesture in the Era of Science Art: *POST OIL UTOPIA* Project

Olga Kisseleva and Alexander Kiryutin

Abstract The authors are describing their work on the "POST OIL UTOPIA" project devoted to the global oil depletion. Some countries, such as Kuwait which is one of the most striking examples of a mono-economy state, could suffer from this crisis heavily in the future. For their artistic project, the authors teamed up with French scientists who work on the revolutionary replacement of petrol-based products with the more environmentally friendly bioderived products. As a result in collaboration with them as well as with Interactive Performance Laboratory, the performance, presented at the Garage Contemporary Art Museum in Moscow, had been created.

Introduction

Our world faces a huge challenge. The global oil crisis is fast approaching, raw material dwindles. Meanwhile, some oil-based chemicals are even used to produce ordinary everyday items (products made of plastic, synthetic resin, rubber … and even soap!). Our current level of scientific development allows us to penetrate so deep inside the chemical structures that the moment is fast approaching for the revolutionary replacement of petrol-based products with the more environmentally friendly bioderived products. To achieve this, French chemists in their laboratories study the behavioral structures of such materials at nanolevel (about 10^{-9} m) (Sorrenti et al. 2013).

The experiments that we are interested in essentially involve adding (aggregating) biosurfactant molecules (represented as globules) in aqueous or oil solutions and watching their behavior. Since these structures (micellae) are classified in a certain way depending on the particle movements and on the proportions of

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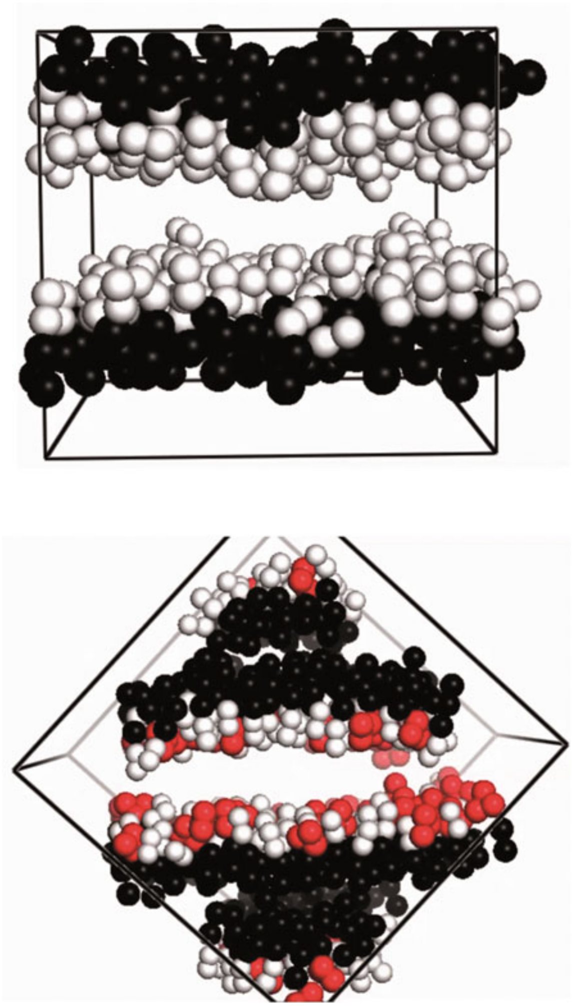

Fig. 1 On the left: membrane structure of a bilayered micelle after adding 216 molecules of C12E2 surfactant in aqueous solution. On the right: the same amount of surfactant plus 70 sugar globules form two triangles in water, such that each molecule can move freely around the structure. (© Stephane Abel.)

participating elements, molecules are divided into hydrophilic (white) and hydrophobic (black) ones. The scientists are particularly interested in an additional aggregation of sugar globules (red) and in the formation of structures with higher level of complexity, which can be seen in Fig. 1.

Purely on a visual level, the images produced by the scientists' state-of-the-art microscopes present the remarkably vivid analogies of the processes unfolding in contemporary society. These analogies embrace certain universal human questions in the fields of political science, sociology, economics, as well as in philosophy, culture, and art.

About the Performance

POST OIL UTOPIA multimedia performance, which formed a part of our project of the same name, was shown at the Garage Museum (Moscow) on December 12, 2015. The performance was created in collaboration with Niki Baccile and Stephane Abel, researches in Nanochemistry Laboratory of College de France, and the Interactive Performance Laboratory of the Polytechnic Museum (Russia), represented by composer Alexey Epishev and choreographer Yulia Chekmas, and headed by the curator Natalia Fuchs. At the core of the performance is the limitless nature of the chemistry's artistic interpretation of a phenomenon. Having reached the level of connections totally inaccessible to a naked eye, we discovered how closely it correlates to the global social processes (structures).

The original concept of *POST OIL UTOPIA* was conceived during Olga Kisseleva's visit to Kuwait in 2014. This Arab country, located in a desert area, is one of the most striking examples of a mono-economy state. Its citizens take pride in their skyscrapers and shopping malls that have "sprouted" out of the sand dunes. But virtually all its riches come from the oil export. The lifestyle of the population is remarkable. Men in snowy white dishdashas, with the equally white ghutras covering their heads, scurry through the endless passages of shopping malls, searching for the luxury items among Chanel and Armani boutiques. Groups of women, wearing voluminous silky black wraps (abayas) that leave only their eyes uncovered, hurry to add to their collections of haute couture clothes. From a birds' eye view, these streets seem to overflow with black-and-white crowds. What will happen to Kuwait if, in the near future, humanity ceases to depend so much on the country's main source of income? What will happen to this country—and to others like it—if their traditional black-and-white masses are sprinkled with the "revolutionary" red element, changing the very nature of their existence? To avoid critical situations resulting from the lack of oil, we need to already start thinking about the future.

POST OIL UTOPIA performance is an outright attempt to imagine a model of future society, functioning without the requisite dependence on the single resource. It is a utopian concept of an ideally organized system, with the characteristics generally similar to the ideas expressed in Thomas More's classical book. Within this system, humanity as a whole labors and acts equally productively to create the highest possible level of comfort. But the sixteenth-century English philosopher could hardly envisage the level of technological progress our modern civilization would achieve and the ways in which his *Utopia* could be interpreted today. Scientific development led to the emergence of the notion of self-organization in the science of the second half of the twentieth century. This term was first used by the English psychologist William Ashby in (1947). Since then, this concept has become quite popular; it is already in use in the complexity physics, as well as in synergetics, chemistry, and a number of other disciplines. The meaning of our performance could be best explained using "order out of chaos" definition taken from the works of Ilya Romanovich Prigogine, Belgian physical chemist and Nobel Laureate of Russian origin who had studied characteristics of various self-organizing systems.

The history of early technological art also contains an episode related to this term. During the 1960s, the English cyberneticist, psychologist, and artist Gordon Pask had been developing an approach of "modelling cognition as an evolutionary, self-organizing process" (Scott 2001). He took part in the 1968 London exhibition "Cybernetic Serendipity" (an event well known to media art historians), where he had shown his installation titled *The Colloquy of Mobiles*. Five hanging mobiles that were using sounds and colors to communicate with each other and with the visitors were, essentially, a take on Pask's ideas of *POST OIL UTOPIA*. Moreover, being both a working scientist and a practicing artist (the concept of "artist as researcher" is described in detail in the ArtScience Manifesto (Root-Bernstein et al. 2011), and we wholeheartedly support it), he was concerned with the question of the artistic relevance of such experiments. For this purpose, he specifically introduced the concept of an "aesthetically potent environment," where "the primary role is played by the viewer—the person who perceives something as art and experiences aesthetic pleasure" (Galkin 2013). Apart from the fact that Pask's works assigned the main roles to autonomous mobiles, *POST OIL UTOPIA* performance, saturated with audio and visual content, definitely has some points in common with the approach of this cyberneticist-cum-artist of the second half of the last century.

A Mode of Self-expression

The 17 min act stylistically based on contemporary choreography was performed at the Education Center of the Garage Museum. It is an unusually laid out space: A square hall is divided by four massive columns, also square in shape (Fig. 2). The main action is unfolded in the central area among the columns; it was complemented by the full-scale media setting: Both the surrounded sound and the video imagery were designed specifically for this project. The video was transmitted on the four screens installed in pairs on the side walls. Seats were arranged in three zones. Sitting inside the central zone, the viewers faced the performers directly more often and had the best overview of the whole area. Two other groups of seats were located somewhat to the back, behind the columns, facing the visual center of the performance—in such a way that some projections appeared outside of the viewers' direct field of vision. However, since one of the main characteristics of all performative practices is the dialogue they create with the viewer, dance choreography was designed in such a way as to allow performers to periodically address all three groups. Consequently, the "scene" could be schematically imagined as a

Fig. 2 Performance POST OIL UTOPIA by Olga Kisseleva in collaboration with Niki Baccile and Stephane Abel, curated by Natalia Fuchs, the Garage Museum of Contemporary Art, Moscow, Moscow. (© Alexander Kiryutin.)

circle within the square of the room. This shape was emphasized by centripetal—and sometimes centrifugal—movements of the performers. As a result, an "aesthetically potent" space had emerged, similar to the extraordinary expressive simulations by nanochemists.

And now we need to consider—what is this space, taken symbolically? Initially, all nanolevel processes are represented within the apparently enclosed cubic space. In fact, these borders are artificial. They represent symbolically the size of a fully formed micelle, which equals approximately 10^{-9} m. This means that 1 L of water simultaneously holds about 10 million of such micellae. By making simple calculations, we can even realize that 1 barrel of oil holds 1 billion 590 million micellae. This knowledge gives us a completely different understanding of what *POST OIL UTOPIA* is about. We can clearly see that the projections covered walls, which serve as constraints, are actually an illusion. And there is an almost infinite number of imaginary micellae, among which our three molecules are moving in a whimsical dance, searching for intersections.

The dance itself was not so much a replication of chemical processes, as their interpretation on a human level. This is proved even by the fact that the real micelle is never formed out of three parts only. It requires dozens or even hundreds of globules (simulations performed by scientists showed this number to be between 20 and 286). The initial preparation stage (recitals took place in August in Moscow) was built around an assumption that the performative act will require about 20 participants chosen among ordinary people, total strangers to each other—not necessarily possessing any choreographic training. Their bodily experience and choreographic vocabulary acquired in the process would have helped them to actualize the concept of the performance using a new language of perception.

This would have created a distinctively anarchic base of the performance as an independent practice, described by Roselee Goldberg (2014a). Taking on the disparate behavior of slowly added to the micelle molecules and performing various roles (white, black, and red), participants were supposed to pass through all stages of POST OIL UTOPIA process. This task was further complicated—but, at the same time, this ensured the experiment's integrity—by the fact that both at their first meeting and during the recitals participants were prohibited to contact each other. All communication had to happen only through the distinctive language of contemporary dance, unfamiliar to some of the participants.

Later, to increase performance laconism and artistic expressiveness, the decision was made to invite three professional dancers. Their movements throughout the whole act resembled molecular movements as close as possible—but did not simply copy them. If we witness the scientific simulations in motion, we will see how the particles exist and what relations are eventually formed between them; how the self-organization process happens at the almost mythical to us level. At first, black-and-white elements are placed in an aqueous medium with set conditions. Muted sound, based mostly on vibrations and coupled with gently swinging rectangular figures projected on screen, creates a mysterious impression of being underwater. (The metaphor of "water immersion" is often used in immersive installations.)

The molecules detachedly disperse across the space, making straightforward and simple movements, exploring their novel surroundings. Some time later, they begin to notice each other; the adjustment process ensues. In the end, they intertwine, finding a new form of existence in a highly dynamic dance accompanied by the powerfully vibrating surroundings. At the very moment when both elements have achieved their most comfortable position and a welcome lull has ensued, the third—red one—element enters the scene. Restless music swells; molecules rush around with strange jagged movements, unable to ignore each other's simultaneous existence. The strict linear imagery that heretofore dominated the projection screens falls apart. Another stage of life has begun.

After this, the same thing happens as before: Only it is now intensified in every way. Fast and sharp movements of the performers are complemented by the dramatic music and the lightness of the images. They struggle; they look directly into each other's eyes, as if communicating information about their condition through their crossed hands. At last, we arrive at the final stage. It is an individual dance of three molecules. But the nature of its individuality is in their communion and their deep understanding of each other, in their equal coexistence. The viewers watch how each of the "members" of this nano-society functions now—but in rapport with the others. At the final note of the performance—which symbolizes the ubiquitousness of represented processes—the molecules dissolve into the projection (i.e., in the medium) (Fig. 3).

Fig. 3 Performance POST OIL UTOPIA by Olga Kisseleva in collaboration with Niki Baccile and Stephane Abel, curated by Natalia Fuchs, the Garage Museum of Contemporary Art, Moscow. Performance episodes. (© Alexander Kiryutin.)

Performance theorists—Roselee Goldberg among them—believe that performance serves as an indicator of the artist's sensitivity to the changing world, as well as the most fruitful way for the artist to "reach the viewer" using dramatic and provocative public statements (2014b). Often this task is impossible without the artist's personal participation. However, this problem is solved differently in *POST OIL UTOPIA*. What could not be expressed by an artist using his or her tools was brought to life by the performance team: dancers Natalia Kroshkina, Kristina Ra, and Igor Tishkov; choreographer Yulia Chekmas; and composer Alexey Epishev.

Conclusion

POST OIL UTOPIA allows us to trace the latest trends in the performance as an artistic genre. First, it is merging with theater and dance (according to Goldberg (2014c)). The choreographic quality, as well as the theatrical staging of performance acts, was both the distinctive features of the first experiments by Futurist and Dada artists, when the language of the genre had not yet been developed. Second, it is interdisciplinarity.

It is widely acknowledged that the merging of art and science has opened new perspectives on various ways in which the artworks can be presented. Diverse forms of collaboration between artists and scientists, as well as different types of interaction strategies, led to the emergence of a new language of performance.

Our project, created at the intersection between art and science, is located within the field characterized by the gap ("complexity limit," according to Dmitry Bulatov (2009)) between technologically innovative character of the scientific discovery and its adoption by society. The distinctive space created through the media setting of this performance, and the universalized language achieved in the form of a fantastical dance as well as, ultimately, an approach to the material chosen by the artist: All of this attests to the performance's liminality and interdisciplinarity. It also confirms an existence of a particular artistic strategy: when an innovative scientific idea is transposed to the worldview of the artist, then interpreted, under the artist's guidance, by other professionals of audiovisual expression, and, finally, is brought to life as a media performance.

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This is described in a number of articles published in major scientific journals, which were co-authored, among others, by the chemists with whom we were collaborating. See, for example: Sorrenti, A., Illa, O., & Ortuno, R. M. (2013) Amphiphiles in aqueous solution: Well beyond a soap bubble. *Chemical Society Reviews, 42*, 8200–8219. Alternatively, in: Baccile, N., Pedersen, J. S, Pehau-Arnaudet, G., & Van Bogaert, I. N. A. (2013) *Soft Matter*, (9), 4911–4922.

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Hearing and Painting: Neuroaesthetic Theoretical Insights

Alain Londero, Capucine Payre, Zoï Kapoula and Jacqueline Lichtenstein

Abstract Painting is essentially a visual form of arts. Apparently, audition and the hearing system seem to be of no avail in the aesthetic experience felt by painters during the creative process of artistic visual patterns, and by beholders while painting viewing. But philosophers and modern neuroscience have challenged this kind of unimodal and classical framework of perception. Any perception, and more importantly the aesthetic one, is a complex multimodal process where all sensory inputs converge and interact along with cognition and behavior. Several of these multifaceted and intertwined interconnections between the visual and auditory sensory modalities are given in the neuroscientific literature. A striking and extensively studied example of such a relationship is auditory–visual synesthesia. On the other hand, the history of arts gives us to know many examples of painters that have been inspired by sounds or music or, conversely, of musicians that have used paintings to inspire their composition. Neuroaesthetics, an emerging field in the wider framework of neuroscience, is aimed at deciphering the neurobiological correlates of such aesthetic experiences. We argue that an in-depth neuroscientific study of these interactions between the auditory modality and the art of painting may help to better understand both the artistic processes and the neurobiology of multimodal perception.

Keywords Multisensory integration · Neuroaesthetics · Arts
Painting · Music

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"… les sons et les couleurs se répondent"

Extrait du poème de Charles Baudelaire intitulé "Correspondances" in "Les Fleurs du Mal" publié en 1857

"… sounds and colors correspond."

Quotation from Charles Baudelaire's poem entitled "Correspondences" in "Flowers of Evil", published in 1857.

« Ce qui serait vraiment surprenant, c'est que le son ne pût pas suggérer la couleur, que les couleurs ne pussent pas donner l'idée d'une mélodie, et que le son et la couleur fussent impropres à traduire des idées »

Richard Wagner et Tannhäuser à Paris, critique de Baudelaire après la première représentation à l'Opéra de Paris le 13 mars 1861.

« What would be surprising actually, is that the sound could not suggest the color, and that the colors could not give the idea of a melody, and that the sound and the colors might be unsuited at translating ideas »

Richard Wagner and Tannhäuser in Paris, Baudelaire's review after the first performance at Opera de Paris, 13th march 1861.

Introduction

In their core essence, pictorial arts are visual. And the visual sensory modality is obviously the one that is mostly involved in the painters' process of artistic creation and in the beholders' aesthetic experience induced by painting viewing (Melcher and Bacci 2013). On the other hand, the auditory system is the sensory system that gives us to interpret and understand the environmental soundscape in which we are constantly immersed, and so independently from any kind of visual stimulus (Snyder and Elhilali 2017). Keeping in mind an aesthetic perspective, the auditory system is the one that allows us to enjoy another important form of arts, music, for which vision seems to play a secondary role (Brattico and Pearce 2013; Kraus and White-Schwoch 2016). Yet, at a first glance, it appears that the visual arts—and pictorial arts above all—have little to share with our hearing skills and with the auditory system. In a letter to Monsieur de Noyers on the February 20, 1636, the French painter Nicolas Poussin even stated that as a painter he "… makes profession of silent things" ("… fais profession des choses muettes"). Then it could be considered rather counterintuitive trying to link or connect painting and hearing skills both in art making processes and in neuroscientific knowledge. Indeed pictorial arts display a soundless image (the painting) almost always embodied in a quiet space (the canvas, the frame, the exhibition) for the perception of which our hearing aptitudes seem to be scarcely useful. Furthermore, if all the different art-based practices have been compared and have shared a reciprocal influence along the history of arts, one should also note that at modern times the artistic production mainly devoted to vision (i.e., painting) and the one mainly devoted to hearing (i.e., music) have in some ways followed opposite paths. With the Realism or Naturalism movements, pictorial arts aimed, in a figurative endeavor, at representing Nature as faithfully as possible but progressively moved to modern abstraction or even to mathematization of painting making. Conversely, music has as evolved from its mathematical Pythagorean and contrapunctic roots to the most contemporary and figurative forms using voices and machine samples or even bird songs (*cf.* Olivier Messiaen *Treatise of Rhythm, Color and Ornithology* 1949–1992, Paris, Leduc, 1994–2002, 7 vol). As regards, the aesthetic experience induced by paintings the role of sensory input and sensory processing—the visual one above all—is indeed crucial (Boccia et al. 2016). Yet, Aristotle in its classical Metaphysics stated that "…there is nothing in our intelligence that has not passed through our senses." But he defined as "proper sensible" specific objects that directly refer to one sense (e.g., sounds for the sense of hearing) opposing them to "common sensible" which can be sensed by more than one sense (e.g., shapes can be sensed by sight and touch) (*cf.* Aristotle, *De anima*, II, 5, 418a, 12–20). According to this theory of perception, later on supported by the philosophical work of René Descartes, John Locke, and Roger de Piles, colors and paintings are to be considered as "proper sensible" of the sense of vision. But artists' intuition and introspection (See above Charles Baudelaire's quotation) and recent neuroscientific data strongly suggest that any kinds of aesthetic experience or art making are a multisensory experience involving complex interactions between the different sensorial inputs and cognition (Londero et al. 2016; Umilta' et al. 2012). Undeniably, modern neuroscience has stressed that there is no visual or auditory perception per se but that perception is almost always, in the real world, a cross-modal phenomenon (Glick and Sharma 2017; Niccolai et al. 2012; Shams 2012; Tang et al. 2016). Then the main aim of this paper is to interrogate how audition and painting may be linked both from an artistic and a neuroscientific perspective, and how this multimodal interaction could be explored within a neuroscientific theoretical framework, embedded in the wider field of neuroaesthetics. This could lead eventually both to a better analysis of the aesthetic interaction between painters and beholders but also, and essentially, to a deeper understanding of the neurobiological processes relying on multimodal sensory integration.

Auditory System Physiology: A Brief Overview

As a whole, the auditory system may be considered as an active transducer (FitzGerald and Folan-Curran 2002). Indeed the ears (external, middle, and inner ear or cochlea) (Saha et al. 2017) transform a complex mechanical stimulus (i.e., the pressure of the environmental sound waves produced outside or inside the body) into electric impulsions that are coded and transmitted, via the auditory nerves (Moser and Starr 2016), to the brain where this information is reconstructed to provide us with a conscious perception of the world of sounds (Carcea et al. 2017). This mechanic-electric transduction is mainly supported by the activation of a small number (i.e., in mankind less than 20000 cells per ear) of sensory auditory cells, topped with stereocilia and located in the cochlea. These so-called hair cells are divided into two different subgroups. The outer hair cells (OHC) display contractile properties and thus support the amplification of and the fine-tuning of the auditory signals (Ashmore 2008). The inner hair cells (IHC) are those actually connected to the fibers of the auditory nerve whose depolarization and spiking are induced by the IHC neurotransmitter release (glutamate) (Ruel et al. 2007) (Uthaiah and Hudspeth 2010). It is out of the scope of this brief overview to go deeper into this very complex physiology of the auditory receptor involving physical, chemical, electrical mechanisms. But one should stress the most important feature of this sensory organ: tonotopy; meaning that each frequency of a complex sound is processed by definite OHC and IHC at a very specific location in the inner ear (Mann and Kelley 2011). This frequency information is then maintained throughout the central auditory pathways (Pollak et al. 2003) up to the primary and secondary auditory cortices which display a tonotopic structure as well (Ahveninen et al. 2016; Brewer and Barton 2016; Saenz and Langers 2014). Similarly, the visual system possesses the same capabilities of spectrally processing the visual scenes or objects to which it is confronted (Olshausen and Field 1996). Indeed the auditory and the visual systems both behave as frequency analyzers sharing common processing properties (Marr 2010; Goffaux and Rossion 2006; Frangeul et al. 2016) and thus eventually interacting in an intertwined way (Beauchamp et al. 2004).

In the brain, the auditory information is actively processed by the central auditory pathways (lemniscal pathways) in order to produce a conscious representation of the surrounding soundscape. Even in very challenging and noisy environments, this complex, automatic, and real-time processing of the auditory scene leads to a strikingly efficient identification and localization of relevant auditory objects or to a filtering of irrelevant auditory stimuli (Vander Ghinst et al. 2016; Lewald 2016). The central auditory pathways eventually connect with other sensory pathways (visual, somatosensory, vestibular…) explaining why multimodal integration is a key property of auditory perception (Pannese et al. 2015; Erickson et al. 2017). The central auditory pathways also connect with other cortico-subcortical networks involved in emotion and memory processing, such as the limbic system (Frühholz et al. 2014). This explains why sounds may be remembered or linked with other perceptive memories and why sounds may evoke complex emotions such as pleasure, sadness, anger, or fear (Kumar et al. 2017). These key connections to non-auditory cortico-subcortical circuiteries are essential for the enjoyable perception of music (Altenmüller et al. 2014). Finally, one should stress the presence of a second, reflex and subconscious auditory pathway (extra-lemniscal pathway) involved in the automatic and irrepressible management of threatening sounds (Meffin and Grothe 2009). This allows us to immediately adapt our behavior with a “freeze, fight, or flight” reaction in case of an alerting sound event in our nearby environment (Misslin 2003) and so even during sleep (for a schematic view of the auditory system see Fig. 1).

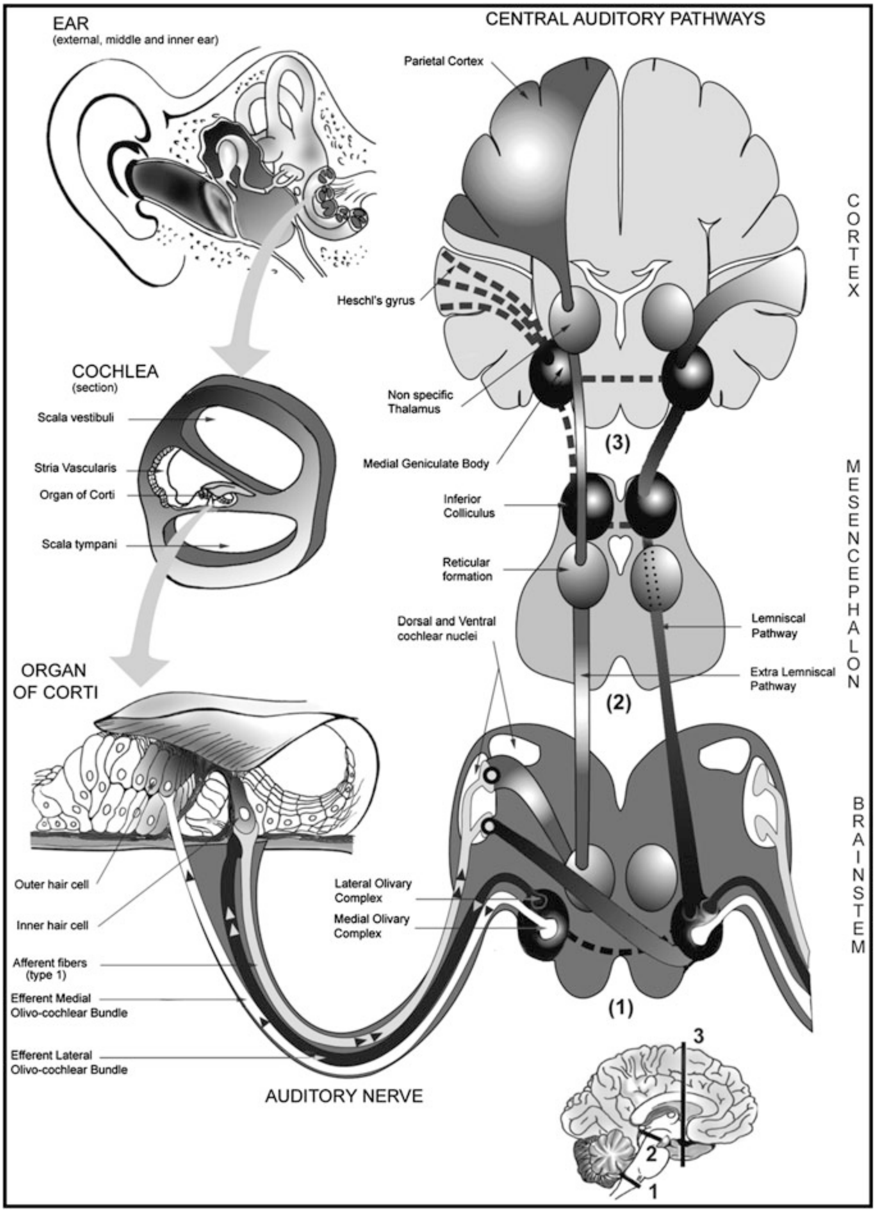

Fig. 1 Auditory system. Adapted from Londero et al. 2006

Interactions Between Auditory, Visual and Somatic Systems: Cross-modal Perception

The classical Aristotelian conception of sensory perception as has been philosophically challenged since the eighteenth century by philosophers such as Denis Diderot (cf. "Lettre aux aveugles à l'usage de ceux qui voient" London, 1749) and later on in the nineteenth century by others such as Helmholtz and Taine. It is no longer upheld by current neuroscientific and philosophical theories of perception. On the contrary, any kinds of perception including the auditory ones are considered to be, in their very core, a multisensorial and multimodal experience involving attention, cognition, and thoughts as well (Cupchik et al. 2009; Alho et al. 2014). This is also true for aesthetic experiences (both from the artists' and beholders' perspectives) (Chatterjee and Vartanian 2014; Marin 2015) even if the visual modality has been more extensively studied in the field of neuroaesthetics (Zeki 1999). Many different examples can be put forward to support this contemporary point of view on perception. For example, it has been shown that color exposure (green, white, or red lights) may influence our auditory perception. When lit by a red light, the subjects judged the same sound as louder when compared to a white light exposure. The green light exposure showed a reverse pattern. In the same study, the somatosensory perception (cold/warm) was also modified by the same color exposure giving further evidence for a cross-modal integration in human perception (Landgrebe et al. 2008). The MacDonald–McGurk effect is another remarkable illustration of a cross-modal auditory/visual illusion showing the strong interference between visual and auditory cues during the perception of speech (McGurk and MacDonald 1976). In this illusion, the perception of a phoneme is modulated by what we see of the movements of the lips. When the syllables /ba-ba/ are spoken over the lip movements of /ga-ga/, the resulting perception becomes /da-da/. The same sound wave results in a different perception when auditory and visual cues are congruent (/ba-ba/), (/ba-ba/) and when they are incongruent (/ba-ba/), (/ga-ga/). Indeed, in the MacDonald–McGurk experiment our auditory perception is evidently altered by this cross-modal interaction between hearing and vision. Another well-known and informative hint on these cross-modal correspondences between audition (sound of words) and vision (shapes) is given by the non-arbitrary relationship found between the phonetic of words and the shapes of the objects they refer to. This has been demonstrated by the classical maluma/takete experiment (Sapir 1929; Köhler 1947) many times replicated subsequently in a variety of research paradigms, e.g., (Parise and Spence 2012). The word "maluma" is more frequently associated with round, smooth, and peaceful shapes or outlines, whereas the word "takete" is rather associated with spiky, sharp-edged, and visually aggressive shapes or figures (Flumini et al. 2014). This very strong correlation has been proven to be consistent and reliable from childhood to adulthood (Ozturk et al. 2013) and across cultures (Davies 1961). Obviously, we do not choose arbitrarily the sounds we want to hear and words we want to pronounce in connection with an object. We name things or characters according to what they give us to see.

Seemingly, sounds and music can also cross-modally interact with other sensory systems. The correspondences between sounds, music, and shape have been demonstrated in musicians and non-musicians subjects by asking them to draw visual representations of what they heard (Küssner and Leech-Wilkinson 2014). It has also been shown that the free body movements that subjects perform when listening to music are consistently linked to the underlying expressive qualities they perceive in the music excerpts (Maes et al. 2014). We speculate that for some painters the same pattern may be a key issue for explaining their artistic expressiveness. For example, Mark Rothko (1903–1970) (http://www.markrothko.org/paintings/) made a strong connection between music and his painting. He eased his artistic production by listening to music as highlighted by his son in this quote "Music was central to my father's world to his own aesthetic sensibilities, certainly, but also to the structure and expressive modes he found as a painter…This leaves us with several questions. How is his love of music reflected in his works of art? More specifically, does his gravitation toward certain types of music reveal parallel preoccupations and communicative strains in his painting?" Indeed Mark Rothko's color field paintings "are like a Mozart aria… making possible the most passionate communication" (Rothko 2015). One interesting way of deciphering the multimodal artistic interaction would be to explore systematically how music modifies the painting technique in a selected sample of painters. Would listening to music systematically modify the subjects the painters choose, the forms they draw, the colors they use, and the gesture or their brushstrokes? Would different kinds of music specifically modify painting techniques? This neuroaesthetic innovative questioning might offer a new insight in these high-level multimodal perceptive, behavioral, and cognitive interactions.

Interactions Between Auditory and Visual Systems: Aesthetic Experiences

The famous French composer Olivier Messien said "I am affected by a kind of synopsia which allows me, when I hear music, and equally when I read it, to see inwardly, in the mind's eye, colors which move with". There is indeed an endless list of artists (Charles Baudelaire, Arthur Rimbaud, Alexander Scriabin, Frantz Liszt, Duke Ellington, Vladimir Nabokov, Sergei Eisenstein…) that have been known to be synesthetes, i.e., reporting diverse cross-modal experiences in perception for example in auditory/visual synesthesia, by seeing colors while hearing music or, less frequently, by hearing sounds while seeing colors or landscapes. This remarkable perceptual skill could be of great importance in their artistic creative processes. Synesthesia may be explained either by neuronal, bottom-up, sense-driven processes which may include patterns of qualitative similarity common to the different sensory modalities or by a top-down, concept-driven interpretation relying on higher level linguistic, semantic, and cultural aspects

(Albertazzi et al. 2015). Even if two aesthetic experiences offered by music and painting do not totally overlap (Miu et al. 2016), experimental evidence establishes strong cross-modal matches between music and colors even in non-synesthete and non-artist subjects. Faster and joyful music (in major mode) has been shown to be associated with light, saturated, and yellower colors whereas slow and sad music (in minor mode) preferentially match with dark, desaturated and bluer ones. Because music and color choices also match with the subjects' choice of expressive faces, these correspondences between music and color are supposed to be mediated by emotional associations (Palmer et al. 2013). At a higher level of perception and cognition, subjects listening to a major track (Mozart) have been shown to use lighter, warmer, highly saturated, and contrasted colors in creating images as compared to a minor track (Albinoni) (Sebba 1991). This effect has also been found for computer-controlled music performances (Bresin and Friberg 2000). Seemingly another study showed statistically significant correlations in the associations between Spanish guitar tracks and paintings (all from the same artist, Matteo Boato: http://www.matteoboato.net/). Moreover, a unidimensional semantic rating scale using adjectives (such as quick, slow, agitated, calm, strong, weak) showed the existence of associations between the visual and the auditory art pieces suggesting that judgments concerning music and painting are underpinned by qualitative similarity patterns, shared by the different sensory modalities even for such complex stimuli (Albertazzi et al. 2015). Moreover, as music has already been proven to have a strong effect on the emotional load, evaluation, and recalling of visual information (i.e., effective pictures, facial expressions, videos, films…) (Hanser and Mark 2013) it may be argued that specific music tracks or sounds could also help beholders to better immerge themselves into artistic paintings and then modify and/or increase their aesthetic experience. To our best knowledge, this kind of neuroaesthetic testing has never been scientifically carried out.

Painters and Music, Musicians and Painting

Vassily Kandinsky (1866–1944) stated that "white sounds like a silence, an emptiness before all beginnings". It has been suggested that Vassily Kandinsky also was a synesthete (Ione and Tyler 2003). As a straightforward example of the direct relationship Vassily Kandinsky drew between musical and painting practices, he wrote in *Concerning the Spiritual in Art* (originally published 1911) (Kandinsky 1977): "Color is the keyboard, the eyes are the hammers and the soul is the piano with many strings. The artist is the hand that plays, touching one key or another purposively, to cause vibrations in the soul". Indeed in the modern history of arts, Vassily Kandinsky has been one of those artists that intuitively established a clear relationship between music and painting. He held music as the ultimate form of abstract art, underlining the power of music for producing extreme emotions only by the means of sounds. In line with this concept, he tried to visually reinterpreted music scores with forms and lines (Figs. 2 and 3).

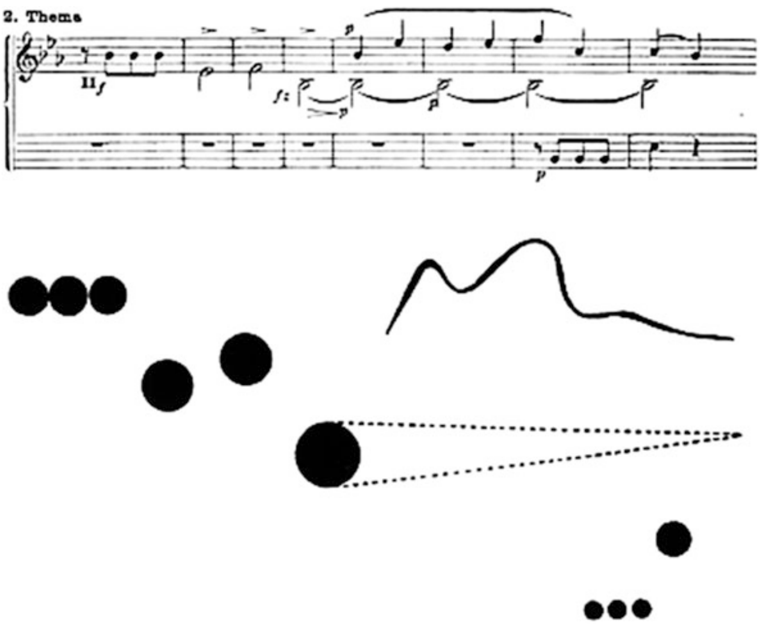

Fig. 2 Vassily Kandinsky (1866–1944) "Point and line to plane" (1926)

Fig. 3 Vassily Kandinsky (1866–1944) "Free curve to the point—Accompanying sound of geometric curves" (1925)

He eventually sublimated his pictorial art through music and tried to create pictorial artworks with shapes and colors that obeyed to the same rules as music. As a painter he actually composed his paintings as a musician would structure his music score (Fig. 4).

In 1911, Paul Klee (1879–1940) joined the almanac "Der Blaue Reiter", founded by Vassily Kandinsky and Franz Marc. Paul Klee was a painter but also a musician. Paul Klee introduced purely musical notions—such as polyphony and rhythm—in his pictorial practice (Düchting 1997). He gave both temporal and spatial dimensions to his paintings. His pictorial work is filled with musical references. In his diary, Paul Klee even stated that "polyphonic painting is superior to music in the sense that temporal qualities are more spatial here". (Tagebuch Nr. 1081, quoted from Christian Geelhaar, «Moderne Malerei und Musik der Klassik—eine Parallele», in: Paul Klee. Das Werk der Jahre 1919–1933. Gemälde, Handzeichnungen, Druckgraphik, Museum Ludwig, Cologne, 1979, p. 37). As clearly demonstrated by the canvas (Fugue in red, 1921) (Fig. 5).

Klee's pictorial practice is inspired by J.S. Bach's musical compositions especially the "Art of the Fugue" (contrapunctus) where the main theme and its multiple variations overlap creating a complex polyphonic musical structure. This canvas brings out something more than the sum of its parts, as do Bach's fugues. On the other hand, many musicians have been inspired by painting. Claude Debussy (1862–1918) was fascinated by the visual notion of arabesque and by impressionist painters such as Joseph Turner (1775–1851), James Whistler (1834–1903),

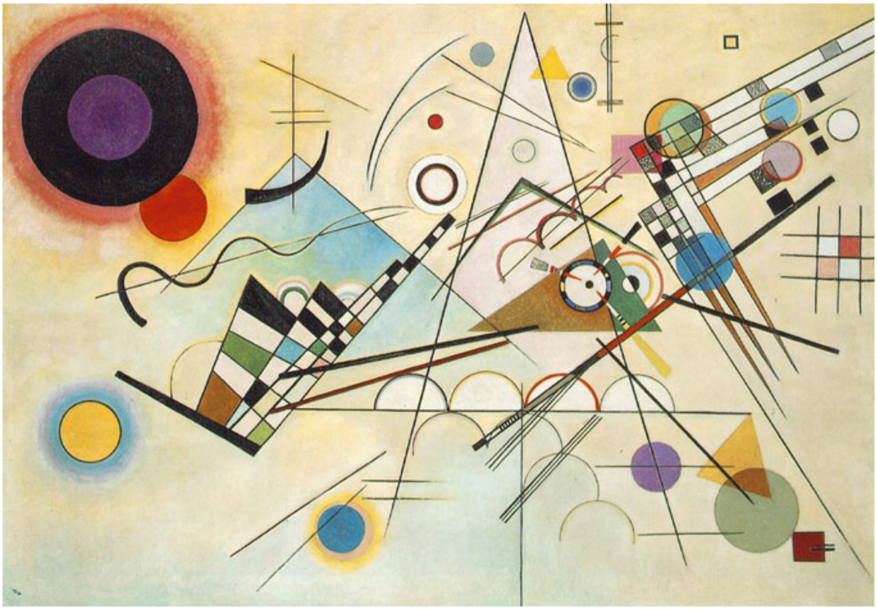

Fig. 4 Vassily Kandinsky (1866–1944) "Composition VIII" (1923)

Fig. 5 Paul Klee (1879–1940) “Fugue in red” (1921)

and Claude Monet (1840–1926). Claude Debussy is considered as the founder of musical impressionism, which aimed at creating emotions similar to those inspired by the masters’ paintings. In such an attempt, Claude Debussy composed cloudy and misty themes. In a similar attempt, the Hungarian pianist and composer Franz Liszt (1811–1886), likely a synesthete, aimed at musically transcribing the canvas “Marriage of the Virgin” by Raphael (1483–1520) and a sculpted effigy by Michelangelo (1519–1533). Later on in 1874, Modest Mussorgsky (1839–1881) also translated into musical language the watercolors of his friend Viktor Hartman (1834–1873). Those musical works are his famous piano pieces “Pictures at an exhibition”. Interestingly, in some kind of virtuous aesthetic circle, those music pieces have been translated in turn into pictorial language by Vassily Kandinsky in 1928. Indeed an in-depth neuroaesthetic study of these interactions between painting and music during artistic production could represent a very promising venue to better understand the intertwined relationship between auditory and visual sensory inputs, artistic creation, and emotion.

Conclusion

Producing an artistic painting or looking at it involves not only the visual system but a complex interplay between all sensory modalities, cognition, and behavior. The involvement of the hearing system in these processes is obviously present for those subjects displaying an auditory/visual synesthesia. But audition may also be of key importance for all subjects, painters, and beholders, engaged in any aesthetic interface. Because vision is the most important sensory modality in humans and because the neuroscience of aesthetics has been initially promoted by vision scientists less attention has been paid to other sensory modalities such as audition so far. But undoubtedly, many painters have already intuitively underlined the importance of sounds, especially music, and hearing in their art making. We argue that an in-depth neuroscientific study of these interactions between the auditory modality and the art of painting may help to better understand both the artistic processes and the neuropsychology of multimodal perception.

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Postural and Emotional Impact of Carsten Höller's Artwork "Light Corner"

Marine Vernet, Aurélien Morize and Zoï Kapoula

Abstract This study is an in situ experiment carried out at the Grand Palais in Paris during the exhibition "Dynamo" in 2013. Visitors of the exhibition were asked to stand in quiet stance in the middle of Carsten Höller's "Light Corner" (2001). This artwork, one of the first of the Dynamo exhibition, was a room (three walls, the fourth side being the entrance) covered with light bulbs flickering while speakers displayed sound vibrations at similar fast-paced rhythms, inducing visuo-auditory hallucinations. Inasmuch as many visitors naturally closed their eyes when the artwork was turned on, we measured the impact of being within the artwork with closed eyes (i.e., experiencing light and color through eyelids, heat sensations, and sounds) on postural control and on subjective appreciation of the artwork (ratings and free reports). Overall, the 18 participants showed very diverse appreciation (from extremely low to extremely high). The main results of our study show that the mean power frequency of the body sway increased, and that such frequency was negatively correlated with the subjective appreciation of the artwork: participants who disliked the artwork more, and participants who spontaneously referred to the violence of the artwork, showed higher frequencies. Thus, our study shows that this artwork impacted in parallel body control and emotions, leaving the causal links between the two to be explored in future studies.

Introduction

Neuroaesthetics is a novel, rapidly expanding research field. A large branch of research studies conducted so far is focused on describing brain areas and networks activated during art perception, either by comparing observation of artistic and non-artistic stimuli or based on individual aesthetic judgment, beliefs, and context (Di Dio et al. 2007; Cupchik et al. 2009; Di Dio and Gallese 2009; Kirk et al. 2009;

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Calvo-Merino et al. 2010; Brown et al. 2011; Ishizu and Zeki 2011; Lutz et al. 2013). Of interest, several of these studies support the theory of embodied perception of art and of motor resonance in front of artwork. Indeed, activation within the parietal and the premotor cortices (Cupchik et al. 2009; Lutz et al. 2013) and desynchronization of mu (8–14 Hz) cortical oscillations (Umilta et al. 2012), generally observed over motor areas during motor preparation, are recorded when participants observe artworks with strong spatial and/or motion components, which are depicted or related to the creative gesture.

Another way to test the theory of embodied perception of art is to directly measure the physiological body response of artwork observers. In this vein, posturography is a tool that bridges the gap between brain and body physiology disciplines and provides empirical data for theories of embodied cognition. Posturography quantifies postural control in upright quiet stance in a noninvasive manner during short periods of time. It provides valuable information on the capacity of the central nervous system to integrate multiple visual, vestibular, cutaneous, and muscle proprioceptive inputs and to generate adapted and corrective muscular responses through the action of a feedback control system (Chiba et al. 2016). Posturography is mainly used in neurophysiology as a tool for diagnosis and follow-up of patients with various pathologies causing postural dysfunction (e.g., vestibular disorders, strokes, Parkinson's disease, neuropathy) (Horak et al. 2009).

Posturography was recently brought to the field of neuroaesthetics. Representation of movements and instability in artworks has been shown to modulate posture control. For example, a picture of a Degas' sculpted dancing ballerina induced greater body sways than a picture of a Degas's sculpted static ballerina, demonstrating that images of body movement internally generate unconscious body oscillations (Nather et al. 2010). Representation of depth can similarly impact posture. Indeed, abstract paintings from Maria Helena Vieira da Silva containing depth elements cause greater postural instability than modified versions of these paintings, which eliminate those depth cues (Kapoula et al. 2011). In another study, posturography and subjective visual vertical were both improved during the visit of the exhibition of sculptures from Richard Serra "Promenade" (2008), created for the series of "Monumenta" installation within the great nave of the Grand Palais in Paris, France (Kapoula et al. 2014). Such improvement could have been caused by the experience of laterally titled monolithic sculpture. Thus, physical and spatial properties of the artwork seem to have a direct influence on the human physiology.

Following up, the current study examines the impact of artworks observed in situ during the exhibition called "Dynamo" at the Grand Palais in Paris, France, in 2013. The spirit of the exhibition was to show how various artists explore vision, space, light, and movement in their works, often inviting the visitor to play an active role in the aesthetical experience. The present study will focus on the artwork "Light Corner" (2001) from Carsten Höller. This artwork, one of the first of the Dynamo exhibition, was a room (three walls, the fourth side being the entrance) covered with light bulbs flickering while speakers displayed sound vibrations at similar fast-paced rhythms.

The specific approach we took to study the embodied perception of this artwork is the combination of subjective experience (ratings of pleasantness and sense of instability as well as free report) with physiological measure of stability and energy to control posture, while the visitors were within the artwork. We aimed to determine which, if any, postural parameters were impacted by the artwork and if such impact was related to the subjective reports as we would expect during an embodied aesthetical experience.

Materials and Methods

The Artwork

The artwork "Light Corner" from Carsten Höller (Fig. 1) is an installation of three wall panels forming a U, holding a grid of light bulbs flickering at a frequency of 7–12 Hz combined with a clicking stereo signal that continues back and forth between two audio speakers. Note that this frequency range corresponds to the cortical alpha frequencies, recorded over the occipital areas when humans are relaxed with their eyes closed, or to the cortical mu frequencies, recorded over the motor areas when humans are at rest. Such oscillation rhythms are decreased upon eyes opening or movement preparation. Interestingly, such frequencies are also in the range of the main postural body oscillations. The front wall of the artwork was about 1.6 m high × 4 m large, whereas the two side walls were about 1.6 m high × 3 m large. A short movie of the artwork can be found here

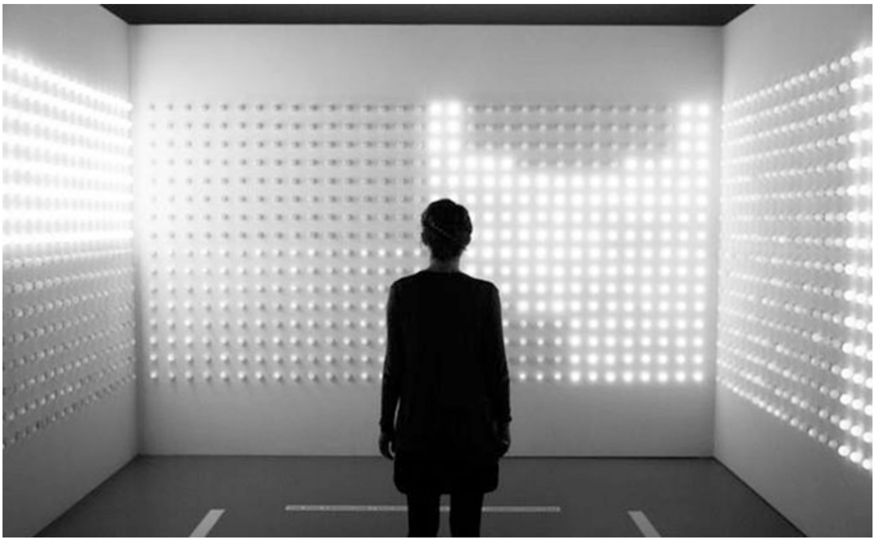

Fig. 1 Picture of a visitor in Carsten Höller's "Light Corner", 2001, displayed at the Grand Palais (Dynamo, April 2013) © Fred Dufour/AFP

(WoocaresReally 2013). The visitor was placed at approximately 2 m from each wall. Thus, the visual angle subtended by the artwork was superior to 230° on the horizontal meridian and 44° on the vertical meridian. This artwork is designed to induce optic and acoustic hallucinations to visitors keeping their eyes opened or closed. The artist has a scientific background. He holds a doctorate agricultural science and has been working as a research entomologist. His artistic work reflects a wish to apply scientific experimentation to art project and to bring biology and aesthetic together, placing the visitor as part of the aesthetical experience.

Subjects

Eighteen healthy participants (mean age ± SD: 38.7 ± 15.8; male/female: 7/11) were recruited at the entrance of the museum. Their frequency of museums or exhibitions visits vary from rarely/occasionally to very often (> 20/year), and two were defining themselves as artists. For the entire experiments, they were wearing flat shoes (no heels). The investigation adhered to the tenets of the Declaration of Helsinki. Informed consent was obtained from each participant after the nature of the experiment was explained to her or him.

Accelerometer

Posture was measured for 30 s per condition. A body-fixed sensor (accelerometer) was used. The accelerometer (DynaPort, MiniMod, McRoberts B.V., The Hague, The Netherlands) was placed at the participant's lower back (L5). The MiniMod makes use of a triaxial seismic acceleration sensor (AXXL202, Analogue Devices, Norwood MA, USA). The sensor's full-scale range is ±2°. The sampling frequency is set to 100 Hz.

Procedure

For each condition, subjects were required to stand upright in standardized Romberg position (feet placed side-by-side with an angle of 30° and heels separated by about 4 cm) and looking straight ahead (or maintaining their head straight ahead with their eyes closed). They were asked to maintain a quiet stance, i.e., arms held side-by-side, silent with teeth unclenched and normal breathing. There were three conditions: baseline, OFF, and ON that will be described below.

Before entering the exhibition, in a neutral space, subject performed a baseline condition during which they fixate straight ahead facing a wall at 3.6 m (angle subtended by the wall >60° × 45°). The artwork was among the first artworks of the exhibition. The artwork alternated between off period with no sound and no light and on period with flickering sound and light. After the baseline 30-s measure, participants were brought inside the Light Corner while the artwork was off (no sound and no light on). They could briefly glance at the artwork, i.e., experienced being inside a small space with three walls regularly covered with light bulbs, so they could have a sense of the space created by the artwork and its anatomical structure. As soon as they were placed in the middle of the room, at 2 m from the three walls, they were asked to close their eyes. Two experimenters stayed behind to secure them. In the OFF condition, a 30-s recording was performed while they kept their eyes closed and while the artwork was still off. In between conditions, subjects kept their eyes closed. In the ON condition, a 30-s recording was performed while the artwork was on, still with eyes closed. At the end of the recording, they could open their eyes and exit the room when they wished to. After the exit period, they were asked to rate how much they liked the artwork (subjective appreciation) and their sensation of instability (subjective instability) on a visual scale (from bottom: not at all to top: extremely). The subject adjusted a cursor on this graphical scale, the position of the cursor corresponding to a 0–10 number that could be written down by the experimenters. Finally, subjects were invited to freely report their impression on the artwork and their subjective experience.

Postural Parameters

The following parameters were analyzed: normalized area (in mm^2/s), root-mean-square of medio-lateral body sway (RMS of M/L in mm), root-mean-square of antero-posterior body sway (RMS of A/P in mm), RMS of M/L velocity (in mm/s), RMS of A/P velocity (in mm/s), and finally mean power frequency (Hz). The first three measures describe the stability, while the last three concern mostly the distribution of energy used to stabilize the body.

Data Analysis

All the data were z-transformed. In a first analysis, we performed a one-way ANOVA with the factor condition (baseline, ON, OFF) for all postural parameters separately. Whenever significant, the ANOVA was followed by a post hoc test of Tukey–Kramer. This analysis revealed that the ON condition significantly increased the mean power frequency (see results below); therefore, the remaining analyses were restricted to this parameter. In a second analysis, we calculated the Pearson correlation between the mean power frequency during the ON condition and the two subjective ratings: appreciation and sensation of instability. Finally, in a third analysis, the free reports were examined. We identified the most used themes and created groups of participants depending on their use or absence of use of vocabulary from those themes. T tests were used to evaluate whether the groups differ in subjective ratings or in their mean power frequency during the ON condition. For all analyses, statistical significance was set at $p \leq 0.05$; the Benjamini Hochberg procedure was used to correct for multiple comparisons using a false discovery rate of 0.05.

Results

Effects of Condition on Postural Parameters

Figure 2 displays all postural parameters for the three conditions. ANOVAs on postural parameters revealed that the mean power frequency (MPF) was significantly modulated by the conditions ($F(2, 17) = 4.52$, $p < 0.05$). Post hoc analyses revealed that MPF was significantly higher for the ON than for the baseline condition ($p < 0.05$). The conditions did not modulate any other postural parameters (all the $p > 0.05$).

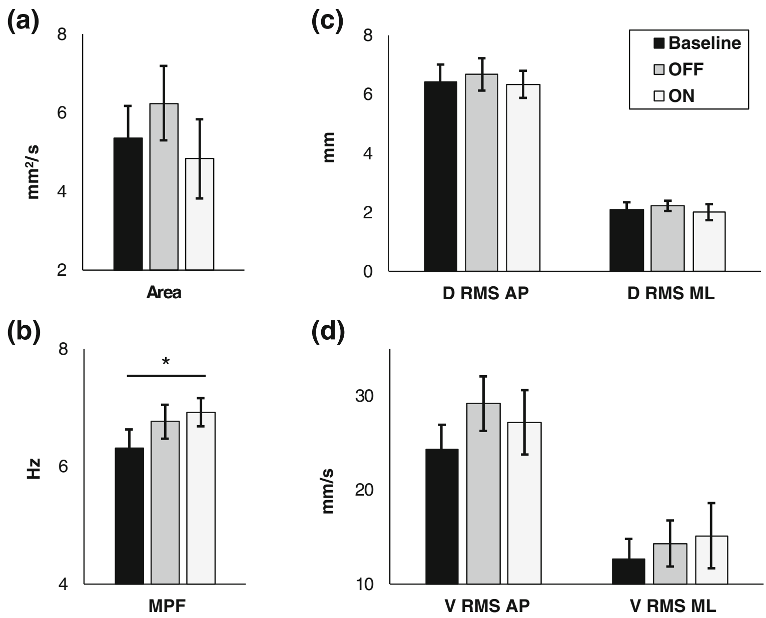

Fig. 2 Postural parameters studied for the three conditions: at baseline, in the artwork when it was OFF and in the artwork when it was ON. **a** Normalized area; **b** mean power frequency (MPF); **c** root-mean-square of the body sway in the antero-posterior and medio-lateral directions (D RMS AP and D RMS ML); **d** root-mean-square of the velocity of the body sway in the antero-posterior and medio-lateral directions (V RMS AP and V RMS ML)

Correlations with Subjective Scores

The correlation analysis revealed that the MPF was negatively correlated with both the subjective appreciation score ($R^2 = 0.36$; $p < 0.01$; $p_{corr} < 0.05$; Fig. 3a) and the subjective instability score ($R^2 = 0.23$; $p < 0.05$; $p_{corr} < 0.05$, Fig. 3b).

Relationship with Free Subjective Reports

The main themes identified in the free comments of the participants were spontaneous references to light or color (seven participants), violence or aggressiveness (seven participants), movement or instability (three participants), heat (three participants) and noise (two participants). The remaining of the analysis focuses on light/color and violence, which are the themes mostly referred by the participants. There is no evidence for different subjective scores or different MPF between participants referring or not referring to light and color (Fig. 3c). In contrast, participants referring to the violence or aggressiveness of the artwork showed a lower appreciation ($p < 0.05$ but $p_{corr} = 0.058$) and a higher MPF ($p < 0.001$; $p_{corr} < 0.05$) than participants not mentioning it (Fig. 3d).

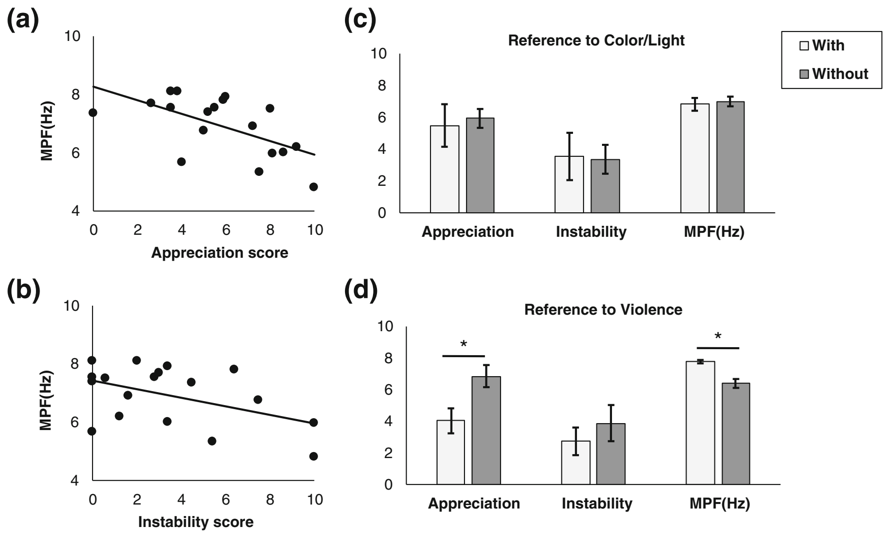

Fig. 3 Relation between physiological parameters and subjective experience. The mean power frequency (MPF) was significantly negatively correlated with: **a** the appreciation score and **b** the instability score. **c** Participants referring to color and light did not differ in their subjective score or in their MPF than participants not referring to them. **d** Participants referring to the violence of the artwork had significantly lower appreciation and larger MPF than participants not referring to it

Discussion

The results showed that, compared to a baseline condition with the eyes open, being in the artwork with the eyes closed increased the mean power frequency; such increase was significant when the artwork was ON. This effect was not only caused by the eyes closeness but was also related to the impact of the artwork. Indeed, further analyses revealed that MPF while the artwork was ON was significantly and inversely correlated with the subjective appreciation and the subjective instability evaluation. Moreover, MPF was significantly higher and appreciation was significantly lower for participants spontaneously referring to the violence of the artwork than for participants making no such reference. Thus, the results indicated that a shift of postural energy expense toward higher frequencies was associated with a lower appreciation of the artwork and spontaneous references to its violence or aggressiveness.

This study revealed how variable the impact of this artwork could be on visitors. The appreciation score varied from not at all (0) to extremely (10), indicating that participants of our study could hate or love the experience of being in this artwork. Whatever its valence, the emotional impact was probably often strong. Art cannot be reduced to experiencing beauty or pleasure, and such strong reaction could contribute, in some visitors, to the sublime experience. It has been suggested that exploring the neurophysiological correlates of the sublime, rather than that of the beautiful, might pave the way to a better understanding of our interaction with art (Trentini 2016). Of interest, seven participants spontaneously referred to the violence and aggressiveness of the artwork, and those participants were likely to dislike the most the artwork and to experience the highest body oscillation frequencies while being within the artwork. Our experiment does not allow us to infer the causality of these relationships. Whether or not unpleasantness impacted the postural control (or vice versa) is open to further investigations. In any case, both were clearly modulated by the artwork. Such findings confirmed the association between the subjective impact of an artwork and its physiological counterparts, usually measured in the brain (Calvo-Merino et al. 2008, 2010; Brown et al. 2011; Ishizu and Zeki 2011; Cattaneo et al. 2015). The present study extends this association to postural body measurements.

In addition to the strong brightness of the light and the loudness of the sound, the fact that the light and sound were coming from different locations on the walls at different times could have also contributed to the aesthetical experience: the participants could have perceived an illusory movement. It has been proposed that such motion illusion is embodied (Nather et al. 2013). Interfering with the instruction to remain static, the illusory motion would have led to higher energy to stabilize the body and to higher frequencies of oscillations. Some participants might not have been aware of such effect, which they could have interpreted as an unpleasant experience. On the contrary, participants not experiencing this conflict would have enjoyed the artwork.

The frequencies chosen by the artist for its artwork overlapped with interesting physiological frequencies: the alpha and mu cortical frequencies, often referred to as the resting frequencies of the visual and the motor cortex, respectively (Niedermeyer 1997). Less is known about spontaneous body oscillations, especially when measured with an accelerometer placed on the lower back. Previous studies have shown values of mean power frequency from 2 to 7 Hz (Lamoth et al. 2009; Lamoth and van Heuvelen 2012), i.e., on the lower end of the frequency band used in the artwork. It is thus possible that the artwork's frequencies had an impact on both cortical and body oscillations. It has been shown that visual and auditory stimulation can, to a certain extent, entrain physiological oscillations (Adrian and Matthews 1934; Herrmann 2001; Will and Berg 2007). Such entrainment might have an impact on cognition, emotions or even induce altered states of awareness, which might have explained their success in art and medicine (Siever 2007). In this study, we did not record electroencephalographic (EEG) signals, but we may hypothesize that cortical oscillations could have shifted close to the visuo-auditory input frequencies. To our knowledge, much less is known concerning body oscillations entrainment. In the present study, we observe that body oscillations frequencies on average increased toward the visuo-auditory input frequencies. Nevertheless, our study was not designed to directly measure such entrainment and we cannot conclude whether this observation reflects an entrainment, i.e., a synchronization of the body oscillations to the artwork frequencies, or a mere destabilization of the postural control. Whatever the exact mechanism, the artist found a way to provoke our physiological system, which might be one (hidden) aim of art (Ramachandran 2005).

We would like to emphasize two methodological aspects of our study. First, as with any neuroaesthetics experiment, we faced the challenge of using a highly complex visuo-auditory stimulus instead of the well-controlled stimuli used in more traditional neuroscience experiment. To map such complexity to simplified measures of the physiological system, it is necessary to collect subjective reports from the research participants. Such reports could take the form of scalable variable such as appreciation and instability score (chosen based on our a priori questions), but also of spontaneous reports, which could further guide the understanding of the mechanisms at play. Considering the subjective experience of research participants is crucial when studying cognition (Rudrauf et al. 2003), let only aesthetic experience.

Second, we would like to underline how each artwork calls for unique experimental procedure (Joufflineau and Bachrach 2016). In our case, we observed that many visitors of the artwork spontaneously closed their eyes upon the start of the light/sound flickering. Such reaction could help to protect oneself against the violence of the visuo-auditory stimulation or to enjoy the heat and sound perception together with the attenuated (and in some case colorful) light perceived through the eyelids. This observation guided our experimental procedure to test the posture of the participants with their eyes closed. In parallel of investigating the neurophysiological universals of art, we think it is also important to dedicate unique methodology to unique artwork.

In conclusion, this experiment shows that the artwork “Light Corner” from Carsten Höller, displayed in the exhibition “Dynamo” at the Grand Palais in Paris in 2013, has a physiological impact on body oscillations. The strong visuo-auditory stimulation increased the mean power frequencies of visitors while they were standing still with the eyes closed experiencing the light (through their eyelids) and sound flickering. We also found an association between high MPF frequencies, low appreciation, and spontaneous reference to the violence of the artistic experience. Thus, our study shows that this artwork impacted in parallel body control and emotions, leaving the causal links between the two to be explored in future studies.

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Gesture: A Transsubjective Tool to Understand a Work of Architecture

Pedro Marques de Abreu, Jorge Tavares Ribeiro, Patrícia Esteves and Zoï Kapoula

Abstract Interpreting pre-existing pieces of architecture is not only a poetical matter that concerns theorists and historians. It is an important hermeneutical issue with many practical repercussions, especially when there is a need to intervene in valuable or historical buildings; it is also pertinent in what regards the didactics of architecture. We propose that the interpretation of architecture in a transsubjective way derives from the analysis of the mechanisms of human perception. When looking at a painting, for instance, cyclic scanning patterns are spontaneously performed by people's eyes. These patterns are primarily dependent on the picture and are, therefore, repeated by different people. Architectural stimuli should induce a comparable response through the engagement of the whole body. The result should be a pattern of movements—particularly of eye gaze and walking trajectory—resembling a slow dance. We name this *gesture*. Our preliminary empirical results substantiate our hypothesis: there seems to be a typical, shared response to the architectural form, expressed in visual exploration, trajectory and cognitive appraisal.

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Gesture—Theoretical Background

Architects who have to make interventions in pre-existing architectural works face a difficult challenge. Unlike a conductor interpreting a symphony but leaving the original score intact for future readers, an intervention in the built environment is typically permanent. Furthermore, unlike a restorer who is only requested to reveal the original colours of a painting, architects are usually asked to accommodate contemporary needs, which may require alterations to the original shape of the building.

This challenge is especially critical in highly valued monuments, in which touristic influx often generates specific needs—such as signage, accessibility, extra restrooms, the addition of information centres and shops. In these cases, interventions must be thoughtful. Even seemingly minor and benign alterations may impact negatively on authenticity and hinder the overall architectonic experience; in turn, this alters the perceived value of the monument—which, in succeeding generations, might result in indifference and neglect.

An adequate interpretation of pre-existing buildings must be made in order to respect its specific character and harmonize any intervention with its core essence. It is not sufficient—and sometimes not even adequate—to use similar materials or to match textures and colours to existing ones; design solutions must be able to follow the building's nature through the use of contemporary shapes and techniques. This is an interpretative issue, which carries many practical consequences; inasmuch as the character of a work of architecture is subjective,[1] how can an architect interpret it not according to his or her personal idiosyncrasy but in a way that will make sense for the whole community as well?

To answer this question, it will be helpful to consider the way in which architecture is perceived.

A parallel has frequently been drawn between architecture and music. The most famous is probably that established by Schelling ([1859] 1999), but Valéry ([1921] 1926) also approached the matter when he wrote: *«Dis-moi (puisque tu es si sensible aux effets de l'architecture), n'as-tu pas observé, en te promenant dans cette ville, que d'entre les édifices dont elle est peuplée. Les uns sont muets, les autres parlent, et d'autres enfin, qui sont les plus rares, chantent ?»*[2]. Architecture, like music, is capable of producing an atmosphere (Zumthor 2006). As often happens when experiencing works of art, approaching a work of architecture suspends the noise of one's thoughts; it quiets, both literally and figuratively, the noisy flow of the world. In the midst of that silence, one can, like Valéry sets forth, hear architecture sing.

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[1]The character of a work of architecture is of a poetic rather than technical nature. It conveys a meaning that is significant to human reality; "it is not (only) pertinent to the *doing* of Men, but to their *being* as well" (Abreu 2007).

[2]This hierarchy established by Valéry between those buildings who are silent, those who speak and those who sing concerns the difference between *architecture* and *plain construction*. Not every construction is a work of art. The hypothesis that we are presenting here applies to works of architecture—those who have a deep human resonance—but not necessarily to every building.

Architecture's song is, of course, a quiet one; it does not loudly request attention; instead, it is there to greet and embrace those who come to hear it. It is also not a self-involved chanting; it is an invitation to dance. It induces movement, both inwardly and externally, as a reaction to that song. When this reaction occurs, it is not like dancing alone or like performing an autonomous dervish-like dance. An architectural work leads through its posture, its balance, the entire expression of existence in harmony with itself and the world. This work is not self-sufficient: its embracing atmosphere tacitly conveys sympathy, empathy, understanding—through the grace of its form and its rhythms. It is an invitation to make its acquaintance. It is not enough to hear the song; it must be followed, *dwelt* on; one must allow oneself to be taken and dance with it (Abreu 2007, 2008).

This is where architecture is different from other types of art. While other art forms may induce "dancing", only architecture generates this "dancing-with". Like music, architecture creates an atmosphere and induces dance, but it accomplishes that in a particular way: by becoming the *alter,* the other with whom a dialogue is created.

It is by engaging with this "other" that its character—the *genius loci*—can truly be understood. Architecture reveals itself in the way in which it makes us move and in the way in which it *moves* us—both physically and emotionally. Each work conveys a specific facet of the architectural scope and causes different repercussions; each tune calls for a different e-motion (like different songs played in a club call for different swaying). Therefore, our hypothesis is that analysing the way in which a person moves through space is the key to understanding the nature of a place—its particular effect and its unique existential purpose.

These observations about the way in which architecture is realized, although specific to this art form, are not isolated in the context of human perception. As such, investigation concerning eye guidance and how people look at paintings can shed a light into the perception of architecture as well.

The whole human body is engaged by the architectural form of a building: looking at it, hearing the sound of one's steps on the floor, smelling the scent of its materials, leaning on its walls (Zumthor 1998; Rasmussen [1959] 2002; Pallasmaa 2005). Architecture encompasses all senses and for this reason it has uniquely complex perceptive reverberations. However, a simpler version of this phenomenon also occurs when looking at a painting. The theme, the technique, the use of light and darkness and colour—they all unite to create a distinctive visual world. Pictorial stimulus engages the eye in a purposeful way, inducing a specific optical experience.

Yarbus (1967) was one of the first to investigate the mechanisms of visual exploration. Using an eye tracker, he found out that when looking at an image, the eye does not scan it uniformly. Instead, it selects certain elements, which are repeatedly fixated, while other regions never receive direct attention. More specifically, the eye focuses on those areas that provide the most useful information for understanding the object. This behaviour was detected for photographs, paintings, drawings—every complex picture.

For instance, when contemplating a photograph of G. L. Petrushavich's sculpture "My Child" (Fig. 1), the observer is immediately attracted to the sleeping child's face

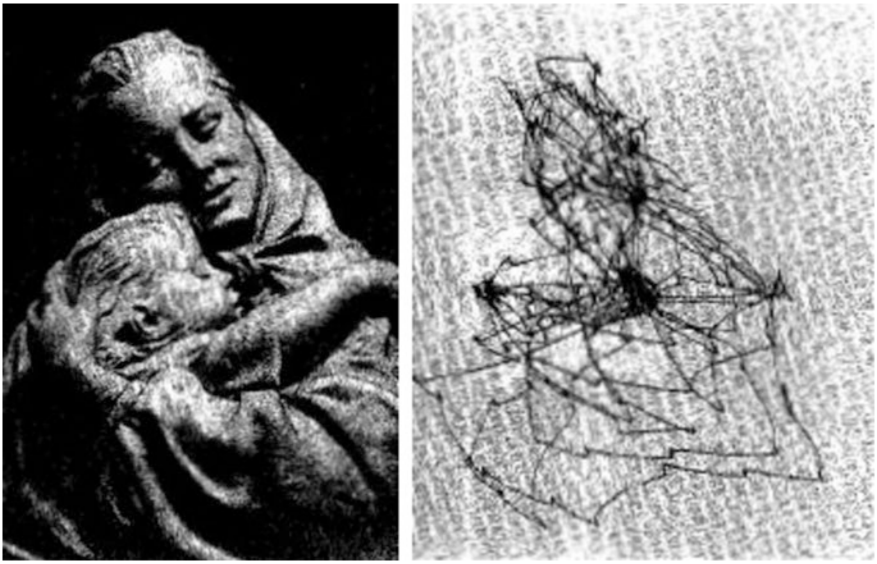

Fig. 1 Photograph of *My Child*, sculpture by G. L. Petrushavich; eye movements registered during free visual exploration of the picture (2 min)

—his closed lids, his lips and nose; next, he looks at the mother's smiling face—her lips are repeatedly fixated; the mother's hand holding her child's head is the third visual reference. The observer understands the meaning of the work—the joy of maternity—by synthesizing the elements into a coherent scene: the child's peaceful sleep, the mother's delight and the love manifest in her caring gesture. Attention triangulates between these elements, forming an exploration pattern in which "the observer's eye repeatedly returns to the same elements of the picture. Additional time spent on perception is not used to examine the secondary elements, but to re-examine the most important elements. The impression is created that the perception of a picture is usually composed of a series of 'cycles'" (Yarbus 1967).

Observing the emergence of a *cyclic perceptive pattern* out of the artistic visual stimulus is of crucial importance.

Further eye-tracking-based research subsequently solidified Yarbus' study.

His observation that when looking at an image, the preferred visual areas seem to be those with greatest semantic value was broadly confirmed (Antes 1974; Nyström and Holmqvist 2008; Nuthmann and Henderson 2010; Einhäuser et al. 2008). As Cristino and Baddeley (2009) point out, while looking at pictures and even in everyday life "people rarely look at the sky. Unless judging the weather or searching for airplanes, the sky rarely contains behaviourally important information". This fact sparks the idea that the underlying biological logic that governs perception is semantical. Moreover, people seem to be able to spontaneously predict with great accuracy where in our surrounding environment they are going to find the most interesting information (Mital et al. 2011; Dorr et al. 2010).

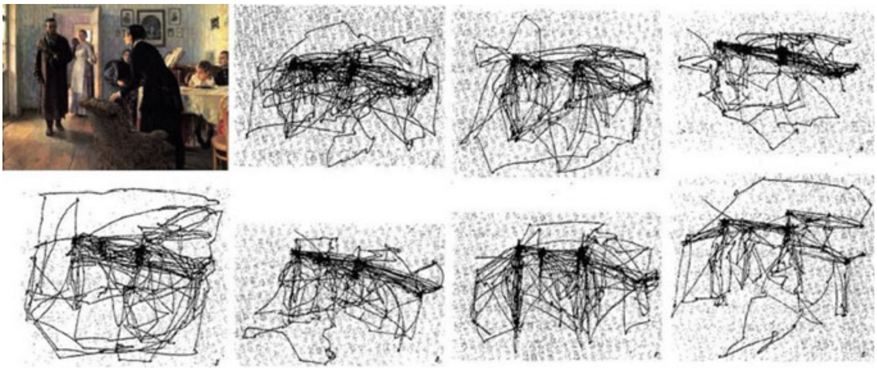

Fig. 2 *An Unexpected Visitor*, by I. E. Repin; eye movements registered for seven subjects during free visual exploration of the picture (3 min)

It is also significant that the perceptual pattern generated by an object seems to be part of the inner mechanism that make subjects understand and memorize it (Laeng and Teodorescu 2002; Humphrey and Underwook 2008; Kapoula et al. 2008). When asked to recall an image or a three-dimensional object that is no longer present, people's eyes re-enact the same motion that was firstly used to apprehend it.

Noton and Stark (1971) and Brant and Stark (1997) named the perceptual patterns emerging from each image "scanpaths". These "scanpaths" were specific to each image and—most importantly—they were recognizable from subject to subject, despite some minor variations.

In fact, this transsubjectivity had already been noticed by Yarbus. He showed how the same viewing strategies were followed by everyone when completing a task and how, when freely viewing complex scenes, different individuals were attracted by the same features (Fig. 2). This tells us that perception is deeply dependent upon stimuli; personal background and preferences of the observer play a lesser role. Perceptive strategies are shared.

Furthermore, works of art seem to be particularly capable of guiding the senses and creating an intense, coherent response in which meaning is conveyed in an especially compelling way (Cavanagh 2005; Johnson 2007; Kersten 2008). This fact, of course, makes sense if it is acknowledged that artistic representation is based on the process of emphasis (on the essential) and exclusion (of the superfluous) (Massironi 2001).

What we propose is that the basic principles of apprehension, which apply to painting, also apply to architecture. The scan patterns performed by the eye when looking at pictures may also offer an insight as to how people explore architectural space. Following this train of logic, architecture exploration would prompt a complex, whole-bodied, three-dimensional version of the two-dimensional scan pattern, encompassing all five perceptive systems (Gibson 1966) and, crucially, a walking trajectory as well as a gaze trajectory.

Fig. 3 *Annunciation*, by Piero della Franscesca (from the Polyptych of St. Anthony)

Furthermore, previous empirical studies suggest that these perceiving patterns might also occur in space. An experiment by Kapoula et al. registered the eye movements and the posture fluctuations prompted by Piero della Francesca's "Annunciation" (Kapoula et al. 2011). This painting has a strong depth cue in the centre (Fig. 3). As a result, the researchers found out that the first fixation was invariably directed at that area, which was "irresistible for the observer's eyes", as opposed to the Virgin or the Angel, which were fixated next. Moreover, there was convergence of the eyes together with sway of the body in the direction of the perceived depth.

This experiment was a first step towards answering the question of what the subjects' response would be if there really was a three-dimensional space in front of them. It supported the idea that spaces could probably trigger certain behavioural patterns and was, for this reason, a further step towards our own empirical research.

We put forward the hypothesis that each piece of architecture will elicit, in those who experience it, a pattern of walking and looking movements (and eventually a given set of emotions) (Abreu 2007). Using the whole human perceptive system, architecture unveils its nature. When entering an interior space, there may be a change in temperature; outside noise is muffled; pupils adapt to a dimmer or brighter light; the head twists to take in the view; there may be a combination of smells exuding from its materials and its objects—which often link to past memories.[3] If, for instance, a person is standing in a dimly lit room and a door opens somewhere, showing beyond it a bright place or something interesting, he may want to walk across the dim room to inspect the space beyond the door. Spatial layout suggests a certain path; where and how one walks is part of the perceptive response to the stimulus that the architectural form enacts; visual, acoustic, tactile, and smell stimuli, but also the proprioceptive stimuli that derive from the perceptive flow. The architectural whole induces a motion pattern, a series of bodily responses to it. Because these responses are mainly determined by the architectural form, we can assume that they are recurrent and that they are transsubjective. We named this typical perceptive sequence g*esture*[4] (Abreu and Esteves 2010, 2014).

Gesture would, therefore, be the *slow dance* induced by architectural stimuli (see footnote 1).

The metaphor between architecture and music can further help specify how each environment shapes behaviour. Architecture conveys a certain *tone* and a certain *rhythm* to those who experience and dwell on it.

The *tone* corresponds to the architecture's pervasive affective hue—it is the first sense of its nature that is put forth. It may be a cosy environment (like that of an Irish pub), a formal one (like Versailles), busy and booming (like a city market) or meditative (like a Cistercian cloister). This character stably influences perception, as well as physical and emotional stance. It must, however, be pointed out that these impressions derive directly from the architectural form. In the examples above, hearing plays a key role: an environment that allows playing and shouting is usually good at absorbing sounds (through its materials—cloth, plaster, wood—or form—open spaces, complex surfaces which dissipate sound); conversely, highly reverberating environments invite stricter attitudes, so as to avoid making loud noises; one is compelled to walk circumspectly in a palace hall, or in a cloister.

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[3]This synesthetic experience was beautifully described by architect Peter Zumthor in the following passage: "Sometimes I can almost feel a particular door handle in my hand, a piece of metal shaped like the back of a spoon. I used to take hold of it when I went into my aunt's garden. That door handle still seems to me like a special sign of entry into a world of different moods and smells. I remember the sound of the gravel under my feet, the soft gleam of the waxed oak staircase, I can hear the heavy front door closing behind me as I walk along the dark corridor and enter the kitchen, the only really brightly lit room in the house. Looking back, it seems as if this was the only room in the house in which the ceiling did not disappear into twilight; the small hexagonal tiles of the floor, dark red and fitted so tightly together that the cracks between them were almost imperceptible, were hard and unyielding under my feet, and a smell of oil paint issued from the kitchen cupboard" (Zumthor 1998)

[4]The word "gesture" proposed by Abreu as a poetical way for designating the above described perceptive phenomenon has, of course, a large semantic range. Most immediately, the word "gesture" commonly defines a self-expressive bodily movement occurring as a part of daily life or in an artistic context, such as dancing.

We would like to make sure that the many semantic possibilities of the word "gesture" do not distract the reader from the meaning that it is supposed to have within the framework of our research. In this framework, "gesture" refers, as a rule, to the series of bodily movements (and the emotional echo that they issue) which occur as a perceptive response to architectural stimuli.

Rhythm is related to time. It derives from the intensity and frequency of stimuli presented to the dweller—for instance, it may be suggested by the size of steps, a set of pilasters in a gallery, a sequence of bays in a wall. It calibrates speed, produces pause and acceleration. For instance, in theatres and stadiums one is usually compelled to slow down when reaching the amphitheatre, after having climbed the stairs and walked the corridors at a steady speed.

As in music, *tone* and *rhythm* converge (i.e. stimuli are spatially distributed and, through the perceptive sequence, also temporally distributed) to produce a "melody". This "melody" may impress the dweller, not in a direct way—like *tone* does—but at a deeper, personal level. It carries the unique sense and significance—the meaning—of that work of architecture.

Through its "melody", a place induces its dweller to dance, to make a characteristic sequence of motions that convey emotions: to make a *gesture*.

Knowing the *gesture* of a place can be a key factor for understanding its character. It would reveal which formal aspects matter the most and guide the architect during the decision-making process.

The premises on which this theory is based are not new. Husserl presumes it when he says that place is understood by the kinaesthesia that is proper to itself: "The place is realized through kinaesthesia, in which the character (das Was) of the place is optimally experienced" (Casey 1998). This thought places bodily movement in the centre of perception, as the action through which the ontological nature of the place is apprehended.

Merleau-Ponty systematizes these themes and recognizes that perception is not linear: there is reciprocity between stimuli and behaviour. "Les mouvements, à mesure qu'ils s'exécutent, provoquent des modifications dans l'état du système afférent, qui, à leur tour, provoquent de nouveaux mouvements" (Merleau-Ponty [1942] 2006). Furthermore, he realizes that exploring behaviour seems to always seek the maximum stimuli that the environment can offer. This supports the hypothesized emergence of transsubjective exploration patterns in works of architecture—they would correspond to the optimal perception sequence for that work.

Johnson (2007) also acknowledges the "maximum rule" proposed by Merleau-Ponty. According to Johnson, the body spontaneously reacts to stimuli by making experience as fertile as possible. Motion, as an interaction with environment, is the motor of its understanding. The sensory-motor systems are the basis for one's dialogue with the world. Importantly, these systems are common to all human beings, which means that settings tend to be read in a similar way. There is a specific human way of being embodied—a "tactile-kinaesthetic" way. It shapes the perception of the world and favours the emergence of a human, transsubjective meaning out of things.

Furthermore, when Wittgenstein refers to architecture, he acknowledges that it induces a physical response—a movement—and that this movement has a meaning. He states that one is compelled to respond to architecture with a gesture: "Remember the impression made by good architecture that it expresses a thought. One would like to respond to it too with a gesture" (Wittgenstein 1980). The word "gesture", as Wittgenstein uses it here, does not denote a mindless bodily reaction: it is an active motion that knowingly rejoinders the "thought" articulated by "good architecture".

Gesture—Empirical Study

This theory, in its novelty, required an empirical inquiry. We designed an experiment to assess whether its predictions would be substantiated in a real architectural setting, i.e. if the theory would be supported or proven untrue (Abreu et al. 2015).

It was not the purpose of our research to statistically validate the hypothesis of *gesture*. Following Popper's views on the nature of the scientific "conjecture", we aimed to determine which experimental circumstances would refute our hypothesis. The falsifiability, i.e. the establishment of a set of occurrences that, if observed, invalidate a theory, is recognized by Popper as crucial for a theory to be considered scientific. In this case, the *gesture* theory would be invalidated if no clear exploration pattern were observed within the subject sample, or if that pattern could not be associated with the architectonical form and character of the building.

The main requirement for this experiment was to register the spontaneous walking trajectory and the eye movements of people wandering inside an architectural piece. These two elements would account for (at least part of) the physical response; some form of emotional and cognitive assessment would also be necessary.

Empirical researches focusing on *in loco* architecture perception are very scarce and usually performed under restrained circumstances. But the creation of progressively lighter eye-tracking devices makes it now possible to capture eye movements in free-roaming exploration. Walking trajectories, aside from the information captured by the eye tracker itself, can also be registered through high-hanging cameras.

Objective emotional appraisal is less simple to achieve. Biosignal-measuring devices, like galvanic skin response detectors, are still overly cumbersome or restrictive, better suited for laboratory studies than for real-world studies.

Our experiment was meant to be a pilot study which would allow us to (a) perfect the experimental protocol; (b) understand the interconnection between different types of data (e.g. the trajectory and the preferred stopping places); (c) understand what types of architectonic pieces could be used for this type of experiment.

More critically, of course, we intended to assess whether a common pattern would emerge in the exploration of space: if, for example, subjects would follow similar pathways, pause at specific locations, recurrently fixate the same areas. Naturally, the perceptive pattern would not be exactly identical for every subject; nonetheless, across the subject sample a statistical commonality could arise.

We implemented an experiment in which we recorded the walking trajectory as well as the visual exploration of fifty subjects freely visiting a building. The use of eye-tracking technology in unrestricted free-roaming conditions for the study of architecture perception made this a pioneer experiment.

We chose the Church of the Monastery of Alcobaça to conduct this experiment (Fig. 4). Its high-renown architectonic qualities and Cistercian simplicity appeared to be especially capable of evoking a homogenous response from different subjects. If our hypothesis were not verified there, its wrong formulation would be conclusively proven.

Our subject sample of 50 participants was mainly formed by first-year architecture students. First-year architecture students were chosen to participate in this experiment because although their sensibility in relation to architecture may be greater than that of general population, they are still relatively naïve and free from constraints acquired by education. Again, if no pattern were apparent with this sample, the hypothesis would be proven wrong.

While the participants freely explored the church, their gaze was recorded using lightweight eye-tracking glasses (Fig. 5). For looking into their emotional response, there was also an open interview phase, in which participants were asked to describe and appraise the architectonic experience of the church.

In addition to our 50-subject sample, we also tracked the trajectory of 467 anonymous visitors of the church. The trajectory of these random visitors was captured for the first 45 m of the nave using a camera affixed to the ceiling.

This first empirical inquiry in respect of the *gesture* theory yielded positive results.

One of the goals of this experiment was to observe visual exploration. Within the church, we selected "hot-spots" (semantically important architectonical features) and "cold-spots" (less important areas) (Fig. 6). If the pattern found for paintings was maintained, "hot-spots" would be visually more attractive, while "cold-spots" would rarely be fixated; this was of course one of the basis for the *gesture* hypothesis.

As regards this church, the above tendency was confirmed. The two extremities of the nave—the presbytery at the east end ("hot-spot" A) and the west interior façade ("hot-spot" B) (Fig. 4)—were the subject of an overwhelming number of fixations (Fig. 7) and longer fixation times (Fig. 8) when compared to "cold-spots". Like the scanning patterns for paintings, fixations were deployed more frequently towards semantically important areas within the context of this space.

Moreover, there was also a slight tendency for subjects to stop for longer periods next to or in front of these conspicuous regions, namely by the entrance and on the crossing (Fig. 9).

The 467 anonymous visitors whose entrance trajectory was captured by the ceiling camera revealed a very coherent behaviour. Among these visitors, an overwhelming percentage took the main nave as a path, as opposed to diverting to the side aisles (Figs. 10 and 11).

The emergence of a clear walking pattern in the larger sample provided one of the most remarkable results regarding the *gesture* hypothesis in Alcobaça (Abreu et al. 2015).

(a)

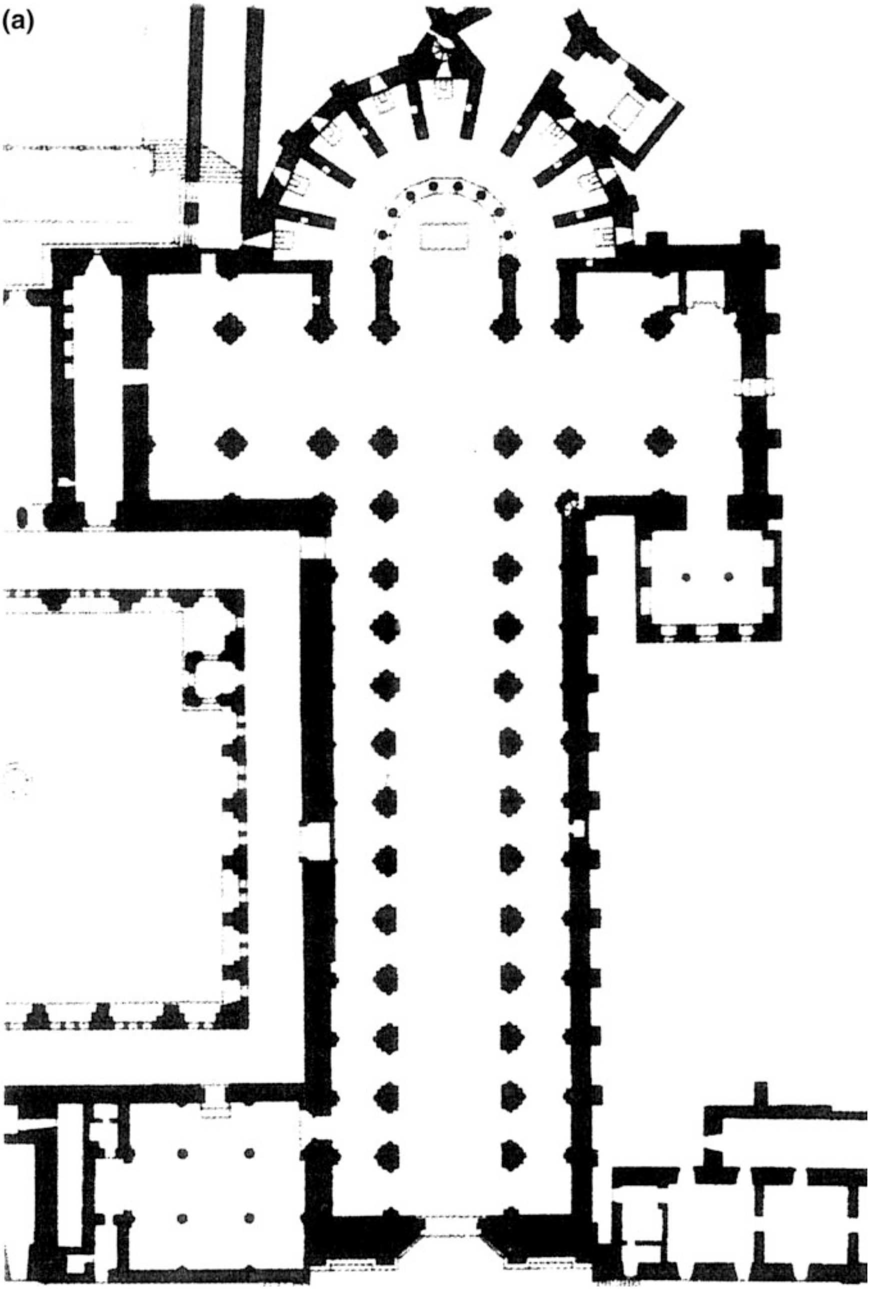

Fig. 4 Church of the Monastery of Alcobaça. **a** Plan. **b** Nave, facing east (apse). **c** Nave, facing west (rose window)

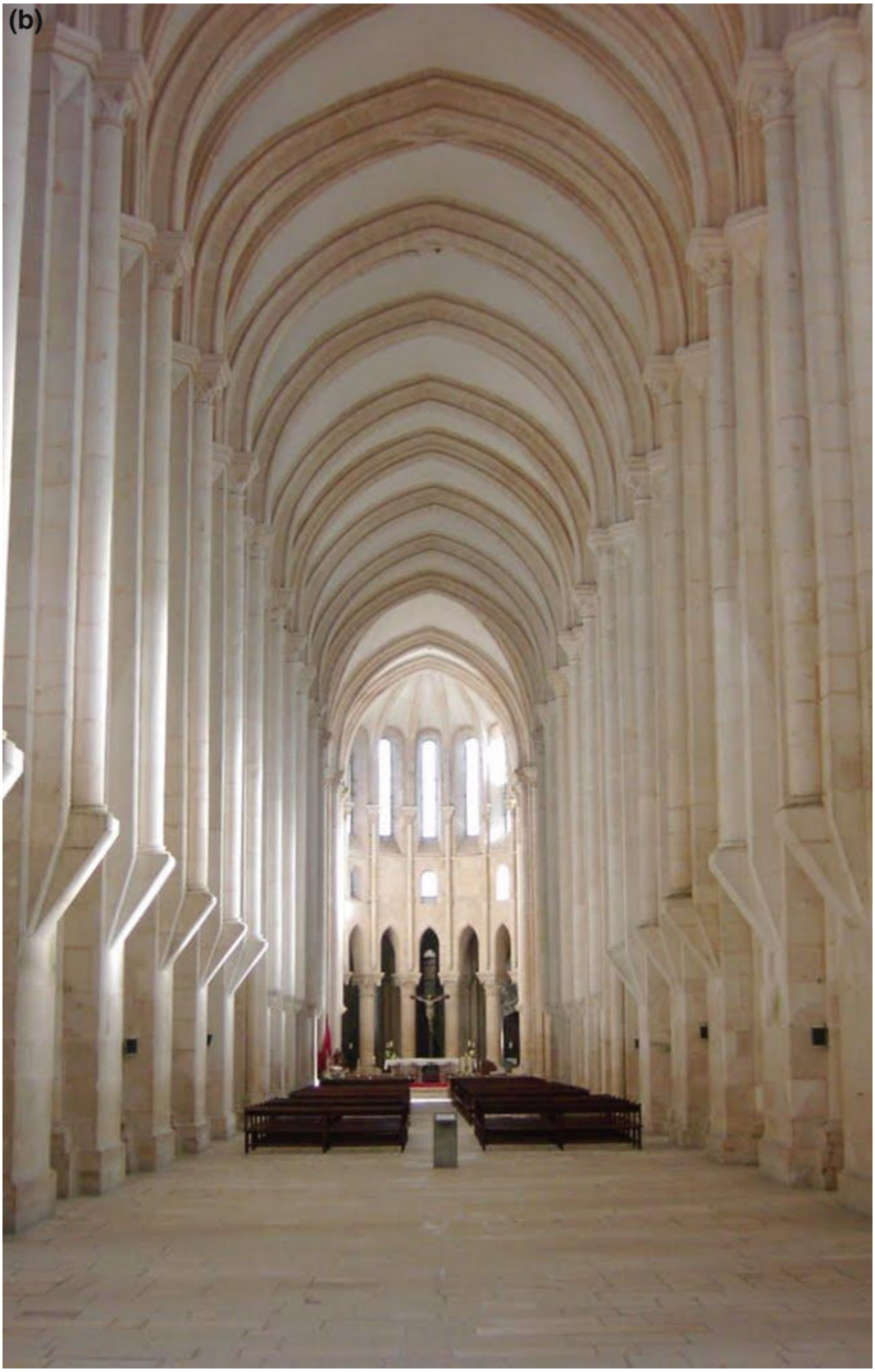

Fig. 4 (continued)

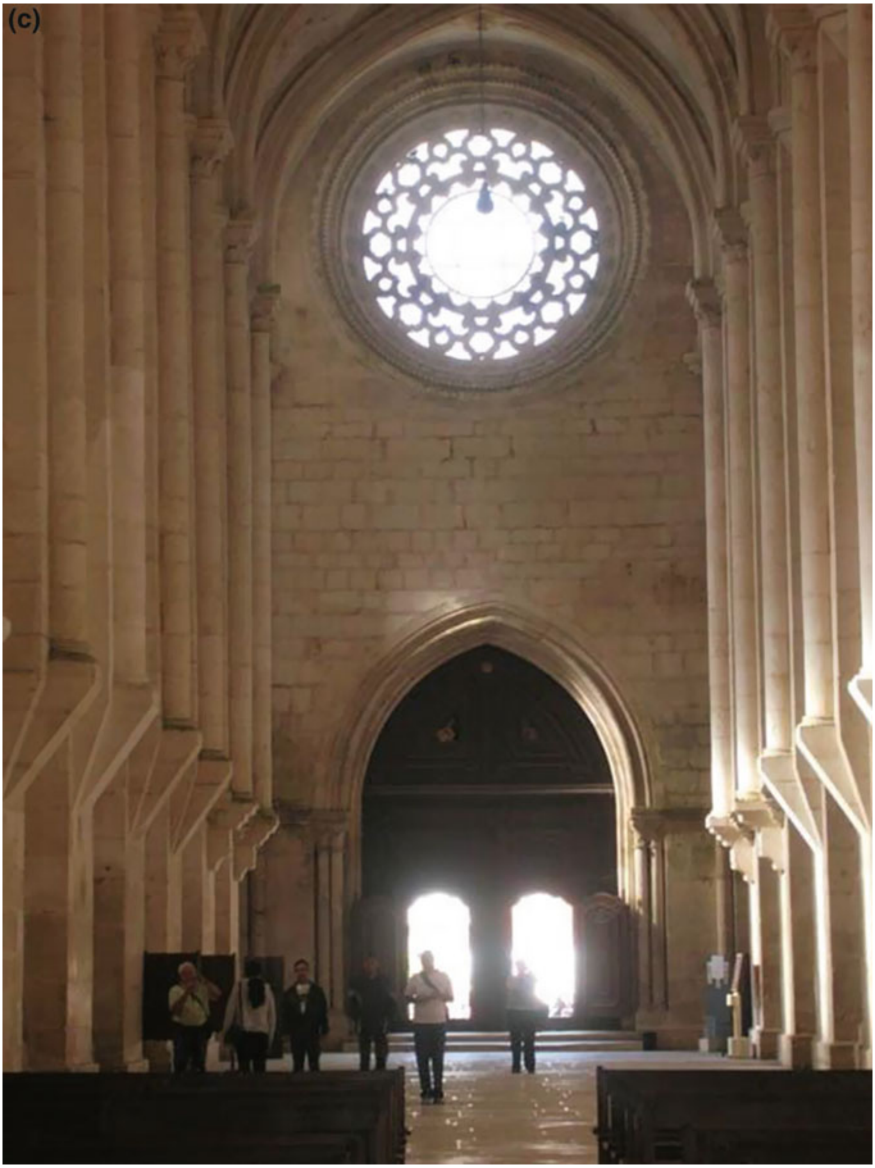

Fig. 4 (continued)

As regards the interviews, some trends related to the description of the space and the experience clearly stood out in terms of frequency. Participants often spoke of *verticality*, *directionality*, *centrality of the crossing*, *simplicity*, *scale* and *tranquillity*. The clustering of these impressions around specific concepts emerges as a shared apprehension of the church. It is quite remarkable that the ideas that the

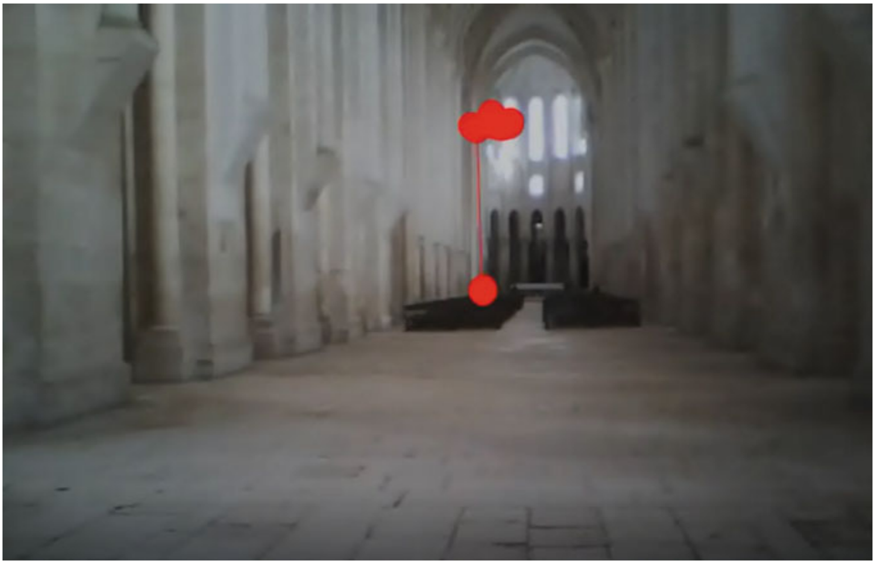

Fig. 5 Eye-tracker screenshot, with red dots indicating visual scanning

students evoked reflect the architectural precepts by which Cistercian architecture is usually described—although it is not likely that first-year students possess any knowledge of such precepts.

There was another prominent observation: although they all agreed in general about the significance conveyed by the church, personal responses varied. The verticality and large scale, for instance, felt welcoming to some—"I felt small (…) at the same time, welcomed", "I thought it was very big. I felt small (…) but small in a pleasant way, (…) I felt welcomed"—but intimidating to others—"I felt small. It was imposing", "we are very small comparing to this, comparing to the whole world". These differences show how some people may have affinity with some buildings, while others may prefer other types of architecture. However, meaning is ultimately accessible to all.

This survey showed very promising results regarding the *gesture* theory. It revealed that the qualities of this specific space are understood in a somewhat objective manner—at the very least, we can say that the qualities of this specific work of architecture are transsubjective. These results, which step into the hermeneutics realm, support the usefulness of *gesture* as a relevant interpretative tool to access meaning in architecture.

It is possible to state that our theory was not invalidated by any of the empirical results.

The preliminary observations seem to indicate that this building's form generates a specific pattern of exploration. The long, repetitive nave with sunlit extremities creates an axial walking movement where the eyes are constantly being drawn to

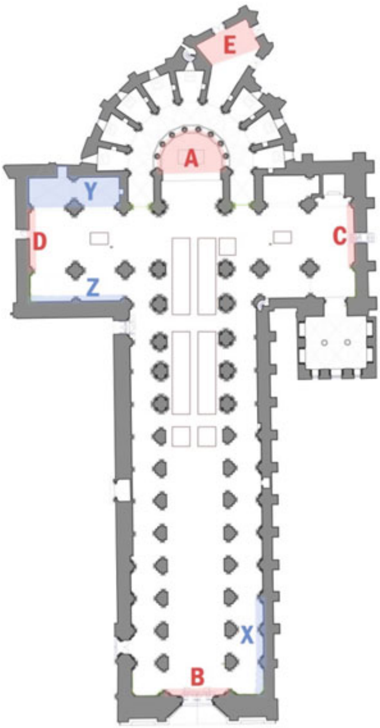

Fig. 6 Location of selected "hot-spots" and "cold-spots". The projected "hot-spots" were: the apse behind the presbytery ("hot-spot A"), the west façade, with the entrance and the rose window ("hot-spot B"), the south façade ("hot-spot C"), the north façade ("hot-spot D") and the passage to the Manueline sacristy ("hot-spot E"). The predicted "cold-spots" were: the first three bays on the south wall of the nave ("cold-spot X") and the east and west walls of the north side of the transept (respectively "cold-spot Y" and "cold-spot Z")

the light ahead. The following results converge to reveal this *gesture*: (a) fixations are concentrated in the extremities of the central nave—the apse with the presbytery at one end and the rose window and door at the other; (b) the places where participants stopped for longest time were the entrance area and the crossing at the end of the nave; (c) the larger subject sample showed that the central nave (as opposed to the lateral aisles) was the clearly preferred path ahead and that walking through this path is the visitor's first impulse.

The experience samples that we obtained in this study—visual, walking, pausing and spoken accounts—all make sense as responses to the kind of "melody" that is produced by the church's form. Its serene *tone*—as given by the height and simplicity of shape—together with the fence-like, monotonous *rhythm* of the columns and the lack of lateral stimuli, create a focus on the apse, where gaze naturally rises to the sunlit windows. Even on the way out, the rose window above the door

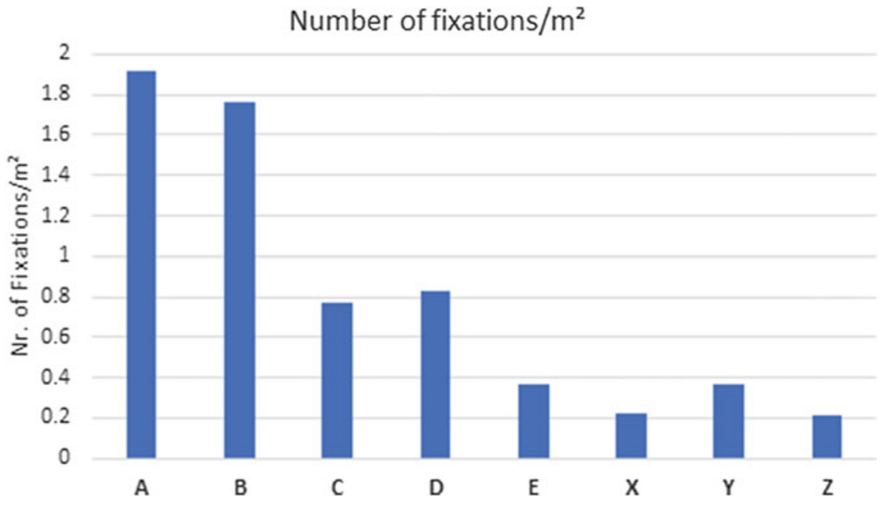

Fig. 7 Univariate analysis of the number of fixations receiver by each “hot” and “cold” spot

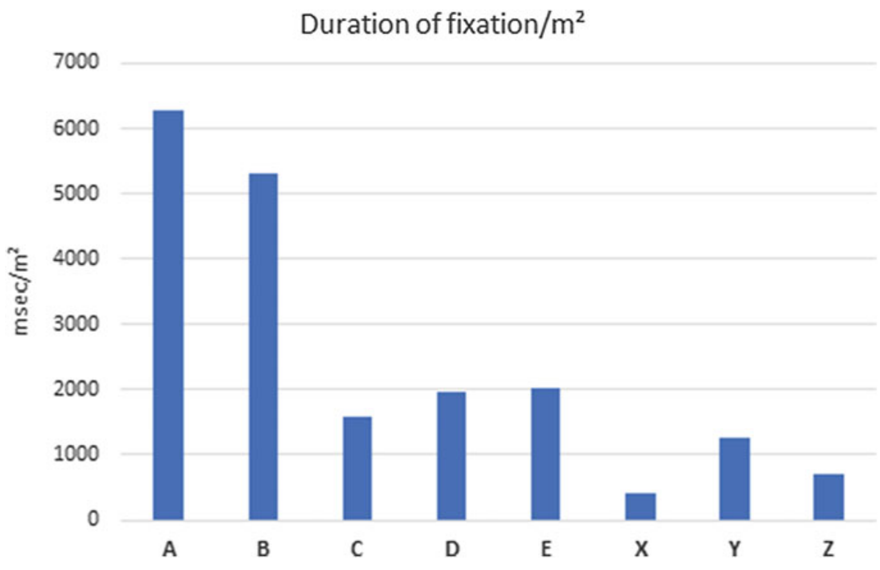

Fig. 8 Univariate analysis of the fixation duration for each of the “hot” and “cold” spots

provides a version of that same pattern. Simplicity, serenity, clarity: the architecture embodies—and communicates, through *gesture*—the Cistercian principles.

Performing this tentative perception analysis in the church of the Monastery of Alcobaça also enabled us to make a few observations as to optimizing the way in which this space should be experienced. The most eloquent example is how

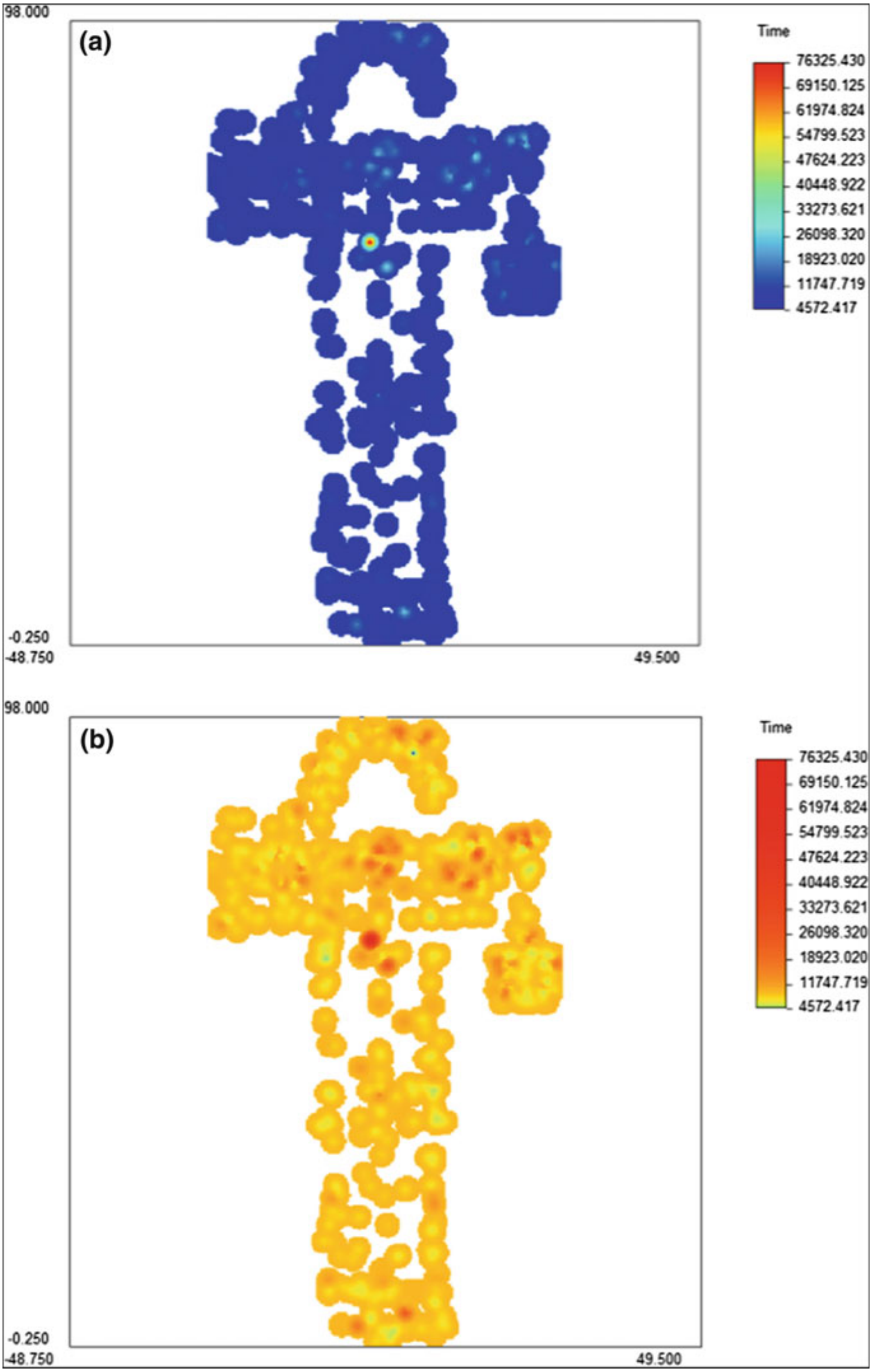

Fig. 9 Spatial estimation of pausing time. **a** Linear scale; **b** logarithmic scale

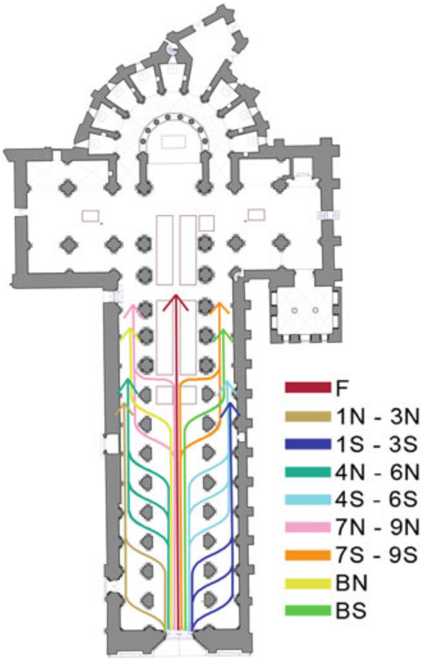

Fig. 10 Caption for all observed entry trajectories. Trajectories not illustrated: F+Sit: Sitting on a bench and then proceeding along the main nave. BS+Sit: Sitting on a bench, then going back, entering the south aisle and proceeding along that aisle. F+ES: Entering the south aisle, moving forward for a few meters and then re-entering the main nave

noticeable the misuse of artificial lighting in the nave has become. The way in which the nave is illuminated in darker days or later in the afternoon is not adequate. The light bulbs are too bright and create an unintentional lighting pattern that draws attention to the ceiling, which is rarely fixated when the lights are off. This superfluous stimulus drives focus away from the apse, which is lit with natural daylight, actively changing the way in which the whole is perceived. As a result, fewer fixations of the apse occurred when the lights were on at the nave, jeopardising the powerful sense of directionality usually conveyed by the church.

There are also two royal tombs, one on each side of the transept, which have a very heavy impact in the gesture of the church. These tombs—richly sculpted and pertaining to two eminent historical figures—were not meant to be placed there and once within sight, draw the majority of attention to themselves and away from architecture.

These examples show both how fragile a building's "melody" is and how using *gesture* as an analysis tool may help guiding interventions which will not harm it.

In order to extend the theory of *gesture*, similar experiments would have to be performed in numerous architectonic spaces with a larger and less homogenous subject sample. We also acknowledge the limits of our approach and

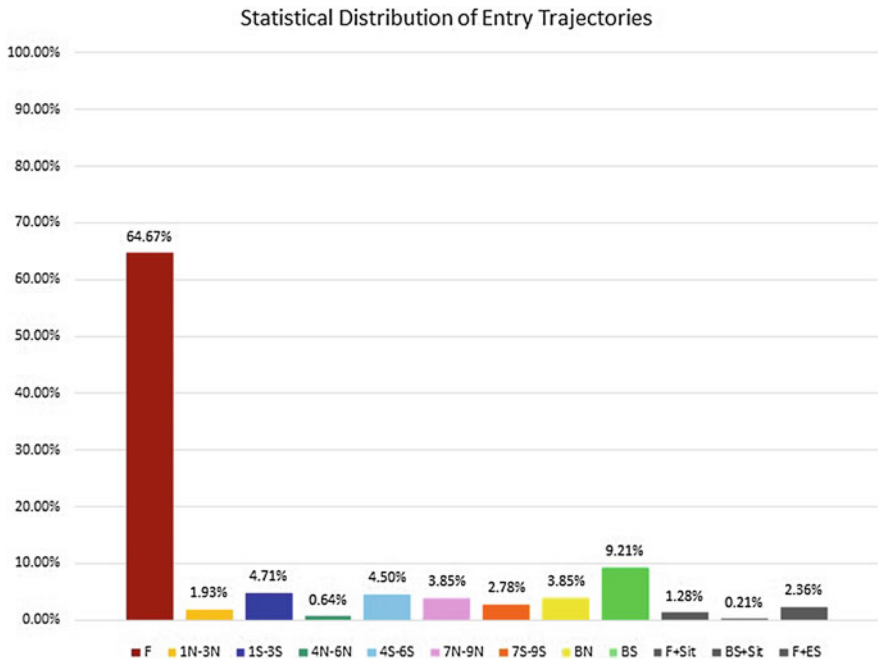

Fig. 11 Statistical distribution of all observed entry trajectories

instruments—human perception is much more complex than visual patterns and walking trajectories can convey. A thorough study of environmental perception would benefit from encompassing other perceptive systems, such as the hearing and the haptic systems, as well as the subjects' emotional response. The present difficulty lies in developing unobtrusive strategies that can accomplish this without hindering the subjects' spontaneity.

Conclusion

The *gesture* hypothesis is uniquely fit to answer the challenge of how to interpret a piece of architecture. Firstly, it derives from the piece of architecture itself: it is independent from external factors. Secondly, it is (at least partially) measurable and verifiable: we can observe trajectories and also gaze. Thirdly, it is transsubjective: perceptive sequences in three-dimensional spaces would be, as happens with pictorial stimuli, statistically similar across individuals.

It seems to us that the *gesture* of a place could work as a gateway to knowing its character. It would reveal which formal aspects contribute most to its essence and could thus guide architects, in their intervention, to improve the overall experience and bring forth the building's nature.

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Out of Perspective

Denis Cerclet

Abstract In this chapter, I focus on the depiction of visual perspective through scientific and artistic disciplines and its importance for relationships between humans and the world. Ways of thinking about vision as perspective are artificial and have been naturalised for centuries. Firstly, I examine perspective and its various uses in Western thought, and then I endeavour to establish links between method and criticism in which the object becomes a symbol of idealism. Finally, I suggest ways we can think beyond perspective.

The Naturalisation of Perspective

Perspective is "a science that demonstrates how to represent three-dimensional objects on a two-dimensional surface, in a way that the image of perspective coincides with that provided by direct vision". P. Reina's definition[1] refers to the use of the word perspective in art, but as we will see, this use is never limited to the world of art: its links to philosophy, social sciences and physical sciences are not just pure forms. Perspective quickly became a way of thinking about the world and the place of human beings within it.

Perspective can be linear, and the construction of perspective image relies on Euclidean or natural geometry and is associated with optics or more simply direct vision. When Fillipo Brunelleschi discussed natural perspective, he was part of an innovative approach opposed to linear perspective. Perspective thus designates the science of artistic representation but which emerged from science. Its public and scenographic expression became associated with its basis in practices suggesting

[1]As cited in Marisa Dalai Emiliani. Preface, In Erwin Panofsky, *La perspective comme forme symbolique*, Paris, Editions de Minuit, 1975, p. 7.

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that human vision is fundamentally perspective. However, it is apparent that this construction only applies if the beholder has the same viewpoint as that of the painter, at the same distance, under the same light conditions with one trained eye.

According to Euclid, vision resulted from direct rays emitted from the eye: all that is visible is situated on the trajectory of these rays, and everything beyond remains invisible. For Euclid, vision was geometric, even if he did not refer to perspective. Over time, the Euclidean system would take root in science and philosophy and geometry would become the single and unique model of “rational thinking” as conceived in the West.

Previously, Stoics such as Chrysippus of Soles and Claude Galien developed the idea that rays emitted from the eyes followed “a straight line, hitting and absorbing the colours of objects in their place”. Simon Gérard[2] describes this as “a sensory projection, analogous to the hand at the end of the arm, a dematerialized quasi-body (vision switches off in the darkness) whose sensitivity thrives, unlike taste and touch, beyond the limits of the body, at a distance, when it comes into contact with objects”. This description is close to haptic perception, the science of touch (Cf. Deleuze, Merleau Ponty).

Ptolemy suggested that rays projected from the eye played a role in the perception of colour, shapes, distance and movement. But for him, the complexity of vision relied upon the synthesis of the head’s position, the eyes and their movements as well as what they perceive. In short, vision was not purely related to the gaze. In art, the play of light and colours strongly contributes to the construction of volume on a flat image. It was upon this ability of the mind to compose images in perspective, already experienced by the spectator, that seventeenth and eighteenth century art would be based upon.

To reach perspective as we know it, it is necessary to address the crucial work of Abu Ali al-Hasan Ibn al-Haytham, better known in the West as Alhazen.[3] This Middle Eastern physicist, astronomer and mathematician created a new theory of optics at the beginning of the eleventh century in Bagdad. Alhazen discussed Euclid’s treaties of geometry and Ptolemy’s dioptrics. Dissatisfied with these writings, he wrote the *Kitab al-Manazir* (The *Book of Optics*) combining maths and physics to study the diffusion of light in transparent and opaque environments and

[2]Simon Gérard. Optics and perspective: Ptolemy, Alhazen, Alberti. *Revue d'histoire des sciences*, tome 54, n°3, 2001. pp. 325–350, 330–331.

[3]Hans Belting. *Florence and Bagdad: Renaissance Art and Arab Science.* Cambridge, MA: Belknap Press of Harvard University Press, 2011.

its perception by the eye. He considered visual perception as an activity specific to the subject. He theorised perception by showing how it results from the training of the gaze. This conception, not totally dissimilar to Ptolemy's, excludes everything related to haptic perception, and the entire procedure becomes confined to the interior of the body. Contact with objects is no longer decisive since the relationship is now performed by light.

For Thomas Aquinas, "just as the light of the sun is the principle of all visual perception, so the divine light is the principle of all intellectual knowledge".[4] He adds, in reference to Aristotle, "And because bodily sight is not effected without *light*, those things which serve for the perfection of intellectual vision are called light: wherefore Aristotle compares the active intellect to light, because the active intellect makes things actually intelligible, even as light somewhat makes things to be actually visible".[5] Natural light ensures the visibility and certainty of objects, while divine illumination makes it possible to reach the substance of things and beings. This process is performed in the single act of vision for humans. Through its two dimensions, light highlights the separation between form and matter, mind and body. It plays a central role in the relationship that humans maintain with their environment. Everything is thus visible in itself, without, however, being excluded from a global order. The senses perceive things in their actual existence, while intelligence grasps the essence of reality "excluding principals of individuation".

The Somme Contre les Gentils carries in its title Thomas Aquinas' desire to distinguish himself from Averroes and Maimonides, earlier commentators on Aristotle. However, beyond their disagreements, these three philosophers were heirs of Greek thought and artisans of reason and the individual. Their ideas would develop in the Christian, Jewish and Islamic worlds.

Nicolas Copernicus replaced Ptolemy's astronomy, which had been in use for the previous fourteen centuries, by formulating a model placing the sun rather than the earth at the centre of the universe. This approach displaced the idea of the world as the central sphere of activity to place it under the authority of a distant landmark. His revolution allowed Galilee to move beyond Aristotle's outdated physics and substitute them with an accurate mathematical reason to comprehend infinity and establish a new visual order.

From 1415, Filippo Brunelleschi began experiments on geometric construction of visual space in the arts by putting forward the idea of the viewpoint as the "origin" of construction. In 1435, Alberti published *Della Pittura* (*On Painting*) in which he explained his method which is based on a simplification of vision and a geometrisation of space. Together, they invented the modern concept of

[4]*The Summa Contra Gentiles,* trans. by The English Dominican Fathers from the latest Edition, Bezinger Brothers, New York, 1924, Book I, Sect. X, p. 32.

[5]Ref. 4, Book III, Sect. 53, p. 507.

perspective. Nature appears as a coherent whole when we fix a viewpoint from which physical light and mental illumination contribute to the production of a landscape.

Descartes was inspired by the idea that thought was not the product of the physical environment. It is only reflection as long as light plays a decisive role. Movement of totally separated things jostles corpuscles which then hit the senses. In this perspective, it is thanks to the absence of void and the bathing of light that all things and all beings are connected. Cogito is the key to all constructions, the point from which the world takes on meaning. But access to the coherence of the world is not given; it is the result of a research posture that Descartes finds in anamorphosis whereby construction of the organisation of the world relies upon mathematisation rather than simple vision.

With Leibniz, we enter a world that is varied but coherent, similar to an orchestra in which each musician plays his part and produces—despite this great diversity—melodious music. Although "the entire universe is represented in all its detail, though always from a different point of view, in each of its parts and even in each of its substantial unities",[6] there is a "concomitance" of Monads. For him, harmony is a divine act rather than being built jointly by actors working together. Thus, musicians do not have to be attentive to each other. It is, as if the conductor, God, ensures each Monad encloses in itself all points of view and is therefore able to perceive and understand them all. "This is why God governs the spirits as a prince governs his subjects, or even as a father takes care of his children; whereas of the other substances he disposes as an engineer manages his machines. Thus the spirits have particular laws which place them above the changes of matter […]".[7] The agreement between substances is not the result of "an influence or a real physical dependence", but a previously established concomitance, creating a viewpoint which contains all perspectives relating to a single universe. Baroque art was inspired by the general architecture of Leibniz's thought, and texts by Cardinal de Bérulle, Charles Boromée and François de Sales bear his imprint, as did the actions of the Capuchin monks.

To make sense of the world's disorder and the sensorial experience, Kant suggested seeking the conditions of objectivity in the "transcendental subject", meaning in a subject that develops an a priori knowledge of objects. Every person has a particular perception of an environment, and it is this experience, as understood by Kant, which allows everyone to relate his partial knowledge to that of all

[6]Gottfried Wilhelm Leibniz, *New Essays on Human Understanding*, Cambridge University Press, 1981, Book 1, Chapter 1, 73.

[7]Gottfried Wilhelm Leibniz, New System of Nature: And of the Communication of Substances, as well as of the Union of Soul and Body, *The Journal of Speculative Philosophy*, Vol. 5, No. 3 (July, 1871), pp. 209–219, p. 211.

other men: “parts can only be understood in respect of the environment that surrounds them”.[8] Kant sparked a revolution comparable to that achieved by Copernicus by placing the transcendental subject at the centre. Like the sun, the subject became a universal absolute, from which the thought of the world could be organised. Knowledge depended neither on objects nor on the sensitive experience, although objects must submit to knowledge and enter into perspective.

Perspective, as a mode of organisation of scattered elements, has become so natural to us that it enforces itself in the organisation of temporal successions and spatial organisations. Perspective relies upon itself, as a starting point of a spatial and temporal succession of events, objects and people within a meaningful totality.

From Limits to Perspective

Over the centuries, natural vision has adapted to artificial vision. In Marcel Duchamp’s words, the beholder, reduced to a pupil, is no longer able to see other than according to the laws of perspective, because in a way the organisation of artworks, and to a greater extent everyday life, is dependent upon the beholder. The world is, thus, put into perspective.

The very expression “out of perspective” succinctly describes the state of disorder the beholder is confronted with when deviating from this mode of construction of the gaze.

Critics have nevertheless emerged. For Nietzsche, the world is a relation of power “a monster of energy, without beginning, without end; […] as a play of forces and waves of forces, at the same time one and many, increasing here and at the same time decreasing there; a sea of forces flowing and rushing together, eternally changing, eternally flooding back”.[9] He does not separate subject from object, actor from act, the act from what it produces. He develops an ecological approach of the individual–environment relationship and, in this sense, criticises Darwin who remains too committed to Descartes’ conception of beings and things as atoms separated from each other. This relationship is also a trajectory, an incessant movement that contributes to modify reality as much as the self. Hence, perspective changes as it is no more a question of a point of view fixed on the environment. However, Nietzsche retains the idea of a viewpoint related to a sensorial device, culture, history, language, class and gender. Therefore, human

[8]Lucien Goldmann, *Introduction à la philosophie de Kant*. Paris, Editions Gallimard, 1967, p. 76.

[9]Fredrich Nietzsche, *The Will to Power* (Notes written 1883–1888), book 4, no. 1067. Trans. W. Kaufmann and R. J. Hollingdale, Vintage Books Edition, 1968, p. 550.

beings, bees and birds have different points of view. Furthermore, science, art and interpretations are for Nietzsche multiple perspectives, varying modes of construction of the relationship to reality.[10]

Alfred North Whitehead greatly influenced the twentieth century. Mathematician and philosopher, he worked to unify knowledge, by aligning the same theoretical problems discussed in physics, maths and philosophy without losing sight of the theological dimension. His work was based upon the categorical rejection of the "bifurcation" between the real and the apparent, substance and attributes and between men and the world. For him, everything was connected within a general process, an organisation of events, a real body from which emerges the subject. The world continually fluctuates while relying on permanency produced by repetition and recognition. Whitehead developed a real cosmology. He abandoned the subject in order to promote a topology. The world no longer consisted of forms, concepts and principals: only forces at play form a field of attractiveness. The connectivity of things and beings in a continuum is at the heart of processuality. Whitehead's treatment of perspective related to his idea that the world is too diffuse and creative to comply with a single point of view: perspectives are multiple because they come from all organisms redefining themselves constantly.

James Gibson's work has been highly influential for many authors. He developed an ecological approach linking the individual to his environment by rejecting the idea of artificial perspective. "The old idea that each observer stands at the centre of his or her private world and that each environment is therefore unique gets its main support from a narrow conception of optics and a mistaken theory of visual perception".[11] For Gibson, the point of observation is in motion and emphasises an ambulatory vision. Observation is not free; it is similar to what Dewey refers to by the term investigation or to what Bitbol calls research. Observers direct themselves, find their way and become acquainted with their surroundings. Affordance is the principal idea articulated in Gibson's work. As he states, "it implies the complementarity of the animal and the environment".[12] Affordances are real because they are characteristics of the physical world and are not restricted to particular phenomenal worlds.

[10]See Clifford Geertz and his use of the point of view and perspective in Local Knowledge: Further Essays in Interpretive Anthropology. New York: Basic Books, 1983.

[11]James Gibson, *The Ecological Approach to Visual Perception.* Taylor and Francis Group, 1986, 43.

[12]Ref. 10, p. 127.

Perspective Today or How to Liberate from It

Ann Veronica Janssens. Mukha, 1997 © AV Janssens. Collection Frac Lorraine

Perspective has become the symbol of a separation between the observer and the world, of static posture and transcendent order. Cézanne very much personalised the liberty taken in perspective, marking the beginning of modern art which reached new forms with Picasso's toying with the relativity of viewpoints. For Cézanne, this concerned painting the primordial world unconstrained by geometrical space, which as Louis Marin reported,[13] "consecrates 'the death' of existential space". We could say that for Whitehead "the human intellect 'spatializes the universe'; that is to say, that it tends to ignore fluency, and analyses the world in terms of static categories".[14] It is then necessary to reconnect with the world and promote activity, which alone makes it possible to account for wholes within a dynamic mode. Which prompted Merleau Ponty to remark that Cézanne's "painting was paradoxical: he was pursuing reality without giving up the sensuous surface, with no other guide than the immediate impression of nature, without following the contours, with no outline to enclose the colour, with no perspectival or pictorial arrangement".[15]

Michel Bitbol worked on the development of a new philosophy that would not break with transcendence, but paired with quantum mechanics. As he specified, "There is no longer a question of counting on a patrimonial ontology (inherited from everyday life and classical physics) to illuminate the new cognitive relationships involved in microscopic physics. It is no longer a question that these cognitive relationships *arise* from pre-existing properties. Rather, it is a question of starting from the product of these relationships, treated as primary, or as *non-arising*, to explore opportunities for a constitution of a renewed objectivity".[16] Bitbol uses Heisenberg's matrix mechanics, with the support of Alain Connes and Jean Petitot, to affirm that "objectified phenomena, meaning invariants of available cognitive relationships, are no longer isomorphic to localised material bodies, but to intensities and frequencies of the spectrum of extended radiation".[17] This is similar to Colwyn Trevarthen's studies of relationship between infants and their mother's in carrying out coordinated actions towards shared goals. He argues, "The fact that we all express essentially the same parameters of musicality, which are evidently innate in all of us, causes us to feel in others the same forces of will and curiosity that impel ourselves to act. We sympathetically receive from other persons the same

[13] Louis Marin, *De la représentation*. Editions Hautes Etudes, Gallimard, Le Seuil, 1994, 11.

[14] Alfred North Whitehead, *Process and Reality*, Edited by David Ray Griffin and Donald W. Sherburne, New York, London, The Free Press, 1978, 209.

[15] Maurice Merleau Ponty, Cezanne's Doubt, *Sense and Non-Sense*, Evanston, Northwester University Press, 1964, 12.

[16] Michel Bitbol, *La mécanique quantique comme théorie essentiellement relationnelle*, Revue du M.A.U.S.S., 2016/1, 47, 65–86, p. 77.

[17] As cited in Michel Bitbol, *La mécanique quantique comme théorie essentiellement relationnelle.* Revue du M.A.U.S.S., 2016/1, 47, p. 76.

internally generated beat and 'intonation' of muscular actions that link our own limbs in co-ordinated purposes, because we instinctively have to".[18]

A survey of a few contemporary artists will enable us to state the issue of perspective.

Sophie Lavaud-Forest has demonstrated how artists, since Cubism, have taken more liberties with the laws of perspective. As an artist, she is interested in immersive digital worlds and declares "the body is immersed and the displacement from the spectator's view point efficiently liberates itself from its immobility, to penetrate, wander and circulate in the infinity of these worlds, through manipulating a multidirectional virtual camera, embedded, or not, as an interface. Emancipated from a fixed point of view and organized once and for all by the painter, the interactor becomes master of his perception, guides his gaze and can thereby establish a direct scopic relation of his body with his vision".[19]

Ann Veronica Janssens, who exhibits across the world, is attentive to the surprises that can arise from everyday experiences. Movement and play with various products and manners cause light effects that undermine acquired routines forcing spectators into positions of physical, cognitive and psychological instability. This vision collapses perspective or multiplies it infinitely by projecting the viewer into the work. However, the work does not pre-exist this encounter. It is a kind of a hyper-reality in reflection. The separation between the viewer's self and his environment fades away. In colourful nebulas, such as the Saint Vincent chapel at Grignan, the viewer is suspended as if he had escaped from reality to reach a new equilibrium. Undoubtedly, this is what one feels during the first moments of a state of weightlessness. Ann Veronica explains that her work entitled Donut (2003) "acts as a centre of diffraction, from whence, after several minutes of exposure, the visitor might mentally move in a virtual space wherein he or she envisions a system of luminous coloured waves, their movement akin to the ricochet effect of concentric waves on the surface of water. This is an experience of spatial and chromatic intensity".[20] During an interview, she evoked a world in reflections and her desire for reflections that question all achievements and broaden perceptions and conceptions. She added "It is possible when you release time for your body, your brain. One must be able to let go, abandon oneself as in strolling. To permeate reality, as well as, be permeated by it. Some of my work can cause states of altered consciousness. The mind drifts and starts to operate differently. It leaves perspective. The 'I' is too formatted, it has limits. This formatting can be experienced as suffering".

[18]Colwin Trevarthen, Musicality and the intrinsic motive pulse: evidence from human psychobiology and infant communication. In Rhythms, Musical Narrative, and the Origins of Human Communication. *Musicae Scientiae,* Special Issue, 1999–2000, 157–213, p. 158.

[19]Sophie Lavaud-Forest, Perspectives numériques. Variabilités, interactions, univers distribués. À la découverte de perspectives renouvelées?, *Communications* 2009/2, n° 85, 55–64, p. 61.

[20]Ann Veronica Janssens, http://www.gms.be/index.php?content=artist_detail&id_artist=29.

Ann Veronica Janssens, Donut, 2005 © Florian Holzerr, courtesy CCA The Wattis Institute, S.F., USA. Programmation lumineuse, durée approximative 10 min en boucle, dimensions variables

It is important to change scale, to let reality flourish and expand until it welcomes you and makes you discover your ability to bring about, in close involvement with it, other states of consciousness, and, certainly, of matter. Because presumably, her works do not impose a point of view they bring forth movement, lead to experimentation and allow the establishment of an ecological relationship with objects.

Frédéric Khodja draws and makes collages.[21] His works recall volume and plans in motion, using perspective to fix them "for reassurance". Then once they are held together, he plays with them. As he himself says, taking the title of Jurgis Baltrušaitis' book,[22] he depraves and distorts perspective. In *La villa Hapax*, he makes assemblages from architectural designs of early twentieth century villas and disrupts the classic ordering of such constructions. The eye is unprepared because it has nothing on which to rest or fix upon to rapidly read the image. There is no affordance to even recognise a reading order. Depiction becomes necessary to compose an image, not as an external object but as the product of an encounter. This is how he went about setting up his temporary exhibition *Je vous ai déjà vu, dessins sensationnels, exposition éclair* (*I have already seen you, sensational designs*).[23] Four hundred and thirty drawings on postcards of 10 × 15 cm format

[21]See http://www.francoisebesson.com/index.php/artistes/frederic-khodja/.

[22]Jurgis Baltrušaitis, Les perspectives dépravées. *Tome 1: Aberrations, essai sur la légende des formes*; *Tome 2: Anamorphoses,* coll. Champs, Flammarion, Paris, 2008.

[23]Frédéric Khodja, Exposition personnelle, Galerie Hus, Section Pigalle, Paris 2015 et revue *Hippocampe*, n°12, Météorologie, juillet 2015.

were fixed on the wall of the gallery without any logic other than that of the gestures that placed them. Frédéric Khodja started the job and his daughter Adèle who came to help him continued. “She sets up a series and creates a communication between us, which is a language. I hang, she hangs an image, I hang an image, and so on. There is a back and forth movement in the space of our bodies hanging images, trying different positions and so on”. For Khodja, the installation itself disrupted the order of the drawings: “We started by communicating through the body, to deteriorate and to deprave the whole to hang the images as such, as part of a corpus”. With his daughter, a trained contemporary dancer, they physically and corporeally composed “a gestural story”, on the walls, which adds to and disturbs the order of the series. Some viewers have felt uneasy about this dispersal of forms and colours and have sought to recompose an order by designating precisely the cards that constituted a series from their remoteness.

Frédéric Khodja. Performance aux écrans bleus, Marveggia, Italie, été 2015

Adrien Mondot and Claire Bardainne[24] hold on to perspective because it allows them to hold together the reality of a scene, the gestures of human beings, dancers, jugglers and musicians and digital images in motion. Thus, the jugglers fling letters of light, dancers have luminous nets for partners that can be manipulated, or a ground that is formed and distorted through algorithms. Everyone works live so that music, gestures and movements coincide creating a spectacle where the real and the virtual work together and intermingle. We could easily talk about the “magico-realism” of these shows if Alejo Carpentier had not theorised this expression to designate the conjunction between realism and magic in the literature.

[24]See http://www.am-cb.net.

The encounter between these two universes can only be achieved from a viewpoint where the "naturalised" rules of perspective are put to work by the minds of spectators. Adrien Mondot, Claire Bardainne and the members of their company use information, of a very diverse but concordant nature to accompany spectators in the production of an augmented reality. Letters fall and bounce on the glass of a bottle, but the letters and bottle only share the same physical world within the spectator's mental space: "for a scene like this to work, we created a false perspective taking into account the ideal viewpoint of the spectator, about 20° on each side. The brain accepts this because we send a lot of other information that converge towards the idea of volume". They set the spectator in front of a "known" situation and can thus shift it to the unknown. The digital fabric is given a weight suggested by the dancer's movements, and the coder who can remove gravity from the textile to raise it in the air and let it fall back, as a simple canvas would do. They embrace perspective the same way that Kant did when he wanted to match the sensations caused by the matter and the categories of thought of the transcendental subject, but they are not duped. Perspective is the ideal instrument for encountering dispersed and profoundly different worlds.

These approaches can be described as ecological because they play with synchronicity and the participation of man within his environment, associating perception with action. And even if there is an exteriority of principle between the real and virtual for Mondot and Bardainne that do not participate in the same physical world, the device they put in place reduces the gap between virtual and real until the spectator brings them together and becomes one with them.

Conclusion

Perspective works well when it involves connecting objects and beings separated in space (Einstein) or in time (Bergson) and distinct worlds: thought and matter, the real and the virtual or the imaginary, things and meanings. However, it becomes superfluous when these beings and objects have no longer their own existence or intrinsic properties (Rovelli). The consequences of such relational realism are: "(a) it is not possible to give a definition of the individual object in a spatio-temporal location; (b) it is not possible to characterize the properties of the objects, in order to distinguish them from each other. This is to say, if we adopt interaction as the underlying level of physical reality, we accept a philosophy of relations".[25] Carlo Rovelli "assume[s] that the world can be decomposed (possibly in a variety of ways) in a collection of systems, each of which can be equivalently considered as an observing system or as an observed system. A system (observing system) may

[25]Michele Caponigro, Ravi Prakash, Interpretations of quantum mechanics and emptiness, *NeuroQuantology*, June 2009, Vol 7, Issue 2, 198–203.

have information about another system (observed system). Information is exchanged via physical interactions”.[26]

Perspective can only be apprehended by the existence of a distant observer, comprised as a located subject, in a pre-existing world, and of their necessary encounter. This difference disappears according to Rovelli: “If different observers give different descriptions of the state of the same system, this means that the notion of state is observer dependent. I have taken this deduction seriously, and have considered a conceptual scheme in which the notion of absolute observer-independent state of a system is replaced by the notion of information about a system that a physical system may possess”.[27] Reality does not exist in itself, regardless of an observer who himself does not exist without his environment. The knowledge we have is related to the network of relationships and to mutual information that constitute the world.

At the same time, in neuroscience, the subject began its swan song under the impetus of Francisco Varela and those influenced by Merleau Ponty, Gibson and pragmatists like Mead and Dewey.

According to Charalambos Tsekeris,[28] individuals are not separated, they are open “beings-in-the-world, deeply immersed in the inescapable conflicted complexity of a networked social reality. The meaningful lived perception and experience (in the here and now) of ourselves and others “emerge of, and through and irreducible grounding of relatedness… no self can be ‘found’, nor individual ‘emerge’ other than via the a priori interrelational grounding from which our unique sense of being arises”.[29]

Perspective has emerged as an efficient architecture of thought and action in various fields such as the arts, sciences and everyday life. It is everywhere and still contributes to support a bifurcation between different styles, between realism and the various attempts at actualisation of transcendental idealism and, more precisely, between ontological or relational approaches of realism. However, it becomes difficult to think that nature is a creation of the mind or that man has no influence on the matter. These two worlds are now entangled and lead us towards the exploration of transdisciplinarity.

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[26]Carlo Rovelli, Relational Quantum Mechanics, *International Journal of Theoretical Physics*, 35, 1637–1657, 1996, p. 10. arXiv:quant-ph/9609002v2.

[27]Ref. 23, p. 15.

[28]Charalambos Tsekeris, Reconsidering the Self in Social Thought: Existential-Phenomenological and Dialogical Perspectives. *Epiphany*, 2015, 8(1), 101–111, p. 106.

[29]Ernesto Spinelli, Practising Existential Psychotherapy: e relational World. London: Sage, 2007, pp. 12–14.

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A Comparison of Change Blindness and the Visual Perception of Museum Artefacts in Real-World and On-Screen Scenarios

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Abstract Change blindness is a phenomenon of visual perception that occurs when a stimulus undergoes a change without this being noticed by its observer. Since it was first described in the 1990s, change blindness has provided a unique means to investigate the role of attention in visual processing. To date, the effect has been produced by changing images displayed on screen as well as changing people and objects in an individual's environment. In this study, we combine these two approaches to directly compare the levels of change blindness produced in real-world and on-screen scenarios. We use a single series of museum artefacts and two groups of participants to simultaneously produce saccade-contingent change blindness in a real-world scenario, and camera pan-contingent change blindness in an on-screen scenario. We present the results in two parts. First, we find no significant difference between the mean levels of change blindness produced in on-screen and real-world scenarios by the same visual stimuli. Second, we identify a group of artefacts that were associated with a high level of change blindness in both scenarios and a group that were associated with a low level of change blindness in both scenarios. We suggest that the difference in change blindness levels results from bottom-up influences including the visible area and contrast of changes. We discuss the relation of these findings to our understanding of change detection as a part of visual processing, as well as the insights they offer to our understanding of the experience of viewing objects within a museum setting.

Keywords Change blindness · Perception · Visual system · Artefact Museum · Screen

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Introduction

Change blindness is defined as the failure to detect when a change is made to a visual stimulus, because the local visual signal produced by the change is obscured by a more general visual signal (Simons and Levin 1997). Obscuring the local signal means either masking it with a global signal, such as an eye blink (O'Regan et al. 2000), saccadic eye movement (Grimes 1996; McConkie and Currie 1996), screen flicker (Rensink et al. 1997), or a cut or pan in a motion picture (Levin and Simons 1997; Simons 1996), or by accompanying the change with multiple local signals at other locations, known as mud splashes, which act as distractions, causing the change to be disregarded (O'Regan et al. 1999). Change blindness is distinct from inattentional blindness, which occurs when an individual is blind to the presence of a whole object while performing a distracting task (such as the well-known 'gorilla in the room' (Simons and Chabris 1999)). In contrast, change blindness occurs when an individual is blind to changes occurring to an object to which they are paying attention. Because of this, when missed changes are later pointed out to the observer, there is often a sense of disbelief at how the changes could have gone unnoticed. This disbelief is the result of a disconnect between the assumption that our visual perceptions are so detailed as to be virtually complete and the actual ability of the visual system to represent and compare scenes moment to moment. In this way, change blindness can be used to investigate the nature of our visual representations, which form the basis of the conscious perception of change (Simons and Rensink 2005).

Further experiments in change blindness have shown that details considered to be important are detected more readily than those that are less important (O'Regan et al. 2000; Rensink et al. 1997), even when the changes are of equivalent physical salience (Kelley et al. 2003). Additionally, change blindness can be overcome if a cue to the visual system is delivered shortly in advance of the change taking place (Scholl 2000). This suggests that attention plays an important role in prioritizing the elements of a visual scene, and determining what is represented and compared and what is not (Simons and Rensink 2005). However, even changes to attended objects can still be missed (Ballard et al. 1995; Simons 1996), leading to the conclusion that attention is necessary, but not sufficient, for change detection to occur. These findings form part of an ongoing debate as to the relative importance of bottom-up (stimulus-driven) factors, such as visual salience, and top-down (goal-driven) factors within human visual processing (Borji and Itti 2013).

In most of the studies published to date, change blindness has been produced using altered photographs or videos of natural scenes displayed on computer screens. More recently, change blindness has also been shown to take place in more naturalistic scenarios. For example, in one real-world experiment more than half of participants failed to notice the changing of a conversation partner in front of them (Levin et al. 2002; Simons and Levin 1998), and in another, more than half of participants were blind to the changing of an object's colour or a printed word's font (Varakin et al. 2007). In our study, we have combined these two approaches to directly compare the levels of change blindness produced in on-screen and real-world scenarios. To achieve this, we use a single series of museum artefacts and two groups of participants to simultaneously produce saccade-contingent change blindness in a real-world scenario, and camera pan-contingent change blindness in an on-screen scenario.

To the best of our knowledge, this experiment is the first direct comparison of change blindness levels produced in on-screen and real-world scenarios. We sought to make this comparison in recognition of the increasing frequency and importance of on-screen visual interactions alongside real-world interactions in modern working and social life. The growing accessibility of high-speed Internet and the capability of smart portable devices have already significantly changed the way that many people receive their visual information. Indeed, a recent report found that adults in the US spend an average of more than 8 h a day accessing media through a device with a screen (*The Nielsen Total Audience Report - Q1 2016*, 2016). For many people, this amount of time will account for the majority of their waking day. Such a rapid and significant change not only poses a series of important questions regarding the nature and quality of our daily visual interactions, but also offers a new means by which to investigate the processes underlying visual perception.

The phenomenon of inattentional blindness has been previously investigated in a museum setting (Levy 2011), but as far as we are aware this also is the first example of change blindness being studied in a museum environment. By conducting this experiment within a museum and using artefacts from its collection, we aim to add to the body of evidence describing change blindness in rich, naturalistic settings outside of the laboratory.

Materials and Methods

We have recruited 62 participants by an advertisement describing a neuropsychological experiment taking place at the Ashmolean museum, Oxford. The group of participants consisted of students and employees of the University of Oxford, covering a wide range of disciplines from Art History and Fine Art to Law and Medicine. While none of the participants were artists, they might all be considered to hold some form of interest in art, or the history of art, given that they responded to such an advertisement. The participants were randomly allocated to take part in either real-world or on-screen scenarios. Thirty-one participants were allocated to each group. The mean age of participants in the real-world group was 22.8 years (SD ± 5.3 years) and 58.1% were female. The mean age of participants in the on-screen group was also 22.8 years (SD ± 5.9 years) and 58.1% were female. This study was carried out in accordance with the recommendations of the Central University Research Ethics Committee (CUREC) with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

The study was conducted in the Ashmolean Museum of Art and Archaeology, University of Oxford. Twelve pairs of artefacts from the museum's collection were used. These included three pairs of Japanese woodblock prints, one pair of Chinese porcelain bowls, two pairs of Iranian tiles, one pair of Athenian lekythoi, one pair of Renaissance bronze medals, two pairs of Anglo-Saxon brooches, and two pairs of English silverware. These artefacts were chosen because although they had all originally been designed to appear identical, through their individual manufacture and subsequent usage they had come to exhibit a range of differences.

Twelve pairs of artefacts were displayed in front of the participants in turn. For each pair of artefacts, participants observed one item for a short period of time before looking to the second item and observing it for the same length of time as the first. As participants looked from one item to the next, the differences between their appearances generated local visual signals, such as differences in colour, shape, or design. However, the transition of looking from one item to the other generated a global visual signal which would to a certain extent obscure the local signals and produce a corresponding degree of change blindness. This degree was measured by participants responding to the question 'did you notice any differences between the two objects?', and describing any differences they did notice on a form after viewing each pair of artefacts. Subsequently, the participants' descriptions were marked as either correct or incorrect according to the actual differences existing between the objects. If a change was missed or identified incorrectly, the participant was recorded as being *change blind*. If changes were correctly identified, the participant was recorded as not being *change blind*.

The degree of change blindness recorded was therefore a reflection of the balance of local and global visual signals being produced by observing these pairs of museum artefacts in real-world and on-screen change perception scenarios.

The length of time for which participants observed each artefact was set at a duration that would produce a change blindness effect appropriate to allow for a comparison to be made between the two scenarios. The requisite duration was determined through a series of trials in which photographs of the pairs of artefacts were observed in series on a monitor for different lengths of time. An observation time of 5 s per artefact with an interval of 2 s resulted in change blindness in 15% of the pairs. When the observation time was reduced to 2 s with an interval of 0.5 s, change blindness rose slightly to 20%; when the observation time was reduced further to 0.25 s with an interval of 0.25 s, change blindness increased to 57%. Given that the motion of turning to look from one artefact to another would produce an interval between fixations of less than 100 ms (Grossman et al. 1988), an observation time of 1 s was chosen in order to achieve approximately 50% mean change blindness in the on-screen scenario. This was thought to be optimal in allowing for a comparison to be made between this and the real-world scenario.

The viewing conditions in both scenarios were controlled in order to standardize the nature and duration of the periods of observation, and the nature and duration of the transition from one artefact to another. The artefacts were placed in their pairs on a table in a room within the museum (Fig. 1a). The artefacts remained covered for the majority of the experiment, and members of museum staff were present to ensure their safekeeping throughout. The items in each pair were placed 40 cm apart, and a chair was placed in front of each pair of artefacts to provide a viewing distance of 75 cm. A high-definition 32-inch LCD screen was also present in the corner of the room with a chair placed in front of it. The real-world viewing scenario consisted of participants sitting in front of and viewing the artefacts on the table before them (Fig. 1b), while the on-screen scenario consisted of participants sitting in front of the screen and viewing the artefacts on its display (Fig. 1c).

The participants' visual fields were restricted by wearing a pair of goggles that were modified for the purposes of this study. Opaque inserts were fitted to the inside

Fig. 1 **a** Experimental set-up within the museum, showing the artefacts (covered), two participants, and an experimenter. **b** The real-world scenario: the participant is sat in front of a pair of artefacts, wearing a pair of modified goggles and head-mounted camera. **c** The on-screen scenario: the participant is sat in front of a monitor, wearing a pair of modified goggles and watching a live feed from the head-mounted camera. Images reproduced with permission from Ashmolean Museum, University of Oxford

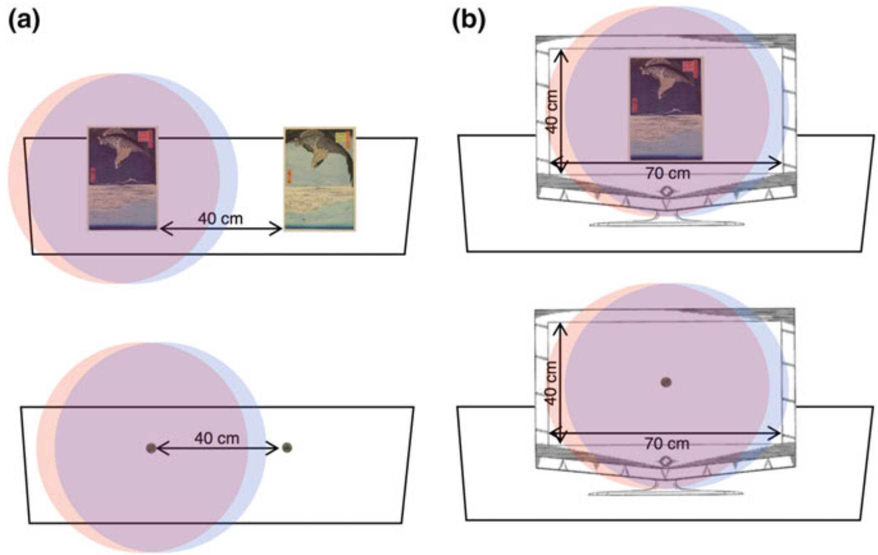

Fig. 2 **a** Real-world participants' views of the largest (top) and smallest (bottom) artefacts through the modified goggles. The whole surface of the largest artefact was visible, but both items of the smallest pair of artefacts were not visible at the same time (to scale). **b** The on-screen participants' views of the largest (top) and smallest (bottom) artefacts through the modified goggles on the screen (to scale). Images reproduced with permission from Ashmolean Museum, University of Oxford

of the goggles to leave a window of 3 cm diameter in front of each eye. This restricted the binocular visual field to an oval of width 63 cm and height 67 cm at a viewing distance of 75 cm. These dimensions were sufficient to contain the whole surface of the largest artefact within the field of view when it was centred on the artefact, while not allowing both items to enter the same field of view when it was centred on one of the smallest pair of artefacts, in both the real-world (Fig. 2a) and on-screen scenarios (Fig. 2b). This step was taken to ensure that participants would not be able to make multiple eye saccades between the items in front of them, which would have added an uncontrolled variable.

Once sat in front of the first pair of artefacts, the participants who been randomly allocated to the real-world scenario began with their head turned towards the item on their left, so that their visual field would be centred on the first artefact. The artefact was initially obscured by a small screen. On an auditory cue, the screen was manually removed by an experimenter so that participants could view the first artefact. This period of observation lasted for 1 s, after which another cue sound signalled for the participant to turn their head and eyes to look at the second item to their right, so that their visual field would now be centred on the second artefact. This period of observation lasted for 1 s also, after which a small screen was manually placed between the participant and the second item by an experimenter so that it could no longer be seen. In this way, both artefacts were viewed for a duration of 1 s, and a visual transition took place between viewings.

The visual transition which occurred in the real-world scenario consisted of a combination of a head rotation and a saccadic eye movement. This combination has been defined elsewhere as a gaze shift (Binder et al. 2009), where gaze is defined as the sum of eye position with respect to the head and head position with respect to the body. When the visual field shifts more than 15–20°, an eye saccade is normally accompanied by a head rotation in order to return the eyes to a neutral position within the orbits and allow the extra-ocular muscles to relax. In this case, the shift was 28.1° ($\tan^{-1}(40/75)$), and participants in the real-world scenario were specifically instructed to turn their head and eyes in order to view the second artefact in each pair.

The coordination of gaze shifts is complex, but the basic elements are well understood (Pelisson and Guillaume 2009). As the head initially rotates and the eyes stay fixed on the first target, eye movement is under the control of the vestibulo-ocular reflex (VOR). Once head rotation has brought the new target into the visual field, an endogenous eye saccade occurs to move the point of foveation from the first target to the second. Following this, though the second target is now foveated there is still residual head rotation due to a lag in the control of head movement relative to that of the eyes, and this is compensated for by a further period of VOR eye movement. The components of the gaze shift are therefore an initial period of VOR, an exogenous eye saccade, followed by a further period of VOR. It is not currently known whether VOR eye movements are able to induce change blindness by themselves, but it is well established that eye saccades can (Grimes 1996; McConkie and Currie 1996). The experimental paradigm used to produce change blindness in the real-world scenario was therefore saccade-contingent, but it may also have been influenced to some extent by VOR eye movement.

While the above processes were taking place, a small head-mounted high-definition video camera was attached to the goggle strap of the participants in the real-world scenario. The camera was connected by an HDMI cable to the high-definition 32-inch LCD screen in the corner of the room, and a live feed from this camera was displayed on the screen in front of the participant in the on-screen scenario. The acuity achievable when viewing this screen was measured to be 20/70, which, although inferior to 20/20 vision, was significantly greater than the level required to resolve the smallest change detected by any participant in the real-world scenario, which was measured to be 20/180 (a change of 2 mm diameter viewed at 75 cm). The footage displayed on the screen mirrored exactly the view that each real-world participant had of the artefacts on the table in front of them, and this screen was observed by the participants randomly allocated to the on-screen group in turn. These participants wore identical pairs of modified goggles to the real-world group (except without a camera attached to the headband), which, as in the real-world group, prevented participants from making multiple eye saccades between the items in front of them.

But, unlike participants in the real-world scenario, on-screen participants did not have to follow instructions to move their head or eyes on auditory cues. Instead, as the real-world participant rotated their head to look from the first item to the second, the head-mounted camera also rotated and the footage on the screen panned across to reveal the second artefact to the on-screen participant. An equivalent change to the contents of the visual field was therefore produced without an equivalent gaze shift taking place. The experimental paradigm used to produce change blindness in the real-world scenario was therefore not saccade-contingent but camera pan-contingent. The other major difference between scenarios was that the artefacts were viewed directly by participants in the real-world group, while they were viewed on an LCD display in the on-screen group. On-screen participants viewed the screen from a distance of 75 cm, and the camera and screen were calibrated so that the representations of the artefacts were displayed at life size in order to match conditions in the real-world scenario. In both real-world and on-screen scenarios, the artefacts therefore subtended the same visual angle. The only difference between the scenarios, then, was the format of display, in that the artefacts themselves were being observed in the real-world scenario, whereas representations of the artefacts were being observed in the on-screen scenario.

The two experimental variables being tested in this experiment, therefore, are the nature of the visual transition between artefacts (a gaze shift comprising saccadic and VOR components in the real-world scenario versus a camera pan in the on-screen scenario), and the format of display of the artefacts (the artefacts themselves in the real-world scenario and an LCD screen in the on-screen scenario). We posit that these variables are the key differences defining the distinction between any real-world and on-screen visual interaction, in that they represent the behaviour of the subject who is viewing and the nature of the object being viewed that are typical of these scenarios. In this way, our results will provide a comparison of the levels of change detection in real-world and on-screen scenarios.

Results

No statistically significant difference was found between the overall mean levels of change blindness produced in the real-world scenario and the on-screen scenario (real-world 42.62%, on-screen 47.35%, $X^2 = 1.626$ $p > 0.05$ 1 d.f. [Table 1, Fig. 3]). The total number of trials per pair of artefacts ranged from 29 to 31 due to a small number of failures by participants to follow the experimental procedure described above (13 failures from 371 trials = 3.5%). The mean level of change blindness produced in the on-screen scenario was close to 50%, as desired to facilitate comparison between the scenarios. One pair of artefacts produced a significantly higher degree of real-world change blindness than on-screen change blindness (pair 2: real-world 86.7%, on-screen 46.7%, $X^2 = 10.800$, $0.01 > p > 0.001$), while three pairs produced a significantly higher degree of on-screen change blindness than real-world change blindness (pair 4: real-world 20.0%, on-screen

Table 1 Table of results. RW = Real-world. OS = On-screen. X^2 test with one degree of freedom

Pair no.	Total trials	Real-world			On-screen			Real-world versus On-screen		Combined RW & OS
		Change detected	Change blind	Change blind (%)	Change detected	Change blind	Change blind (%)	X^2	P value	Mean change blind (%)
1	29	4	25	86.2	8	21	72.4	1.681	0.194	79.31
2	30	4	26	86.7	16	14	46.7	10.800	0.001	66.67
3	31	27	4	12.9	27	4	12.9	0.000	1.000	12.90
4	30	24	6	20.0	15	15	50.0	5.934	0.015	35.00
5	31	30	1	3.2	29	2	6.5	0.350	0.554	4.84
6	31	27	4	12.9	28	3	9.7	0.161	0.688	11.29
7	30	4	26	86.7	6	24	80.0	0.480	0.488	83.33
8	29	10	19	65.5	7	22	75.9	0.749	0.387	70.69
9	29	23	6	20.7	16	13	44.8	3.835	0.050	32.76
10	29	28	1	3.5	17	12	41.4	11.997	0.001	22.41
11	30	16	14	46.7	18	12	40.0	0.271	0.603	43.33
12	30	9	21	70.0	2	28	93.3	5.455	0.020	81.67
Total	359	206	153		189	170				
Mean				42.62			47.35	1.626	0.202	44.97

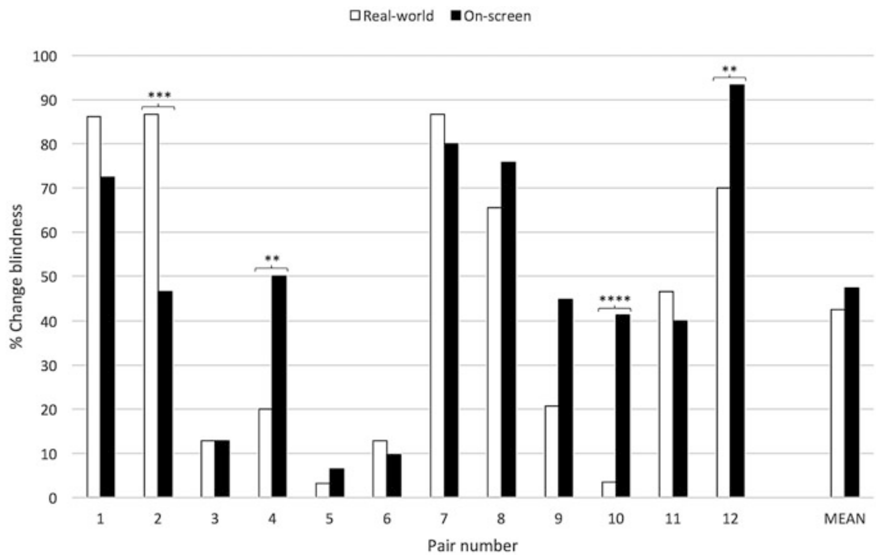

Fig. 3 Levels of change blindness in real-world and on-screen scenarios produced by each pair of artefacts and the overall mean. Asterisks denote level of significance (X^2 test with one degree of freedom. No asterisk = p > 0.05; * = 0.05 > p > 0.02; ** = 0.02 > p > 0.01; *** = 0.01 > p > 0.001; **** = 0.001 > p)

50.0%, $X^2 = 5.934$, $0.02 > p > 0.01$; pair 10: real-world 3.5%, on-screen 41.4%, $X^2 = 11.997$, $0.001 > p$; pair 12: real-world 70.0%, on-screen 93.3%, $X^2 = 5.455$, $0.02 > p > 0.01$). But in the other eight pairs there was no significant difference between the levels of change blindness produced. It follows that, overall, whether a visual interaction takes place in the real world or on a screen, as defined by the nature of visual transition and the format of display, has no significant effect on the balance of local and global visual signals produced during that interaction. This result will be discussed later on in the discussion section.

Since there was no significant difference between the levels of change blindness produced in real-world and on-screen scenarios, we have combined the data from the two groups to compare the levels of change blindness produced by each pair of artefacts amongst all participants (Fig. 4). Doing so, the results can be divided between three pairs of artefacts which produced a level of change blindness greater than 75% (pairs 1, 7, and 12, 79.31–83.33%), and three pairs of artefacts which produced a level of change blindness lower than 15% (pairs 3, 5, and 6, 4.84–12.90%). Since the global visual signals produced by either gaze shift or camera pan were consistent across all pairs, it follows that the local visual signals produced by the changes between the artefacts in pairs 1, 7, and 12 were weaker than those produced by the changes between the artefacts in pairs 3, 5, and 6. These local signals arose from the differences in appearance of the pairs of artefacts, which will also be analysed in the discussion below.

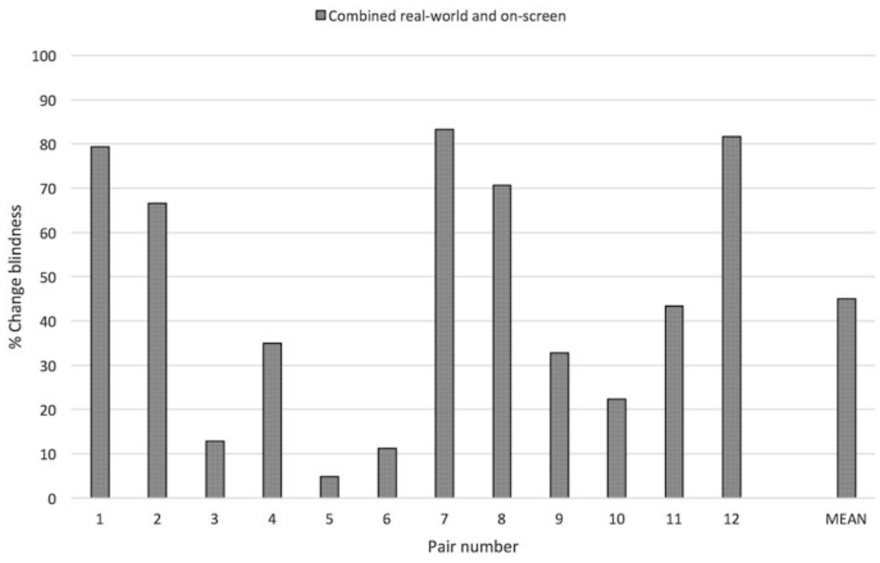

Fig. 4 Levels of change blindness combined from real-world and on-screen scenarios produced by each pair of artefacts and the overall mean

Discussion

From the results of this experiment, we offer three main findings. First, we find that change blindness does occur in a museum setting when similar artefacts, in this case some more than 2,000 years old, are viewed briefly one after another in both real-world and on-screen scenarios. This is an important addition to the body of evidence demonstrating that change blindness takes place in rich and complex environments outside of the laboratory.

Second, we find that there is no significant difference between the levels of change blindness produced in real-world and on-screen scenarios. This result reflects the effects of our two experimental variables on the process of change perception, namely the nature of the visual transition and the format of display.

The nature of the visual transition corresponds to the nature of the global visual signal. Comparing a gaze shift with a camera pan, because the change to the contents of the visual field is the same in both, there is no difference in terms of the information received by the visual system. But because the former is associated with eye movement and the latter is not, there is a difference in terms of the signals being sent to the systems controlling these movements.

Previous studies have reported enhanced change detection associated with the movement of hands towards an object (Tseng et al. 2010) as well improved visual perception with merely the presence of hands near to an object (Abrams et al. 2008; Dufour and Touzalin 2008; Lloyd et al. 2010; Reed et al. 2006), the intention to act on an object (Vishton et al. 2007), and even the imagination of acting on an object

(Davoli and Abrams 2009). However, our findings do not provide evidence of an equivalent association between eye movement and change detection performance.

We reason that this result reflects the fact there would have been no drive in the evolution of the visual system to enhance levels of change detection in response to eye movements, or conversely dampen change detection in their absence. Before motion pictures were developed at the turn of the twentieth century, the human visual system would never have been exposed to a change to the contents of the visual field in the absence of eye movements. Consequently, there has been almost no time for natural selection to differentiate the levels of the change detection that might be appropriate for when the contents of the visual field change in the absence or presence of eye movements. We, therefore, suggest that there is no reason why the visual system would process real-world and on-screen scenarios any differently in this way.

It is also conceivable that change detection might be affected by the format of display of the artefacts in this experiment, which was the second experimental variable being tested. For example, it might be expected that direct observation of artefacts in the real-world scenario would result in stronger local visual signals than the indirect observation of artefacts on-screen. In light of the evidence cited above, the association between action and enhanced perception could be extended to suggest that a real-world object, with the potential to be acted upon, would be perceived more strongly than an on-screen object, which ultimately remains virtual (although the screen which displays it is itself a real-world object). However, our findings provide no evidence in support of the idea that the format of display affects the level of change blindness.

Of course, it is possible that the overall result of there being no significant difference between scenarios is the product of significant but opposite effects attributable to the two experimental variables cancelling each other out. The design of our experiment does not allow us to either accept or reject this explanation. However, for the reasons given in the explanations in this section, we believe it to be more likely that the result reflects a lack of any effect attributable to either experimental variable.

We reason that the lack of an effect of the format of display on change blindness levels reflects the fact that there would also have been no drive in the evolution of the visual system to strengthen local visual signals from real-world objects compared to on-screen objects, or conversely weaken local visual signals from on-screen objects. The primary difference between real-world and on-screen displays is that, in the real-world, three-dimensional objects reflect light which goes on to enter the eyes, while on a screen the same light is captured and processed by a camera before being emitted from a two-dimensional screen to then enter the eyes. As some of the artefacts used in this experiment demonstrate, the human visual system has been processing two-dimensional representations of three-dimensional objects for thousands of years. The earliest cave paintings that have been discovered date back to 15,000–10,000 BC. Human beings and especially the human nervous system have undergone significant changes over this period of time, but we reason that in this period there has been no drive to either significantly strengthen or weaken the local visual signals formed from the observation of two-dimensional objects. The subjects of the earliest two-dimensional representations were bison, mammoth, and reindeer, the prey of those who depicted them on the walls of their dwellings. This alone is testament to the fact that the ability to create and understand representations of the surrounding environment is likely to have conferred a selective advantage over the recent course of our evolution. Meanwhile, the importance of processing elements in three-dimensional environments has not diminished, promoting the development of a visual system equally adept at interpreting two-dimensional representations and three-dimensional reality.

Reflecting on the rapid recent increase in the amount of time spent engaging in on-screen visual interactions, we may in fact consider it unsurprising that this study found no significant difference between change detection performance in real-world and on-screen scenarios. If the visual system did not perform equally in these two scenarios, we would likely not have been inclined to exchange so many of our real-world interactions for on-screen ones. Our finding of equivalent visual performance in real-world and on-screen scenarios, therefore, might provide an explanation on the ease with which we have made this transition.

The third and final finding of this study is that it identifies a group of artefacts which produced a high level of change blindness, and a group which produced a low level of change blindness across both scenarios (Fig. 4). The variable responsible for this result was the variation of local visual signals between the twelve pairs of artefacts, produced by the differences in appearance within each pair.

Broadly, the division between high and low change blindness groups of artefacts can be explained by the fact that the differences in appearance of pairs one, seven, and twelve are relatively subtle compared to those of pairs three, five, and six, resulting in weaker local visual signals.

Taking pairs one and three, both Japanese woodblocks prints, as an example, the items in both pairs are the same size as each other and share the same designs (Figs. 5a and 6a). The items in pair one, the wave prints, also share very similar colouring (Fig. 5a). The only differences in colouring between the items in this pair are the subtle changes in hue to the border and box containing script. These changes in colour are slight and cover a small proportion of the visible surface of the artefacts. By contrast, the items in pair three, the eagle prints, are more obviously different in colour (Fig. 6a). For instance, the colour of the sky changes from dark blue to light blue between the two prints, and the colour of the boxes containing script changes from pink and red to green and orange. Collectively, these changes represent a more significant colour change and cover a larger proportion of the artefact's visible surface, compared to the wave prints. It is these local visual signals which account for the lower level of change blindness amongst participants viewing pair three compared to pair one (12.90% vs. 79.31%, respectively).

Pair seven, the Athenian lekythoi, produced a high level of change blindness similar to that produced by pair one, the wave prints. The items in this pair are the same size as each other, share the same red-figure colouring, and have near-identical designs, except for the depiction of the object in the figure's right

Fig. 5 **a** Pair 1: Utagawa Hiroshige, *The Sea at Satta in Suruga Province* from *Thirty Six Views of Mount Fuji*. Woodblock prints with *bokashi* (tonal gradation). 1858–9 AD. 22.4 × 34.0 cm. **b** Pair 7: Athenian red-figure lekythoi. *Nike flying with phiale* (left). *Nike flying with thurible* (right). 490–480 BC. 32.4 cm (left) and 31.8 cm (right) tall. Images reproduced with permission from Ashmolean Museum, University of Oxford. **c** Pair 12: Isaac Dighton, Silver toilet dressing table service, two of fourteen. 1699–1700 AD. 10.3 cm (left) and 10.5 cm (right) tall. Images reproduced with permission from Ashmolean Museum, University of Oxford

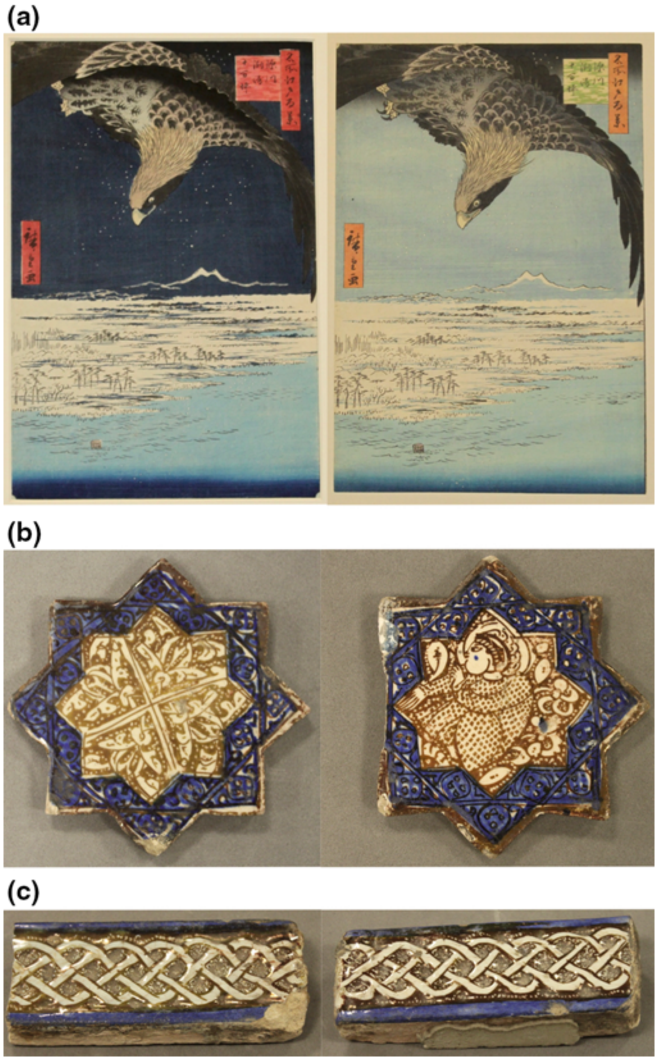

Fig. 6 **a** Pair 3: Utagawa Hiroshige, *Jūmantsubo Plain at Susaki, near Fukagawa* from *One Hundred Famous Views of Edo*. Woodblock prints with *bokashi* (tonal gradation). 1856–8 AD. 22.0 × 32.8 cm. Images © Ashmolean Museum, University of Oxford. **b** Pair 5: Iranian star tiles. Late thirteenth–fourteenth century AD. 16.0 × 6.5 cm. 15.0 × 15.0 cm (left). 13.0 × 15.0 cm (right). **c** Pair 6: Iranian tiles with interlacing pattern. Thirteenth century AD. Images reproduced with permission from Ashmolean Museum, University of Oxford

hand, which changed from a *phiale* to a *thurible* (Fig. 5b). As for pair one, this change covers a small area of the visible surface of the artefacts and so represents a relatively small local visual signal, which translates to a high level of change blindness (83.33%). Similarly, pair twelve, the silver flasks, also produced a high level of change blindness (81.67%). The two flasks are practically identical, save only for the uppermost tip which has been displaced atop the first item (Fig. 5c). Again, this change represents a small area of the artefact's visible surface, and so only produced a small local visual signal.

The items in pair six, the Iranian tiles with interlacing pattern, are the same size as each other and share the same design and colouring (Fig. 6c). However, the first tile has an area of damage to its corner and the second tile carries an extra piece of cement on its front. These changes together account for a large area of the artefacts' visible surfaces and as such constitute large local visual signals responsible for a low level of change blindness (11.29%). The items in pair five, the Iranian star tiles, produced the lowest level of change blindness of all (4.84%), with only three of the 62 participants not noticing any changes between them. These artefacts manifest differences in both the design of their central area, and also in that one of the points on the second tile has been broken off (Fig. 6b). These two changes constitute large local visual signals accounting for a very low level of change blindness.

The characteristics of changes that produced the most easily detected local visual signals include a large visible area of change, and high contrast changes in colour. Both of these characteristics, area and contrast, can be directly related to the retina, where light from the visual field is transduced by photoreceptor cells, and contrast is enhanced by lateral inhibition of neurons in the layers between the photoreceptors and retinal ganglion cells. Because these characteristics are amongst the first to be encoded by the visual system, they are possible candidates for bottom-up influences on the prioritization of what is represented and compared during the process of conscious change perception. In line with this, it has been shown that highly salient objects, where salience includes colour, intensity, and orientation (Itti and Koch 2000; Koch and Ullman 1985), attract visual fixations earlier than less salient objects (Underwood and Foulsham 2006; Underwood et al. 2006), and it is well established that the larger a surface is within the visual field the more likely it is to be fixated (Peschel and Orquin 2013).

However, it is clear that areas undergoing change can be fixated within a change blindness paradigm pre- and post-change without the change itself being perceived (O'Regan et al. 2000). It has also been shown that bottom-up factors can at times be overridden by top-down cognitive influences, such as the consistency of an object within the gist of a scene (Stirk and Underwood 2007; Underwood and Foulsham 2006), and the specific task the viewer is asked to perform when observing a stimulus (Underwood et al. 2006). In this experiment, the absence of peripheral vision made it difficult for participants to determine the gist of the scene they were viewing (Larson and Loschky 2009), and participants were specifically instructed to look for a difference between the artefacts which was equalized across conditions. For these reasons, we suggest that bottom-up factors were relatively spared from being overridden by top-down effects, and were therefore able to exert their own influence on the processes of representation and comparison, and ultimately change blindness. In this way, our findings support a role for bottom-up factors including a large visible area of change and high contrast colour change in determining what elements of a visual scene are represented and compared in the process of conscious change perception in both real-world and on-screen scenarios.

The methods used in this study carry their own limitations. We will discuss them in relation to the two main comparisons performed in this experiment. Namely, the comparison of real-world and on-screen scenarios, and the comparison of the twelve pairs of artefacts. Regarding the former, first, by comparing the performance of two different groups of participants in real-world and on-screen scenarios, we introduced the potential for selection bias. Unfortunately, we saw no practicable alternative to this, as a change cannot be shown to the same participant more than once in a change blindness experiment. To mitigate this bias, we recruited over thirty participants that we randomly allocated to each group, which resulted in very similar demographics being represented in both.

Second, while it was important to control the conditions in which the artefacts were observed, this was at the expense of the naturalism of the viewing experience. The viewing distance and placements of the objects were similar to what would be found in a natural museum environment, but the brief periods of observation and the removal of peripheral vision using modified goggles were both unnatural. However, the conditions were the same for participants in both groups. Third, by recording changes which participants described incorrectly in the same way as changes that were not described at all, we set a relatively high threshold for change detection to be achieved. Our methodology did not distinguish between the experience of completely missing a change and the experience of sensing that a change had occurred but not being able to describe that change correctly.

Regarding the comparison between the twelve pairs of artefacts, first, it is possible that the performance of participants changed over the course of the experiment as they proceeded through the twelve sets of observations. It is both conceivable that their performance may have improved due to a learning effect or conversely have worsened due to fatigue. We expect that because each observation was only brief, and the number of observations was relatively few, neither of these effects are likely to have impacted significantly on the levels of change blindness recorded over the course of the experiment. Each set of twelve trials took less than 10 min to perform. Although the order in which the artefacts were viewed was not varied between participants (which could have mitigated any such effects), the levels of change blindness produced from pair one to pair twelve bear no relation to either an increasing or decreasing trend. Finally, the collection of artefacts used as visual stimuli did not contain a control pair, in that there was no pair of artefacts that were truly identical to each other. If such a pair had produced a change blindness level of 100% it would have strengthened the confidence with which we can draw conclusions from our dataset.

Conclusion

Simons and Rensink, in their 2005 review of the field, identified a number of themes to be explored as change blindness research moves forward (Simons and Rensink 2005), including the extension of change blindness demonstrations into more complex events and environments. We believe that our study has achieved this, through the demonstration that change blindness does occur in a museum setting when similar artefacts are viewed briefly one after another in both real-world and on-screen scenarios.

Previous studies involving change blindness have exhibited the phenomenon in either real-world or on-screen scenarios. Here, for the first time, we directly compare the two and find no significant difference between the levels of change blindness produced. We suggest that this result is to be expected given the evolution of the human visual system, and also considering how readily on-screen visual interactions have been adopted in recent years. Furthermore, we describe a set of conditions that produce a higher level of change blindness in both scenarios, and suggest that since top-down factors were equalized across conditions, bottom-up factors, including a large visible area of change and high contrast colour change, might be responsible for the result.

Further future directions which the authors identified in 2005, and which remain relevant today, include the use of 'attention tracking' paradigms to study the locus of attention during visual search tasks (Tse et al. 2003), the investigation of the role of expertise in enhancing change detection (Jones et al. 2003; Werner and Thies 2000), and the exploration of change blindness in the context of conditions such as dyslexia and neurological lesions (Pisella et al. 2004; Rutkowski et al. 2003). We hope that these directions may be pursued fully to shed more light on our understanding of the visual system and how it processes the environments around us.

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Part III
Music, Mathematics and the Brain (Moreno Andreatta)

Composing Music from Neuronal Activity: The Spikiss Project

Alain Destexhe and Luc Foubert

Abstract We describe here an attempt to compose music, constrained by recordings of brain activity where excitatory and inhibitory neurons were discriminated and used to trigger simple tones or more complex sounds. We used experimental recordings of brain activity under the form of "spikes", recorded with microelectrodes in human subjects. The recordings come from different sources, which have been all published in the neuroscience literature. We emphasize here the natural rhythmical activity of neurons, in particular, that of inhibitory neurons. Inhibitory neurons are thus naturally suited for driving bass sounds and rhythmic sections. The sparser activity of excitatory neurons is exploited here to reveal melodic capabilities, which are sometimes exacerbated by subjective choice of scales and tones. We explain step by step how this can be done and provide examples of musical sequences and tracks composed from neuronal activity during different brain states, such as wakefulness, deep sleep, or paradoxical sleep (dreaming). We suggest to extend this approach to more global signals, such as the electroencephalogram or neuroimaging signals.

Introduction

Making music from brain activity has a long tradition, with the first attempt dating back from Adrian and Matthews (1934), who listened to the electroencephalogram (EEG) translated directly to an (analog) audio signal. Another pioneering approach was the experience of Alvin Lucier using EEG for composing his "Music for Solo Performer" (1965), often referred to as the "brain wave piece." In this setup, the

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brain waves of a solo performer were made to excite percussion instruments. Since then, there were many attempts to translate EEG activity into some form of music. For the majority of these approaches, the musical transduction was generated by filtering the EEG in the different frequency bands, such as delta (0.5–4 Hz), alpha (8–12 Hz), beta (15–25 Hz), and gamma (40 Hz and higher). The signal in the frequency band is quantified in amplitude, power, duration, and these signals are used to drive or modulate musical compositions. For example, notes can be triggered by the instantaneous power in each frequency band. A recent study by Lu et al. (2012) followed this classic procedure to generate music using different frequency bands in the EEG and found that it had a strong random character and was not very enjoyable. They found that using another type of signal (from functional Magnetic Resonance Imaging, fMRI), the music obtained corresponded better to the type of music we are used to listen and was more enjoyable. Today, there are many commercial and free systems to propose this approach with affordable portable EEG devices.[1]

Brain music can also be made from discrete signals, such as the activity of single neurons. Conventionally, for researcher in electrophysiology, the derivation of the activity of a single neuron recorded by an electrode into an audio amplifier is well known to greatly help the identification and discrimination of neuronal sources by ear, much more than from visual inspection onto an oscilloscope. Moreover, several theoretical and experimental works reveal the synergetic interactions between neural cells as a way to be gathered into neural assemblies for particular perceptive and cognitive coding and then insist on their synchronous ("or co-rythmhic") properties (Gray et al. 1989; von der Marlsburg 1994). One of the first "sonification" of direct activity from neurons was due to Rodolpho Llinas (shown in a conference in Knokke, Belgium, 1986) and consisted of different "beeps" triggered by the activity of different simultaneously recorded neurons in cerebellum. A similar idea was simultaneously implemented by the group of Ad Aertsen based on monkey unit recordings in cerebral cortex (Aertsen and Erb 1987), an approach called the "neurophone." There are also various other old and more recent examples of sonification of brain activity that can be found.[2]

Music from neurons can also be used as a way to "visualize" the activity in different states of the brain. An attempt called "Neuronal Tones" was published on the *Internet Archive* by Alain Destexhe in 2006 (http://www.archive.org/details/NeuronalTones). This computer-generated music was based on recordings of multiple neurons with microelectrodes in cats during wakefulness and sleep (Destexhe et al. 1999). A given neuron was associated with a fixed tone, and every time this neuron fires, a note is emitted. The music produced gives an idea about the

[1]For example, see the "MindMidi" approach (http://www.mindmidi.com), which is free and produces quite enjoyable music from the EEG. A short recent article reviewing the most interesting attempts to produce or compose music from EEG derived signals can be found here: https://creators.vice.com/en_us/article/10-pieces-of-music-created-by-brainwaves.

[2]for example, see the proceedings of the "International Conference on Auditory Display," ICAD, http://www.icad.org, which is running regularly since 1992.

distributed firing activity of those neurons. The "Neuronal Tones" compares brain activity not only in different wake–sleep states but also with randomly generated notes with the same statistics. Interestingly, the firing of one isolated neuron during wakefulness is undistinguishable from that of random (Poisson) activity, but the distributed activity (i.e., the "melody") in synergy with the group of many recorded neuron is clearly different. This suggests that what makes our brains non-random is not in the firing pattern but lies in the respective timing of the firing activity between different neurons.

In the more recent "Neuronal Melodies," the same approach was applied to human neuron recordings and was published on the *Internet Archive* by Alain Destexhe in 2012 (http://www.archive.org/details/NeuronalMelodies). Here, a dataset of 92 neurons was used—these neurons were simultaneously recorded in the temporal cortex of human subjects, and the main originality of these data is that excitatory and inhibitory neurons could be discriminated (Peyrache et al. 2012; Dehghani et al. 2016). This allowed us to create a musical sequence with two instruments, a woodblock for excitatory neurons and a xylophone for inhibitory cells. From these melodies, one can hear that the distributed firing activity is almost identical during dreaming compared to wakefulness, which emphasizes the high similarity between these two different brain states. These human neuronal melodies were constructed during wakefulness, slow-wave sleep and REM sleep, as well as during an epileptic seizure. In the "seizure melody," the activity starts with normal "Wake" activity, following by an epileptic (focal) seizure, which can be heard very well while listening to that melody.

In the present chapter, we illustrate a different approach, based on the same data (Peyrache et al. 2012; Dehghani et al. 2016; see Fig. 1). Instead of uniformly converting neurons to notes, as in the approaches reviewed here, we have made a more complex conversion by associating selected groups of neurons to different scales and tones, based on the similarity of their rhythmical activity. The goal is here not to study neuronal activity, but to use neuronal activity to drive music composition. This is called the "Spikiss Project" (Destexhe and Foubert 2016a, b).[3]

A Brief Overview of Different Brain Songs

We start by an overview of different tracks created from human brain activity, and next we explain in detail how these sequences were constructed.

[3]Note that the present musical work was published early 2016 on the *Internet Archive* (https://archive.org/details/Spikiss, https://archive.org/details/Spikiss-Sleep, https://archive.org/details/Spikiss-Rem) as well as on *SoundCloud* (https://soundcloud.com/search?q=spikiss). A similar approach called "Neuron Song" was also proposed later in 2016 by Kristin Klark based on patch-clamp recordings (https://www.youtube.com/playlist?list=PLIgiB4tiZmmSF8_m69Z_PbLfxiCEqGO8E) and also aimed at creating music based on brain recordings.

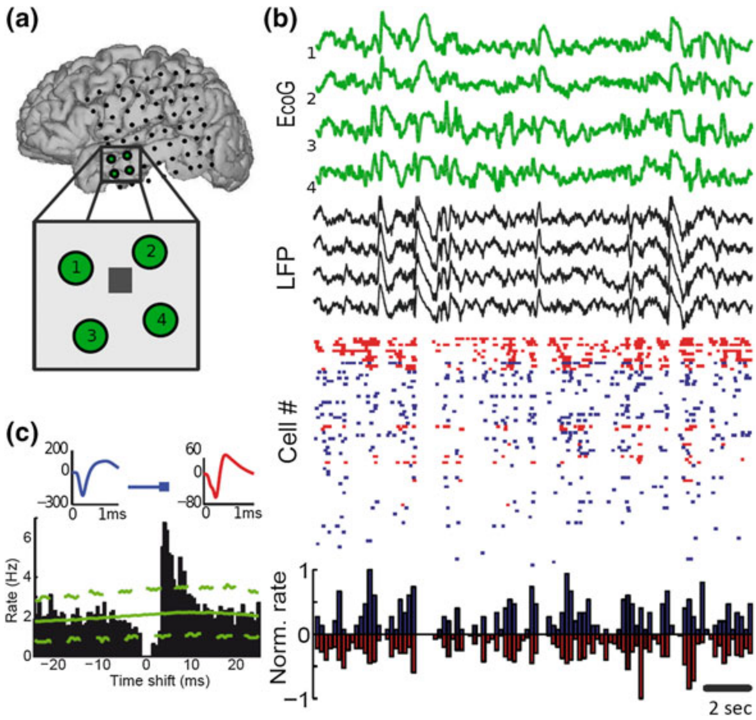

Fig. 1 Human recordings of excitatory and inhibitory neurons. **a** Implantation of an array of microelectrodes in the human temporal cortex. **b** Example of signals obtained with the array, during a period of slow-wave sleep. The surface recordings are shown in green (EcoG) and in black the recording in depth (local field potential, LFP). The red and blue dots show the firing of individual neurons (Cells: red = inhibitory, blue = excitatory; population activity shown in the bottom graph). **c** Example of functional identification of excitatory and inhibitory cells from cross-correlograms. Modified from Peyrache et al. 2012, where all details can be found

"Wake Beats"—Music from the Awake Brain[4]

The first song we illustrate is based on recordings of single neurons in the awake human brain. In particular, we have used recordings where it was possible to formally identify excitatory from inhibitory neurons, and the corresponding spikes were used to drive music. Of course, this was made under certain arbitrary rules or subjective choices to make the music enjoyable.

As explained in section "Detailed Description on How to Generate Brain Songs from Excitatory and Inhibitory Neurons", the principle is that the timing of the spike is used to trigger a given sound. This is done in such a way that each neuron has its own, private sound. This sound can be a bass, a percussion, or something more melodic such

[4]The "Wake Beats" song can be listened at http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Wake%20Beats.mp3 .

as bells, xylophone. The inhibitory ("fast spiking") neurons are generally more rhythmic and can be used to drive the bass and drum sections. The excitatory ("regular spiking") neurons fire more sparsely and are more appropriate for the melodic sections.

In the first part of the track (first minute), the activity of the different neurons is strictly respected, as well as the respective timing of the spikes of the different cells. However, in the second part (starting after the first minute), we have followed a different strategy using loops to be anchored on the signature/tempo grid. This second strategy was explored as a naive intuition from contemporary electronic music that rigid quantized loops would sound better. Thus, we have selected, from the neuronal activity, periods where the activity of the neurons was particularly rhythmic and interesting (based on totally subjective criteria!). We have isolated these periods, defining "loops" that can be played several times and in any order. This was done for the different sections, such as the bass and rhythmic activity, as well as for the melodic activity. In addition, we have used more sophisticated sounds from analog and/or digital synthesizers. So in this second part, the respective timings of one cell against another were not always respected, but all the music events are driven by neuronal activity.

This illustrates the power of neuronal activity to generate music. Neurons follow collective dynamics and have correlations with each other, and fire together within an ensemble activity which is complex, but not random. Neurons also display marked rhythmic properties, especially for inhibitory neurons which naturally form rhythmic and bass sections.

Note that in this example, all neurons considered were simultaneously recorded by a system of 100 microelectrodes, and the activity was slowed down by about 30%. A natural but slightly fluctuating subjective tempo was estimated around 140 BPM at which data were imported in the sequencer but then slowed down by playing the overall sequence at 110 bpm as a global ~30% time stretch.

"Slow Waves"—Music from the Sleeping Brain[5]

This second track was composed from neurons recorded in humans, during slow-wave sleep. For this track, we decided to come to the initial strategy constraining all respective timing of spikes events among each other thus avoiding "loops" in order to keep the hidden synergy and rhythmicity between cells. A major problem occurring here is then the complete disconnection between all spike-triggered events with the rigid signature/tempo grid used as a container substrate in the sequencer. As above, data were imported at a natural tempo estimated around 140 and slowed down at 110 with this impossibility to lock a precise metronome on the sequence because of a slightly drifting tempo but having the

[5]The "Slow Waves" song can be listened at http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Slow%20Waves.mp3 .

enjoyable surprise of a more natural sounding interplay between events. As above also, the inhibitory neurons form the rhythmic sections, while excitatory neurons drive the melodic parts. Unlike wakefulness, the activity consists of “Up” and “Down” states, where the neurons oscillate slowly between active and silent periods. We have exploited these dynamics and used slow sound envelopes to follow the modulations the slow waves of sleep.

In the first seconds of the song, one can hear very well the “Up/Down” states typical of sleep, because the bass fires in intermittency, so do all neurons. The slow sounds were driven by excitatory neurons. In the second part of the song, we have used two versions of the slow envelopes (“Woo-Woo”), with major and minor scales, then back to major. The third part (second half of the song), used further slow sounds, mixed with neuronal activities. Note that here, there were no “loops,” the respective timings of the different neurons were strictly respected.

See details in section “Generating Songs from the Sleeping Brain”.

“REMiniscence”—Music from the Dreaming Brain[6]

This third song was composed from neurons recorded in humans, during paradoxical sleep, also called “rapid eye movement sleep” or “REM sleep.” The REM activity is very similar to wakefulness, but we wanted to make it sound a bit different. So we have emphasized the rhythmic sections, still made from inhibitory neurons, and use the excitatory neurons to drive melodic instruments like bells or sounds that evoke the strangeness of dreams. For this track, we defined a third tempo strategy by directly stretching all imported events by exactly the same amount in order to keep their coherence and to approximately match a signature/tempo grid played at 110 bpm. This helps to synchronize BPM-driven effect such as delays and includes external rhythmic loops to enrich the final mix as a taste of exploration.

In the first part of the song (first 2:30 min), the rhythmic section made by inhibitory neurons is emphasized, together with the melodic section made by excitatory neurons (bells and voices). In the second part of the song (up to 3:25 min), the rhythmic section is now accompanied with bells and a drum kit to form a particularly rhythmic ensemble. In the third part, excitatory neurons drive a synthesizer, along with slower sounds and voices which illustrate the strangeness of dreams. The timing between the different neurons was in general respected all through the song. See details in section “Songs from the Dreaming Brain”.

The same approach can be followed using recordings of neurons during different brain states, such as different stages of sleep or epileptic seizures for example. It is also possible to consider other signals such as the electroencephalogram (EEG) or the local field potential (LFP) as we are currently working onto.

[6]The “REMiniscence” song can be listened at http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20REMiniscence.mp3 .

Detailed Description on How to Generate Brain Songs from Excitatory and Inhibitory Neurons

We now explain how we have translated human brain activity into music. In the song "Wake Beats," we have used recordings at the level of single neurons in human subjects, and in particular, we have used the spikes from identified excitatory or inhibitory neurons, to drive music. Of course, this was made under certain arbitrary rules and subjective choice made on tones and scales mappings to make the music enjoyable! We explain how we have done this step by step.

Recordings of Single Neurons

We provide here some general explanation for the non-specialist, about the type of signals that we use in our project. If you are familiar with neural recording techniques, you can skip this section.

Neurons emit electrical impulses called "spikes." These electrophysiological events show very precise timing (less than 1 ms) and are used by neural cells to transfer local activities through wide communication networks. These dense interplays are also likely used to gather different assemblies of cells into synergetically reconfigurable ensembles. These spiking events can be recorded using microelectrodes, as typically shown in Fig. 2. This example shows the signals from four microelectrodes, during a few seconds. In these four simultaneous recordings,

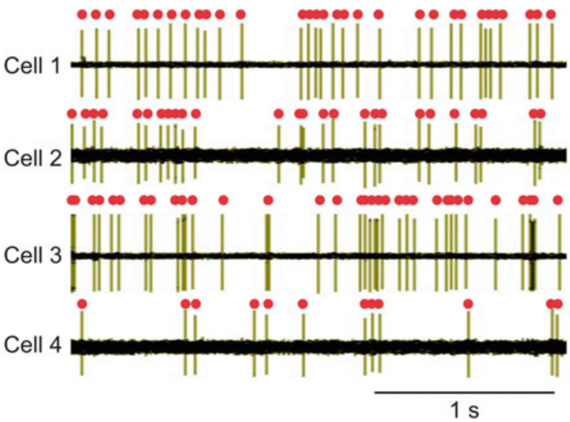

Fig. 2 Example of neuronal activity recorded by four microelectrodes in the brain. The four signals shown come from four different microelectrodes, each of which detects the impulse activity (spike) from a different neuron. The four different simultaneously recorded neurons are labeled "Cell 1" to "Cell 4." For each cell, the spikes are seen as sharp and brief deflections (vertical green bars). The red dots on the top of each signal indicate the time of each spike

one can see very well spikes which appear as vertical deflections (green also indicated by red dots). Each one of these spikes is generated here by a single neuron, and one different neuron is seen by each electrode, so we see here the activity of four neurons altogether.

The electrophysiologists routinely record neurons with such microelectrodes. Instead of representing the full signal, as in Fig. 2, it is more compact to detect the spikes numerically (red dots) and display them as a series of dots, as represented in Fig. 1b (blue and red dots; see also red dots in Fig. 2). Such a compact representation only contains the timing of the different spikes of each cell and is called a "raster." We will see below more examples of such rasters.

How to Convert Neural Recordings into Music?

To convert neural recordings into music, and in particular spikes recordings, we will proceed by examples. We take advantage of the fact that neuron spikes are impulses, well defined in time, so we can use them to trigger particular musical "events". These events are traduced through the MIDI protocol as "notes" having fixed length and fixed velocity and mapped onto the keyboard (initially, white keys of the C-major diatonic scale) in a random order of cells identification (from 1st to 100th cell). This MIDI mapping into a sequencer framework (Ableton, Live9 software) will allow easy affectations and routings of each event to any kind of sound synthesis by conventional MIDI manipulations. This way, when a neuron emits a spike, a sound is played, in a way that each neuron has his private sound, as shown in the examples below.

Example 1 As a first example, let us consider one single neuron (e.g., "Cell 2" above). One can select a "bass" sound and play this sound each time the neuron emits a spike.

To listen to that example, click on "Bass Neuron" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Bass%20Neuron.mp3).

Example 2 Let's try now a more complicated combination, where four different neurons are played simultaneously. To keep its identity, each neuron will play a different percussion sound with a "drum kit" mapped on the keyboard. The raster of these four neurons is shown in Fig. 3.

These neurons were chosen because they are particularly rhythmic. They are all inhibitory ("fast spiking") neurons. To listen to that example, click on "Drum kit Neurons" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Drumkit%20Neurons.mp3).

The rhythmical character of these neurons is quite striking!

Example 3 We now take five different neurons, corresponding to the raster shown in Fig. 4.

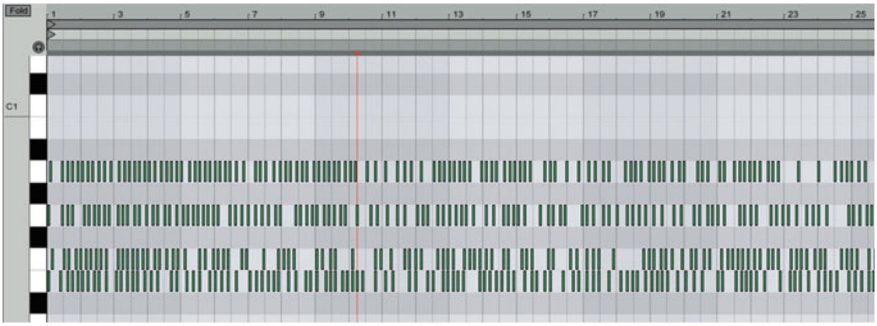

Fig. 3 Raster of four inhibitory neurons in an awake human subject, mapped on the C-major diatonic scale

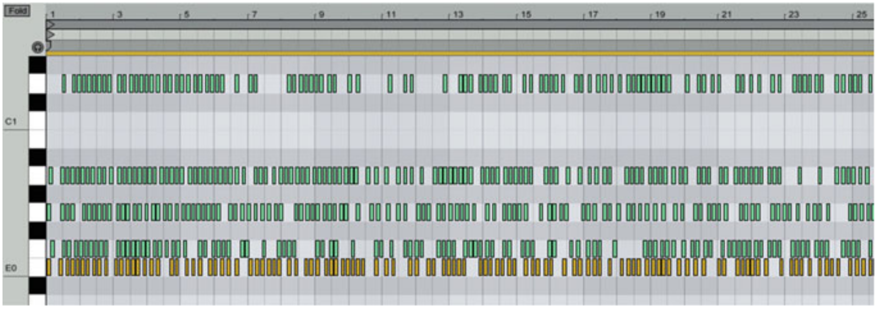

Fig. 4 Raster of five neurons in an awake human subject (C-major diatonic scale). Similar to Fig. 3, these neurons are inhibitory

We now associate these neurons to a “steel drum” sound, and each neuron corresponds to one note on the steel drum mapped on major scale. In other words, each time the neuron spikes the note specific to that neuron is played once. Thus, each neuron has its own note, and the melody is here created here by five neurons playing together on a steel drum.

To listen to that example, click on “Steel drum Neurons” (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20SteelDrum%20Neurons.mp3).

Example 4 In this example, we show that same scale mapping but other sounds than percussion are possible. For example, one can take a slow sound (with a slow attack and a long decay time) and associate this sound to the same neurons as in Example 3. Similarly, each neuron still has its own note.

To listen to that example, click on “Woo-woo Neurons” (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20WooWoo%20Neurons.mp3).

Example 5 We can now try to combine some of the examples above. Combining Example 1 (single bass) with Example 4 (woo-woo) gives a more elaborated combination.

To listen to that example, click on "Woo-woo and Bass" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20WooWoo%20and%20Bass%20Neurons.mp3).

Example 6 Still going further in complexity, let us now consider the activity of 14 excitatory neurons, which correspond to the raster shown in Fig. 5.

In this example, spikes (or "event") from the pool of about 80 excitatory cells have been randomly affected and mapped onto the C-major scale. Because of the too many events of high density mapped on the wide tessitura of the 88 notes keyboard produces a very unpleasant "musical overload," we selectively discard cells (or lines on the raster plot/keyboard) either by random and/or by subjective aesthetic selection/deletion. Let us now associate these neurons to an instrument, a synthetic bell. As above, to keep track of the neuron's identity, we assign a specific note to each neuron, and that note is played once when this neuron fires a spike. To listen to that example, click on "Neuronal Bells" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Neuronal%20Bells.mp3).

Example 7 Finally, to illustrate a first combination of several instruments, we combined the examples above into a mix. To listen to that example, click on "Neural mix" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Neural%20Mix.mp3).

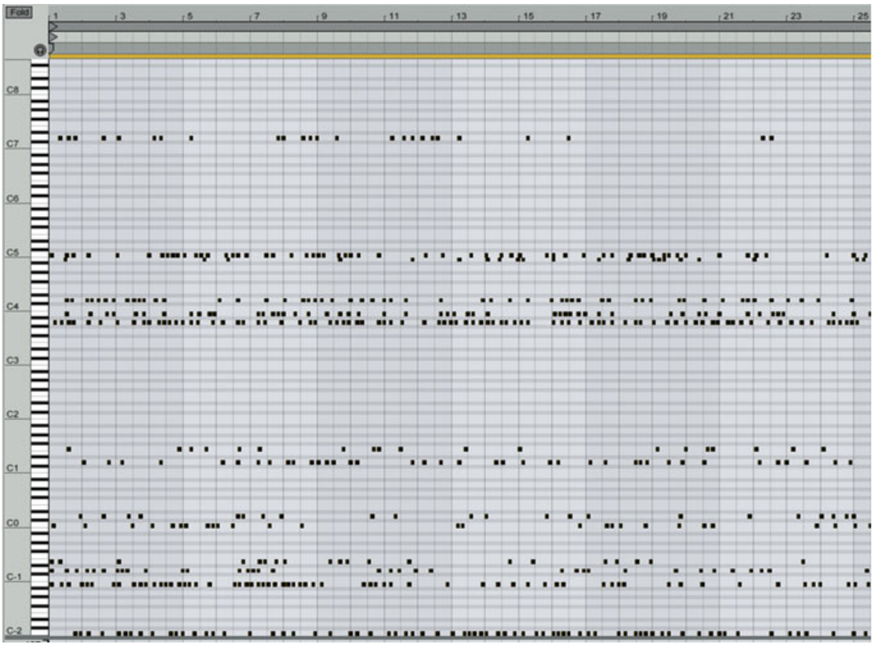

Fig. 5 Raster of 14 neurons in an awake human subject, mapped on the C-major diatonic scale. These neurons are all excitatory ("regular spiking") neurons, and they were selected among a larger set of neurons

In this example, all neurons considered were simultaneously recorded by a system of 100 microelectrodes. Also note that in all of the above, the activity was slowed down by about 30% compared to real-time. This is the strategy used for the first part of the song http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Wake%20Beats.mp3 (first minute). As described above, the respective timing between different neurons is strictly respected, as well as the respective timing of the spikes of the different cells. In the second part, we defined "loops" by selecting some moments where the activity was particularly rhythmic. These loops were replayed at different times, and thus in this case, the respective timing of the different neurons was not respected, although each instrument was played from neuronal activity (this strategy was abandoned for the following tracks in order to keep the prevalent coherence between cells events).

Generating Songs from the Sleeping Brain

We now explain how we have translated human brain activity into music, for recordings made while the subject was sleeping, in the deep "slow-wave sleep" phase. This corresponds to the song "Slow Waves" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Slow%20Waves.mp3).

Excitatory Neuronal Activity During Slow-Wave Sleep

The principal difficulty with sleep recordings is that unlike during wakefulness, the neurons' activities are not sustained, but they occur through "waves" of activity, separated by "pauses" where the neurons are silent. This intermittent dynamics, often called "Up" and "Down" states, are paralleled with the production of slow waves in the brain, hence the term "slow-wave sleep." An example of this activity is depicted in the raster of Fig. 6.

One can see very well the different waves, which appear as vertical structures (between 10 and 20 waves are visible). To listen to that example, click on "Sleeping Bells" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Sleeping%20Bells.mp3).

One can hear very well the intermittent character of the neuronal spikes (compare with the similar sound during wakefulness, "Neuronal Bells"; http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Neuronal%20Bells.mp3).

Even if this intermittency may seem problematic at first sight, it can be exploited to obtain nice musical effects. For instance, one can play the excitatory cells above to a slow sound. To listen to that example, click on "Sleeping Waves" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Sleeping%20Waves.mp3).

This gives a clear impression of slow "waves," and indeed they are entirely generated by the neuronal activity of a sleeping subject.

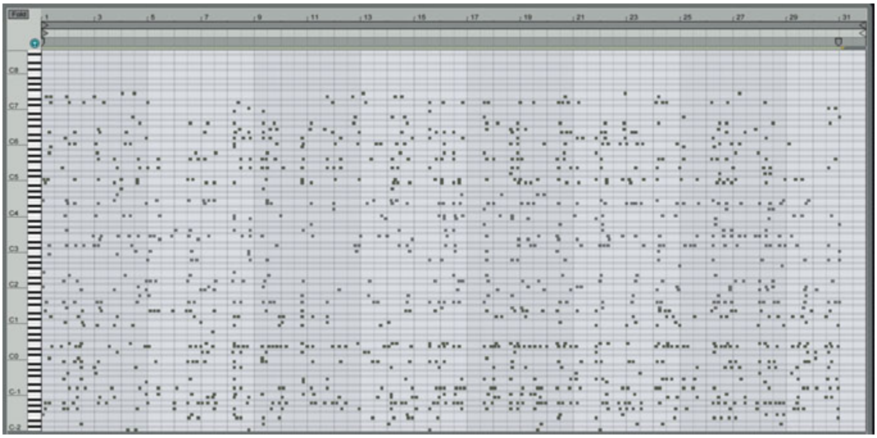

Fig. 6 Raster of excitatory neurons during slow-wave sleep. One can see very well vertical bands, which shows that there are many silences in the activity. The neurons were mapped on the C-major diatonic scale

We can also use sounds intermediate between fast and slow, which allow us to better hear the melody played by neurons. To listen to that example, click on "Sleeping Mid-Waves" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Sleeping%20Mid-Waves.mp3).

These are all generated from the same set of excitatory neurons. Notice that as described in section "A Brief Overview of Different Brain Songs", for this track, absolutely no quantization has been applied on these events so the signature/tempo grid is here completely irrelevant and no metronome-click nor any bpm effect could be synchronized here with this track.

Activity of Inhibitory Neurons During Slow-Wave Sleep

The intermittent character of neuronal discharges during sleep also applies to inhibitory cells. The activity of 11 inhibitory neurons during sleep is displayed in the raster of Fig. 7.

Selecting the four most rhythmic inhibitory neurons from this example, one can play them on a bass (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Sleeping%20Bass.mp3) or on a drum kick (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Sleeping%20Kick.mp3). Here also, one can clearly hear that the intermittent character is also present in inhibitory cells, but it does not alter their rhythmic capabilities.

Taking five neurons from this group, one can also use the same slow sound as for wakefulness (the "Woo-Woo"), mapping them on either a major scale (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Sleeping%20Major-Woo.mp3) or on a

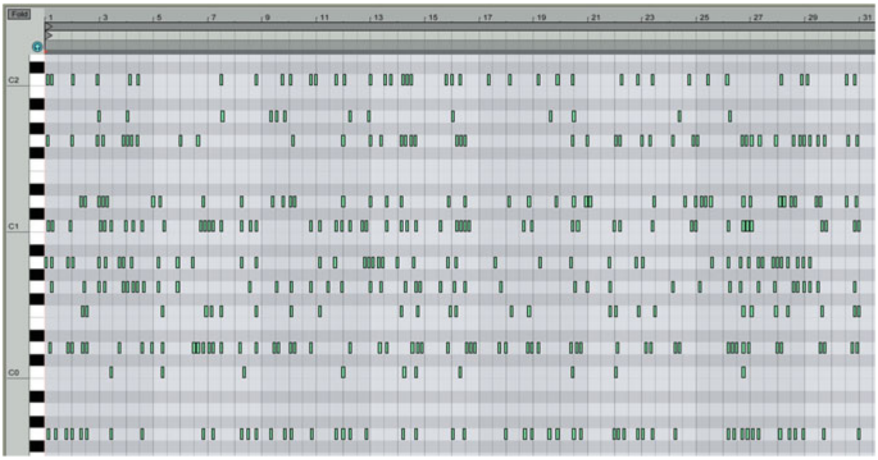

Fig. 7 Raster of 11 inhibitory neurons in a sleeping human subject (C-major diatonic scale)

minor scale (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Sleeping%20Minor-Woo.mp3). Here again, one can hear very well the intermittent character of the neuronal discharges during sleep.

These different elements were assembled to compose the track "Slow Waves" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Slow%20Waves.mp3). Here, the first 2 min was made from the sounds described above.

By listening to this song, one can clearly hear that the intermittent character of neuronal discharges is well coordinated between cells. This coordination makes the music coherent because all sounds are modulated by the same envelope; this envelope corresponds to the "slow waves" of sleep, which we hear musically.

Similar to the first part of the Wake Beats track, the activity of the different neurons is strictly respected, as well as the respective timing of the spikes of the different cells, but here for the whole duration of the track. In the last part of the song (after the second minute), different slow sounds were used to further augment the impression of "slow waves." Here again, all the musical events come from neuronal activity.

Songs from the Dreaming Brain

We now describe how we have composed a song based on the activity of the dreaming brain, using recordings made while the subject was sleeping, in the "rapid eye movement" (REM) sleep, also called "paradoxical sleep," where most dreams occur. This corresponds to the song "REMiniscence" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20REMiniscence.mp3).

Excitatory Neuronal Activity During REM Sleep

One of the most striking features of REM sleep is that the activity of the brain is very similar—almost undistinguishable—from that during wakefulness. Like in the waking state, the activity of neurons is very irregular and asynchronous. We recorded neurons during REM sleep, and 14 excitatory neurons were played on synthetic bells. To listen to that example, click on "Dreaming Bells" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20Bells.mp3). One can hear very well the irregular aspect of the neuronal spikes (compare with the similar sound during wakefulness, "Neuronal Bells," http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Neuronal%20Bells.mp3).

One can also play the excitatory cells above to a very high sound, like that of clochettes (small bells). In that case, 18 excitatory neurons were used. To listen to that example, click on "Dreaming Clochettes" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20Clochettes.mp3). We can also use bell sounds at more medium frequencies, using 18 other excitatory cells. This complements very well the clochettes. To listen to that sound, click on "Dreaming midBells" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20midBells.mp3). As done in other songs, one can also use excitatory neurons to drive slow sounds. For example, one can take one of the sets of 18 excitatory neurons played on the same slow "Woo-Woo" sound considered in Wake Beats, click on "Dreaming Woo" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20Woo.mp3).

Finally, to better illustrate the strangeness of dreams, we also have used sounds that remind this strange character, such as voices (also from 18 neurons). To listen to that sound, click on "Dreaming Voices" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20Voices.mp3). We also used other sounds that remind screams (from the same set of 18 neurons). To listen to that sound, click on "Dreaming Screams" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20Screams.mp3). These are all generated from the same ensemble of excitatory neurons, split into groups of 18 cells.

Activity of Inhibitory Neurons During REM Sleep

Like in other brain states, the inhibitory neurons are very rhythmic, and we can exploit this rhythmicity to form the bass and drum sections. In the REM sleep song, we have given a particular emphasis on this rhythmicity. As a first example, we have chosen a set of seven particularly rhythmic inhibitory cells and used these neurons to drive a drum kick. To listen to this sound, click on "Dreaming Kick" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20Kick.mp3). To further enhance the rhythm, we have duplicated this kick and shifted the duplicate by about half a second, which yields a double kick, of particularly striking rhythmicity. To listen to this sound, click on "Dreaming Double Kick" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20KickDouble.mp3).

Finally, we have used two very rhythmic inhibitory neurons to pilot a "Virus" type of synthesizer and tuned by hand the filtering of the sound. This provides a changing rhythm, which was also used in the rhythmic section. To listen to that sound, click on "Dreaming Virus" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20Virus.mp3).

We have assembled all of the above sounds to compose a full song called "REMiniscence" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20REMiniscence.mp3).

In this song, although the activity was very similar to that of wakefulness, we voluntarily made it sound very different. We explored in this track other scale mapping such as pentatonic or blues scale. We have emphasized the rhythmic character of the inhibitory neurons. Similar to the Wake Beats or Slow Waves songs, the activity of the different neurons is strictly respected, as well as the respective timing of the spikes of the different cells. Moreover, we defined for this track an optimal strategy to keep the coherence between all events and adapt the naturally fluctuating but subjective tempo of the cells ensemble activity to the rigid signature/grid of the sequencer. For this, we simply adapt by ears the stretching of all MIDI events selected all together to the most natural sounding metronome clock. Doing this way for each part of the song, the naturally drifting tempo of the cells assembly can be kept in sync and locked to a regular grid along several measures, and short repetitive sequences, loops, or bpm effect could be synchronized on the global sequence. Thus, we used few additional drum loops samples and an octave-pumping bass to enrich the final mix, but all the rest of the music comes from neuronal activity.

Conclusions and Perspectives

In this chapter, we have provided an overview of an approach to drive music composition from the activity of the brain. We have considered as example recordings of the human brain with microelectrodes. The particularity of these recordings is double: First, they provide unit recordings of single neurons, which is a rare opportunity to access single neuron activity in humans and in different brain states. But the most original aspect of these data is the fact that we could separate excitatory from inhibitory neurons, and that this separation was confirmed by direct neuron-to-neuron interactions (Peyrache et al. 2012). This type of data is very interesting and powerful to generate music, as it appears that inhibitory neurons are remarkably rhythmic and this rhythm is fundamental for this kind of musical composition.

It is important to note that contrary to previous approaches (Aertsen and Erb 1987; Destexhe 2006, 2012), where the music was used as a way to "visualize" neuronal activity, the present approach is aimed at generating musicality with an exploration of subjective aesthetics. The goal is to explore the melodic capabilities of neurons on different scales and exploiting their naturally rhythmic character. It must also be noted that each track described here ("Wake Beats," "Slow Waves," "REMiniscence") was composed with different criteria. It is thus not apparent that the neuronal activity is very similar between Wake and REM sleep, which is a fundamental feature found in animal recordings (Destexhe et al. 1999). This similarity can be found in the "Neuronal Tones" and "Neuronal Melodies" approaches (Destexhe 2006, 2012). Early attempts (Aertsen and Erb 1987) focused only on awake activity in monkey and did not compare with sleep stages. Future musical experiments will explore the remaining set of data recorded during the occurrence of epileptic seizures and the exploration of additional parameters in present in electrophysiological signals (LFPs) to drive other modulations in sound synthesis. Moreover, other scales and melodic modes such as Ionian, Dorian, Mixolydian, or Aeolian among others should also be explored further in conjunction with these recordings of neural activities.

Future approaches should examine other brain signals, such as the local field potential and electrocorticogram, which are also available in human microelectrode recordings. The electroencephalogram (EEG) and magnetoencephalogram (MEG) are also among possible signals to be exploited.

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Luc Foubert has a background in fundamental physics with a long-time interest in electronic music and its impact and potentialities on states of mind. After a master's degree in photonic and signal processing, he obtained a Ph.D. on neurophysiology of sensory perception. Focusing his academic work on the foundations of biological structures underlying sensory processing, he keeps exploring the subtle relationships emerging between visual and auditory perceptions and their impact on the mind and body equilibrium. The "Spikiss project" is a natural outcome of his ongoing work and his research trajectory between art and science.

Music, Mathematics and Language: Chronicles from the Oumupo Sandbox

Moreno Andreatta, Martin Granger, Tom Johnson and Valentin Villenave

Abstract What is music… if not, at the end of the day, an accessible, fun and expressive way to engage with mathematics and language? **Oumupo** (*Ouvroir de Musique Potentielle*, a Workshop for Potential Music) is a group where musicians and theorists can explore this open question through different exercises and experiments.

A Potential History of Potential Creation

In 1960, François Le Lionnais and Raymond Queneau founded a collective comprised of writers and mathematicians, whose singular objective was to reinvigorate literary forms. This collective, called **Oulipo** (*Ouvroir de Littérature Potentielle*, or Workshop for Potential Literature), has been the source of audacious and thought-provoking works such as Queneau's *Hundred Thousand Billion Poems* (1961) and Perec's *A Void* (1969); it continues to exist today and has been supplemented for the past two decades with a separate, though perhaps equally interesting, online community: the Oulipo mailing list.[1]

From Oulipo's very inception, François Le Lionnais also imagined extending the scope of its approach to various other disciplines. In this spirit, he founded several other Ou*x*po workshops: Ou*pein*po (as in "Potential Painting"), Ou*math*po, Ou*ci*-

[1]http://www.graner.net/nicolas/OULIPO/listeoulipo.html

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*né*po… Music was very much included in Le Lionnais' scope, and several Ou*mu*po groups did coexist (in a rather informal way) over the next few decades. It was not until 2011, however, that an actual, established **Ouvroir de Musique Potentielle** did take place; while still resolutely part of this tradition, it remains an active and constantly evolving group.

Ou*x*po groups are concerned with inventing new structures and forms: their experiments may, however, vary in scale, from macroscopic structural constraints to a more minute level where they may be led to reinvent the very language through which their art is expressed. For example, a writer that forbids the use of certain letters or patterns of letters is then forced to express herself within a restricted subset of the normally available lexicon, thereby needing to resort to unknown words, unknown or archaic formulations that may surprise the reader. The words take on a quality in and of themselves as *signifiers* in addition to, or even before, being understood as *signified*.

In this sense, Oumupo is not only brought to re-evaluate purely musical constructs (harmony, rhythm, melody, timbre) but also to draw parallels between these devices and other areas of study: texts or words, graphic arts, but also mathematical objects—automata, geometry and numbers. As it happens, music often is an excellent and accessible way to wrap one's head around abstract notions or challenging mathematical problems—and in a reciprocal manner, mathematics may be a constant source of inspiration in the elaboration of new musical processes. The next sections aim to cursorily introduce a few of these avenues.[2]

Ou*x*pian Games and Inventions

As early as 1962, Le Lionnais laid out some useful ground rules in a text later known as the *First Oulipo Manifesto*, detailing the group's orientation and modus operandi.[3] Interestingly, he made the point that Oulipo was not a literary movement, nor had it any intention of turning into one—in fact, the very notion of "inspiration" (and with it any sense of ethereal poetry, randomness or surrealist-like dream associations) was repeatedly rejected. In its place, Oulipo members were aiming to conceive a seemingly scientific method from the ground up (remotely inspired by the Bourbaki group that, at the time, was in full trend in the French mathematical field), deriving new "potential" structures and constraints from existing works (even going as far back as classical antiquity and medieval literature), as well as from *not-yet-existing* works.

Interweaving the study of past artistic works with the creation of entirely new material (the "analytical" and the "synthetical" approach) remains one of Oulipo's

[2]Some of these examples have been presented in the French popular science magazine *Maths Langages Express*, intended for a large public audience (CIJM 2017).

[3]Oulipo has had three consecutive manifestos, the first two of which are included in a 1973 book signed collectively (Oulipo 1973); the third one was drafted during the 1970s but only published much more recently, nearly half a century after the group's foundation (Oulipo 2009).

most decisive choices—one that resonated with both artistic audacity (the group co-opted Marcel Duchamp as one of its very first corresponding members, which he gladly accepted) and the modernity of a society yet to come: it would be decades before "remix" even became a word.

This two-pronged approach (dubbed respectively "anoulipism" and "synthoulipism") is still found today in every Ou*x*po group in existence; it has grown much richer precisely due to the increased diversity in "potential" disciplines and languages. For example, the *pictée* ("pictation"), a game originally proposed by Ou*pein*po and therefore relevant only to graphical expression (the game consists of describing an existing artwork to somebody who then produces a new drawing based only on the given clues), was adapted by Oulipo as the *textée* ("textation"), and more recently by Oumupo as the *chansonnée* ("singtation"), where it becomes even more amusing since one has to account for both the lyrics and the music.

Many literary forms can be straightforwardly transposed to the musical realm. A foremost example is the palindrome: as a literary (and possibly religious) practice, it dates back at least to ancient Rome, but it was applied to music at least as early as the fourteenth century—as a matter of fact, collecting and reviewing existing examples of musical palindromes and *anacycli* (as well as writing new ones) has been one of the tasks that Oumupo member Valentin Villenave has set out to accomplish.

Not all literary constraints are as easily converted into musical exercises. At least as old (if not older) as the palindrome, is the well-known "lipogram": a text written without using one or more letters of the given alphabet. The obvious musical equivalent would be the "liponote" whereby one is prevented from using a specific pitch (or a degree of the scale)—preferably one of the most essential, in the same way that there is not much point to a lipogram in X or Z. But unlike the lipogram, the liponote quickly proves to be of limited interest. Not only does it hardly make sense in atonal music, but even in classical music one can write around the missing pitch through modulations, substitutions and ornaments. This led Valentin Villenave to suggest another Oumupian exercise: the "lipoval", where a specific *interval* is banned, both between simultaneous and consecutive notes (even accounting for added notes in-between). Depending on its scope (which can be of any length, from a single bar to the whole piece), this constraint may become more challenging (and, much like the lipogram, may remain unnoticed by both performers and listeners).

The Conquest of Niagara: A Radical Approach to Sound Compression!

A peculiar example of "anoumupism" (the musical equivalent of "anoulipism" as explained above) has been proposed by one of our contributors, Martin Granger, with regard to a problem of the utmost importance in the digital age—namely music compression.

Fig. 1 J. S. Bach finally streamlined and enhanced for optimal efficiency: a long-overdue revamping, courtesy of Oumupo!

The entire history of musical compression can be summed up in a single phrase: putting as much information as possible into the smallest space possible. But why on Earth would anyone want to fill a hard drive with 10 years of music? No one in their right minds, nowadays, would ever spend ten years of her life actually listening to the stuff? What an outrageously futile (not to mention, financially unrewarding) activity! Therefore, the time has come to provide the modern citizen with innovative compression solutions that actually correspond to people's needs. To name but a few of these:

- The **acceleration** of recorded music is a compression method as old as the record itself. In playing a 33 RPM record at a speed of 45 RPM, one achieves a time reduction of 36% (an acceleration of 136% is even possible at 78 RPM). Of course, analog time compression pushes the original frequencies higher, thereby causing the music to be transposed. Which is why only certain pieces lend themselves to this treatment—for example, "interesting" results are obtained with Erik Satie's third *Gymnopédie*, entitled *slow and grave*.
- The **removal of redundant patterns** is a very efficient method that does not induce any loss of information. Indeed, many composers (undoubtedly out of complacency or sheer laziness) routinely engage in self-plagiarism and shamelessly reuse entire fragments already written: repeat signs, repeated measures, ostinato patterns… Removing all of these is straightforward enough. Take, for instance, the famous first prelude (BWV 846) in C major in J. S. Bach's *Well-Tempered Clavier* (see Fig. 1). Every bar is made of two identical eight-note patterns, of which the last three notes are actually played twice. An efficient algorithm would first remove one half of each measure, then the last three notes of the remainder. We are left with only 5 notes per measure instead of 16 notes, thus amounting to a 69% temporal gain!
- The more difficult method of **superposition** requires searching similar passages in one or several works and playing them simultaneously. An interesting research subject is the "rhythm changes" (nicknamed *anatole* in French), the chord progression underlying many jazz standards and popular music. By superposing all of the works constructed using this sequence, one could gain quite a lot of time!
- Last but not least, **random superposition** allows for extremely efficient temporal gains, at the price of dramatically reducing the music's signal-to-noise ratio. For example, Heinrich Ignaz Franz von Biber's *La Battalia a 10* (1673) superposes eight popular melodies in different tonalities and tempos to evoke the

theme of drunken soldiers. That 8/1 compression rate allows for an 87.5% reduction in time. In a similar vein, *Folk Music* by Zygmunt Krause (1972) offers a superposition of 20 folk melodies—a whopping 95%!
Pushed to its extreme, this logic would allow one to listen to *all possible music* at the same time. Also known as "white noise", this is compression at its limit, as the quantity of musical information tends towards zero.

In other words, let us be proactive for once and skip directly to the ultimate compression: the inevitable day where listening to music will be indistinguishable from hearing the sound of Niagara Falls.

Coding and Counting

Given the number of mathematicians that were (and still are) involved with Oulipo, one can but wonder why its sister group Oumupo did not take off immediately when a few informal meetings took place between François Le Lionnais, Michel Philippot, Pierre Barbaud and a few others in the early 1970s. Indeed, music is, in and of itself, a mathematical language, as Leibniz famously posited in his 1712 letter to a young Goldbach: *Musica est exercitium arithmeticæ occultum nescientis se numerare animi* ("music is a hidden exercise in arithmetics, where the mind is unaware it is counting").

Any musician can attest how ubiquitous numbers are in the musical field, in many different forms. To demonstrate their versatility, one may translate a given numerical sequence through various methods; in Figs. 2, 3, 4, 5, 6, 7, 8, 9 and 10, we will be using the first decimals of the number π as an example.

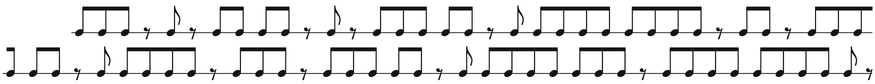

Fig. 2 π's first decimals in base 10 (3.141592653589) as rhythmic patterns of various lengths…

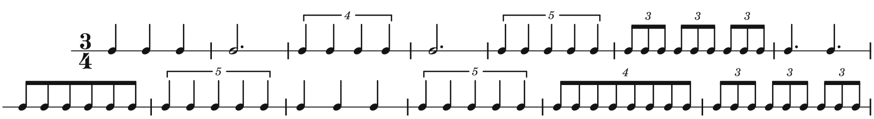

Fig. 3 …And as quantities of events per measure, with variable speeds

Fig. 4 π's first decimals expressed through scale degrees. The zero is rendered by a rest

Fig. 5 π's first decimals used as cumulative intervals between notes

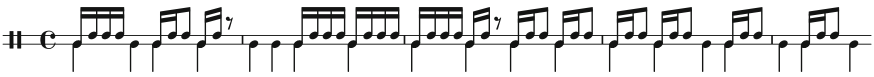

Fig. 6 First digits of π's expansion in base 4 (3.021003331222202020), expressed through pure rhythm. Patterns now occur in a way that becomes much easier to identify by ear

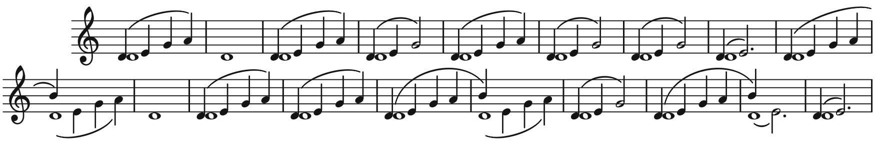

Fig. 7 First digits of π's expansion in base 5 (3.032322143033432411), played along a pentatonic scale. The specific colour of this scale adds to the fascinating, hypnotic effect of the repetitive counting pattern

Fig. 8 First digits of π's expansion in base 12 (3.184809493B918664573A6211BB151551 A05729290A780)…

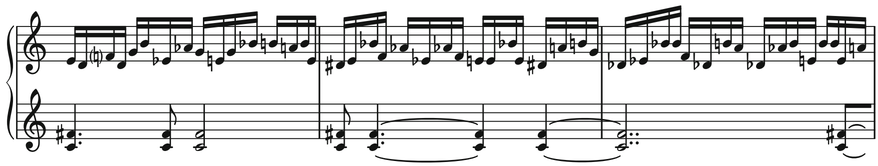

Fig. 9 …And back to base 10, but with a twist: a second voice provides the two pitches missing from the total chromatic space

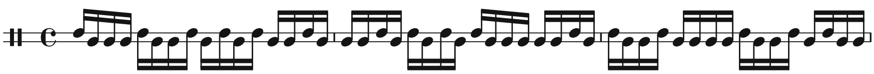

Fig. 10 First "phigits" of π's expansion in the golden base (100.0100101010010001010101 0000010100100001001010100). Unlike base 2, this expansion is not evenly distributed between zeroes and ones, which makes performing it as a rhythm more dynamic and captivating

- **Rhythms**, which include the duration of notes and rests, but as well the number of repetitions of a note or a group of notes (Fig. 2). This even extends to the quantity of events within a single structural unit (e.g. the number of notes in a measure; Fig. 3).
- **Absolute pitch**, as the degrees of the diatonic scale (Fig. 4) that are often numbered with Roman numerals or designated with letters of the alphabet. Since the twentieth century, it is even possible to designate a pitch by its periodic frequency in hertz.
- **Relative pitch**, or the interval between a pitch and another one, played either in a sequential or simultaneous manner. By counting the number of semitones between two notes, it is possible to establish detailed metrics of chords and harmonies (Fig. 5), although base 10 may not be the most appropriate system here, as we will see. In a similar line of thought, the *Tonnetz* (described in a later section) is an original and interesting tool.

In many cases, expressing a number or a mathematical operation through musical elements requires to first find the most appropriate **numeral base**. While we are used to manipulating numbers in a base 10 scheme, musical organization tends to be conceived in entirely different ways.

- Beats and measures are often counted in units that are 2^x, leading to a measurement system in base 4 (the four-bar “hypermeasure” that is the bread-and-butter of European Common Practice musical bar structure) or base 8 (the “count to eight” more common for dancers). At a lower level, sixteenth notes are prevalent in many Western musical traditions: Fig. 6 is an attempt to express the number π in a manner more suitable to such musicians.
- The diatonic scale, an omnipresent seven-note construct in many different musical traditions (to begin with the Western one), would therefore require to count in base 7. Pentatonic scales, which comprise five notes, are found in many Eastern cultures: Fig. 7 is generated again from the number π, in base 5.
- The chromatic scale, used since the time of Pythagorean theorists, requires the partitioning of a musical octave in a 12-semitone scale. Today, this scale is a strict geometric series (where each note is incremented by a factor of $2^{1/12}$), at the basis of the traditional 12 equal temperament system (henceforth 12-ET system).

While the ubiquity of 12-ET makes base 12 an obvious choice for turning numbers into notes, it is nevertheless possible to cheat through various means of musical cunning. For example, a ten-note set can be derived from the 12-note space by omitting two notes from the chromatic collection, i.e. by removing them altogether, or by making them into pedal or drone tones. Compare, for example, Figs. 8 and 9 where the number π is expressed in proper base 12 and in base 10; the harmonic language becomes perceptibly poorer, but remains musically interesting.

Different numeral bases may be also be combined: for example, an integer sequence in base 10 may provide intervals between notes as seen above (Fig. 5), while another sequence in base 2 will determine, for each of these notes, whether

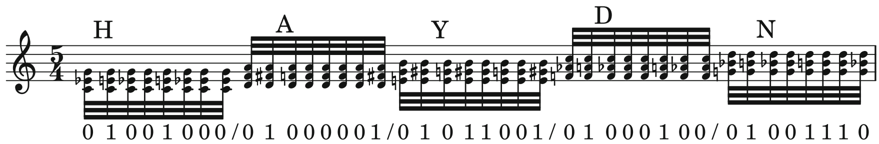

Fig. 11 A wholly impractical way of turning words into notes: letters are encoded in UTF-8, then expressed in binary and converted into minor and major triads!

the melody must go up or down—and other sequences in other bases may even be used at the same time, for example to determine durations and dynamics. Thus, music may be generated procedurally while remaining diverse and surprising.

Furthermore, other numeral bases may be of interest to musicians, for example when using microtonal resources (translating hexadecimal numbers into 16-ET pitches and so on), or specific modal scales that are not octave-bound. Even simpler, the binary base remains an useful engine to switch between two possible choices (e.g. between "up" and "down" as mentioned above, or between major and minor triads, as illustrated in Fig. 11). Lesser-known is the *phinary* base[4] (built upon the ϕ "golden ratio" number), which allows for a very surprising syntax—where, for example, "11" may be rewritten as "100"—that is prone to generate some exciting rhythmic structures.

Translating words into pitches has also been challenging for many centuries; where many composers opted to use only letters from A to G (and H in German, which is evidently convenient when B-A-C-H is involved), some astute tricks had to be found (e.g. translating S into *Es*, meaning "E flat"). Others opted to simply cycle through the diatonic scale, thus reducing each additional letter to its modulo. Which is why, when several French composers wrote musical tributes to Haydn in 1908, the letters Y and D had to be played as a repeated note (a choice bitterly disputed by Saint-Saens who, alongside with Fauré, refused to have any part in it for that very reason). As a matter of fact, we have yet to find a definite, practical way of translating the whole alphabet into distinct pitches.

Combinatorial Procedures

Combinatorial composition has always been an essential part of Ou*x*po activity—in an article included in *La Littérature Potentielle* (Oulipo 1973), French mathematician and Oulipo member Claude Berge starts by referring to both Leibniz's *De Arte Combinatoria* (1666) and Euler's *Briefe an eine deutsche Prinzessin* (1769). Another Oulipo member with a specific interest in systematic combinations was Raymond Queneau, who turned the medieval *sextine*'s permutation scheme (based

[4] This base was first described by George Bergman at a very young age: he was fourteen when his paper was published (Bergman 1957), but is said to have written it two years earlier.

Fig. 12 Combinatorics at its most extreme: Tom Johnson's *Chord Catalog* for keyboard (1985) is performed by sequentially playing all of the 8178 chords possible within one octave

on a set of six-verse stanzas) into a much more complete and rational tool, opening the way to an entire field of new poetic forms: *terine*, *quatrine*, and ultimately, *quenines* and *pseudo-quenines* of any order.

Such procedures are gladly used by Oumupo, even more happily so since music provides us with ways of taking advantage of these schemes as two-dimensional matrices. Another, more recent example of an interesting combinatorial game is the *Eodermdrome*, a recombination of a five-element set using specific paths through a non-planar graph. This was initially described by G. Bloom, J. Kennedy and P. Wexler in 1980, then introduced in France by Oulipo member Jacques Roubaud, and expanded upon by the Oulipo list, which in turn brought it to our attention.

Music, compared to literature, is combinatorially agnostic: the constraint of meaning attributed to words that make certain literary combinations valid and others not, tends to lose its relevance in music. For example, the word *note* can have its letters reorganized into *tone*, or the proper noun *Eton*, whereas *neto* (a Spanish word) is not in the English lexicon, and *eotn* does not appear to be a word in any language. Musical notes, on the other hand, can be combined in any order and carry a subjective argument in musical time. Therefore, we Oumupo composers are often prone to present every possible result of a given musical set (an example of which may be seen in Fig. 12), rather than having to make arbitrary choices based on whether we like some results more than others.

Several classic mathematical tools can be used to articulate music's combinatorial potential: magic squares, symmetry, Pascal's triangle, the sieve of Eratosthenes, prime numbers and many others. Stochastic processes may also be of use, although the strictest Ou*x*po line of thought tends not to be interested in pure randomness; what follows is an example toeing the line of our field of study.

Attractors

Attractors are a tool used by composers looking for music that contains qualities of both structure and chaos.

One interesting example of attractors in music comes from the Moscow-based composer Sergei Zagny (born in 1960), whose electronic composition *Formula 1*

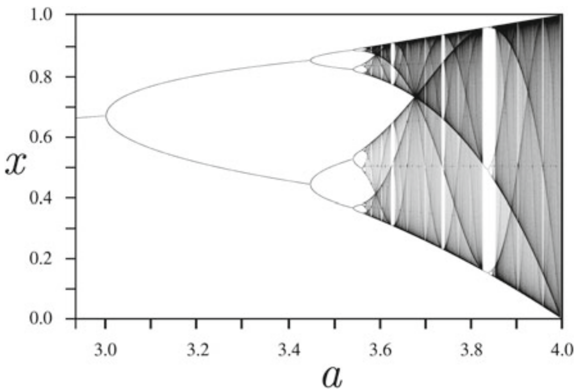

Fig. 13 Bifurcation diagram for Verhulst's "logistic map"

```
a = 2.6; x = 0.5; ct = 0;
While[ct <= 30, ct++; x = N[a*x*(1 - x)];
Print[ct, "  ", x]]

0.652        0.59153      0.6282324    0.6072475    0.6200956    0.6125017
0.6170938    0.6143529    0.61600210   0.61501311   0.61560712   0.61525113
0.61546514   0.61533715   0.61541316   0.61536717   0.61539518   0.61537819
0.61538820   0.61538221   0.61538622   0.61538423   0.61538524   0.61538425
0.61538526   0.61538527   0.61538528   0.61538529   0.61538530   0.61538531
0.615385     ...
```

Fig. 14 With $a = 2.6$ and $x = 0.5$ as a starting point, x becomes 0.65 then 0.59, 0.62, 0.61, etc., until it stabilizes at 0.615385

(Zagny 2000) is based on mathematical equations elaborated by the Belgian mathematician Pierre-François Verhulst (1804–1849). In 1845, Verhulst described a possible model for animal population growth through an equation that came to be known as the "logistic map" (Verhulst 1845): a variable x (which must always stay between 0 and 1) is recursively multiplied by $(1 - x)$ and then by a factor a (that can be defined between 0 and 4). The resulting curve (illustrated as a bifurcation diagram in Fig. 13) has both chaotic and fractal properties, which makes it particularly interesting for musical purposes.

Using different initial values for a, we can observe the following iterative results, as detailed in Figs. 14, 15 and 16.

Although not a member of Oumupo, Zagny demonstrates a relevant approach to automated composition, where controlled chaos remains both ordered and reproducible. Thus, attractors illustrate an underlying thema through most of our own musical research, as elaborated below: the tense equilibrium between unpredictability and determinism.

```
a = 3.56994; x = 0.5; ct = 0;
While[ct <= 30, ct++; x = N[a*x*(1 - x)];
Print[ct, "␣␣", x]]

0.8924852   0.3425553   0.8039914   0.5625865   0.8785026   0.3810437
0.8419688   0.4750099   0.89025510  0.34878611  0.81085612  0.54751813
0.88442414  0.36491215  0.82733816  0.50996617  0.8921318   0.34354919
0.80510320  0.56016621  0.87956222  0.37817323  0.83950124  0.48101125
0.89119826  0.34615727  0.80799328  0.55384229  0.88213630  0.37117431
0.833238    ...
```

Fig. 15 $a = 3.56994$, which is one of Feigenbaum's constants. The result is much more chaotic. In spite of the large differences between later smaller significant figures, the system audibly alternates between two poles—one close to 0.8 and the other close to 0.5. The attractor thus becomes seemingly periodic

```
a = 3.745; x = 0.5; ct = 0;
While[ct <= 100, ct++; x = N[a*x*(1 - x)];
Print[ct, "␣␣", x]]

0.936252    0.2235243   0.6499864   0.8520045   0.472226    0.933367
0.2329368   0.6691459   0.82910610  0.53062711  0.93273712  0.23495613
0.6731714   0.82394615  0.54324616  0.92924617  0.24622518  0.69506619
0.7937520   0.61309721  0.88834822  0.37145123  0.87436424  0.41139425
0.90684826  0.31635927  0.80995328  0.57646429  0.91435430  0.29327331
0.77620432  0.65054933  0.8513734   0.47388935  0.93369736  0.23184237
0.66695238  0.83186539  0.52379640  0.93412941  0.23043642  0.66412143
0.83537644  0.51502445  0.93540546  0.22628347  0.65567148  0.84549549
0.4892250   0.93581551  0.22494552  0.65292153  0.84867454  0.48095855
0.93489256  0.22795457  0.65908658  0.8414759   0.49957660  0.93624961
0.22352662  0.6499963   0.85199864  0.47223465  0.93336366  0.23292767
0.66912668  0.82912969  0.5305770   0.9327571   0.23491372  0.67308573
0.82405574  0.54298175  0.92933276  0.2459577   0.69454378  0.79451379
0.61141780  0.8897681   0.36733582  0.87033883  0.42262184  0.91382785
0.29490886  0.77872687  0.64530888  0.85717689  0.45848390  0.92979591
0.2444692   0.69169993  0.79862694  0.6022895   0.89707396  0.34578797
0.84718898  0.4848399   0.935388100 0.226337101 0.655782    ...
```

Fig. 16 $a = 3{,}745$. After a few iterations, we reach the "period five window", where the attractor loops around five values that begin, respectively, with 0,8, 0,5, 0,9, 0,2 and 0,6. This configuration is less stable, and the numbers obtained are completely dispersed. Nevertheless, if one listens to the result in time, one can hear an emergent logic in a random alteration between five distinct values. In this way, music may reveal more clearly what a purely numerical system often obfuscates (graphical representations also are an efficient tool in this regard, as illustrated in Fig. 13)

Tracing Paths Through the *Tonnetz*

The *Tonnetz* (tone-network) is a geometrical structure originally introduced by the Swiss mathematician Leonhard Euler (1707–1783). First in 1739, then in his 1774 treaty *De harmoniæ veris principiis per speculum musicum repræsentatis* ("On the actual principles of harmony as represented in a musical mirror"),[5] Euler introduces a representation of musical pitch in a two-dimensional space (see Fig. 17, left). The space's two axes are the perfect fifth and the major third. After the octave, these are the two most "consonant" intervals, meaning that their relation can be expressed with low integer ratios (respectively 3:2 for the perfect fifth and 5:4 for the major third).

[5]A comprehensive list of Euler's work may be found on the Euler Archive's website; see bibliography.

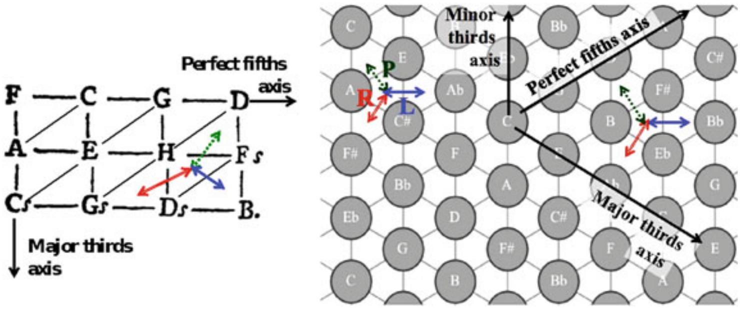

Fig. 17 Symmetries in the *Tonnetz*: three transformations of a B major triad (B-D♯-F♯ or H-Ds-Fs in German), in Euler's representation (left) and in the model preferred nowadays (right)

The modern version of the *Tonnetz*, more commonly used in contemporary musical discourse (see Fig. 17, right), makes use of these two axes and adds a minor third axis so that the two-dimensional plane is now divided into triangles. By construction, one side of every triangle always is a perfect fifth, so that all triangles correspond to major and minor triadic chords. Moving outward from the barycenter of the triangle (e.g. corresponding to C-E-G), one notices three major axes of symmetry that allow for paths through the *Tonnetz* that are achieved by changing one of the three chordal notes by one semitone or one whole tone at most.

- The *relative* chord (*R*)—C-E-A in the above example.
- The *parallel* chord (*P*)—C-E♭-G.
- The *leading-tone* chord (*L*)—B-E-G.

An interesting consequence of this partitioning is that major chords only ever lead to minor chords and, inversely, minor chords only ever lead to major chords.

From this triangulation of the musical plane, one can derive its dual graph: a hexagonal tiling (not unlike a bee's nest) where every note finds itself at the centre of a hexagon surrounded by six summits—the six notes with which it can form a major or minor chord. By means of the three operators *R*, *P* and *L*, all of which preserve two out of three notes in a three-note chord and change the moving note by no more than a whole tone, one can navigate through the lattice to create harmonic progressions that only require minimal voice-leading (Andreatta and Baroin 2016).

Of the many different paths that can be traced through the *Tonnetz*, some have particularly interesting qualities. For example, from any given chordal point on a hexagon in the *Tonnetz*, it is possible to create a path that exhausts all twenty-four major and minor chords without repetition. We call this path a *Hamiltonian* traversal—the word Hamiltonian coming from an analogous operation in graph theory. If a path is cyclic, one calls it a "Hamiltonian cycle". An exhaustive research has shown that there are 124 of these Hamiltonian cycles through the *Tonnetz* that can be classified according to their internal symmetries. There are, for example, cycles that zigzag because they are comprised of only two elemental symmetries (e.g. alternating *L* and *R* operations). Other cycles traverse the 24 major and minor

1. C-Cm-A♭-A♭m-E-C♯m-A-Am-F-Fm-C♯-B♭m-F♯-F♯m-D-Dm-B♭-Gm-E♭-E♭m-B-Bm-G-Em ⟶ PLPLRL
2. C-Cm-A♭-Fm-C♯-C♯m-A-Am-F-Dm-B♭-B♭m-F♯-F♯m-D-Bm-G-Gm-E♭-E♭m-B-A♭m-E-Em ⟶ PLRLPL
3. C-Cm-E♭-E♭m-F♯-F♯m-A-C♯m-E-Em-G-Gm-B♭-B♭m-C♯-Fm-A♭-A♭m-B-Bm-D-Dm-F-Am ⟶ PRPRPRLR
4. C-Cm-E♭-E♭m-F♯-B♭m-C♯-C♯m-E-Em-G-Gm-B♭-Dm-F-Fm-A♭-A♭m-B-Bm-D-F♯m-A-Am ⟶ PRPRLRPR
5. C-Cm-E♭-E♭m-F♯-B♭m-C♯-Fm-A♭-A♭m-B-Bm-D-F♯m-A-C♯m-E-Em-G-Gm-B♭-Dm-F-Am ⟶ PRPRLRLR
6. C-Cm-E♭-Gm-B♭-B♭m-C♯-C♯m-E-Em-G-Bm-D-Dm-F-Fm-A♭-A♭m-B-E♭m-F♯-F♯m-A-Am ⟶ PRLRPRPR
7. C-Cm-E♭-Gm-B♭-B♭m-C♯-Fm-A♭-A♭m-B-E♭m-F♯-F♯m-A-C♯m-E-Em-G-Bm-D-Dm-F-Am ⟶ PRLR
8. C-Cm-E♭-Gm-B♭-Dm-F-Fm-A♭-A♭m-B-E♭m-F♯-B♭m-C♯-C♯m-E-Em-G-Bm-D-F♯m-A-Am ⟶ PRLRLRPR
9. C-Em-E-A♭m-A♭-Cm-E♭-Gm-G-Bm-B-E♭m-F♯-B♭m-B♭-Dm-D-F♯m-A-C♯m-C♯-Fm-F-Am ⟶ LPLPLR
10. C-Em-E-A♭m-B-E♭m-E♭-Gm-G-Bm-D-F♯m-F♯-B♭m-B♭-Dm-F-Am-A-C♯m-C♯-Fm-A♭-Cm ⟶ LPLRLP
11. C-Em-G-Gm-B♭-B♭m-C♯-C♯m-E-A♭m-B-Bm-D-Dm-F-Fm-A♭-Cm-E♭-E♭m-F♯-F♯m-A-Am ⟶ LRPRPRPR
12. C-Em-G-Gm-B♭-B♭m-C♯-Fm-A♭-Cm-E♭-E♭m-F♯-F♯m-A-C♯m-E-A♭m-B-Bm-D-Dm-F-Am ⟶ LRPRPRLR
13. C-Em-G-Gm-B♭-Dm-F-Fm-A♭-Cm-E♭-E♭m-F♯-B♭m-C♯-C♯m-E-A♭m-B-Bm-D-F♯m-A-Am ⟶ LRPR
14. C-Em-G-Bm-B-E♭m-E♭-Gm-B♭-Dm-D-F♯m-F♯-B♭m-C♯-Fm-F-Am-A-C♯m-E-A♭m-A♭-Cm ⟶ LRLPLP
15. C-Em-G-Bm-D-Dm-F-Fm-A♭-Cm-E♭-Gm-B♭-B♭m-C♯-C♯m-E-A♭m-B-E♭m-F♯-F♯m-A-Am ⟶ LRLRPRPR
16. C-Em-G-Bm-D-F♯m-A-C♯m-E-A♭m-B-E♭m-F♯-B♭m-C♯-Fm-A♭-Cm-E♭-Gm-B♭-Dm-F-Am ⟶ LR
17. C-Am-A-F♯m-F♯-E♭m-E♭-Cm-A♭-Fm-F-Dm-D-Bm-B-A♭m-E-C♯m-C♯-B♭m-B♭-Gm-G-Em ⟶ RPRPRPRL
18. C-Am-A-F♯m-F♯-E♭m-B-A♭m-A♭-Fm-F-Dm-D-Bm-G-Em-E-C♯m-C♯-B♭m-B♭-Gm-E♭-Cm ⟶ RPRPRLRP
19. C-Am-A-F♯m-F♯-E♭m-B-A♭m-E-C♯m-C♯-B♭m-B♭-Gm-E♭-Cm-A♭-Fm-F-Dm-D-Bm-G-Em ⟶ RPRPRLRL
20. C-Am-A-F♯m-D-Bm-B-A♭m-A♭-Fm-F-Dm-B♭-Gm-G-Em-E-C♯m-C♯-B♭m-F♯-E♭m-E♭-Cm ⟶ RPRLRPRP
21. C-Am-A-F♯m-D-Bm-B-A♭m-E-C♯m-C♯-B♭m-F♯-E♭m-E♭-Cm-A♭-Fm-F-Dm-B♭-Gm-G-Em ⟶ RPRL
22. C-Am-A-F♯m-D-Bm-G-Em-E-C♯m-C♯-B♭m-F♯-E♭m-B-A♭m-A♭-Fm-F-Dm-B♭-Gm-E♭-Cm ⟶ RPRLRLRP
23. C-Am-F-Fm-C♯-C♯m-A-F♯m-D-Dm-B♭-B♭m-F♯-E♭m-B-Bm-G-Gm-E♭-Cm-A♭-A♭m-E-Em ⟶ RLPLPL
24. C-Am-F-Dm-D-Bm-B-A♭m-A♭-Fm-C♯-B♭m-B♭-Gm-G-Em-E-C♯m-A-F♯m-F♯-E♭m-E♭-Cm ⟶ RLRPRPRP
25. C-Am-F-Dm-D-Bm-B-A♭m-E-C♯m-A-F♯m-F♯-E♭m-E♭-Cm-A♭-Fm-C♯-B♭m-B♭-Gm-G-Em ⟶ RLRPRPRL
26. C-Am-F-Dm-D-Bm-G-Em-E-C♯m-A-F♯m-F♯-E♭m-B-A♭m-A♭-Fm-C♯-B♭m-B♭-Gm-E♭-Cm ⟶ RLRP
27. C-Am-F-Dm-B♭-Gm-G-Em-E-C♯m-A-F♯m-D-Bm-B-A♭m-A♭-Fm-C♯-B♭m-F♯-E♭m-E♭-Cm ⟶ RLRLRPRP
28. C-Am-F-Dm-B♭-Gm-E♭-Cm-A♭-Fm-C♯-B♭m-F♯-E♭m-B-A♭m-E-C♯m-A-F♯m-D-Bm-G-Em ⟶ RL

Fig. 18 Twenty-eight Hamiltonian cycles with an internal periodicity

chords without internal symmetries, i.e. without any recurring sub-pattern. Figure 18 inventories the 28 Hamiltonian cycles in the *Tonnetz* having internal symmetries. We find here, in positions 16 and 28, two zigzag configurations that allow one to visit every possible minor and major chords once and once only (the first solution actually being a retrogradation of the second one, and conversely).

It is worth noting that all other paths generated by the repetition of a couple of symmetric operations, such as *PR* or *LP*, will create chord progressions that are shorter than 24. These two non-Hamiltonian cycles are represented in Fig. 19.

The classification of chord progressions in the *Tonnetz* opens up a wide array of possibilities in the study of musical harmonic organization. From an Oumupo point of view, it gives way to new experiments in composition and writing, particularly in sub-genres that masquerade as “pop” music but actually rely on formal, learned and constraint-based writing. *Hamiltonian Songs* are now the subject of concerts and workshops; in 2016 a Hamiltonian Cabaret, proposed by Fabrice Guedy, Moreno

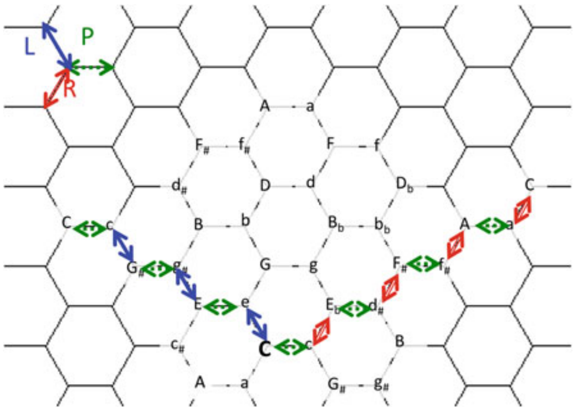

Fig. 19 Two "zigzag"-shaped harmonic cycles that encompass less than 24 chords: *PR* then *LP*, respectively, 8- and 6-chord long

Andreatta and French singer-songwriter Polo, allowed students to dive into this universe for an entire week. They created a song whose harmonic structure (see Fig. 20) is based on one of the periodic Hamiltonian cycles listed above.

Putting a limited set of resources in the most efficient and rational order has long been an obsession of all Ou*x*po groups, to begin with Oulipo; one is reminded, for example, of the so-called Knight's Tour that Georges Perec used in *Life, A User's Manual* (1978), envisioning his whole "novels" as a 10 × 10 chessboard.

Hamiltonian graphs demonstrate, once more, the flexibility of music in comparison with words and letters. Using all 24 triadic chords without any repetition (or, in the case of serial music, all 12 tones of a given series) seems far more

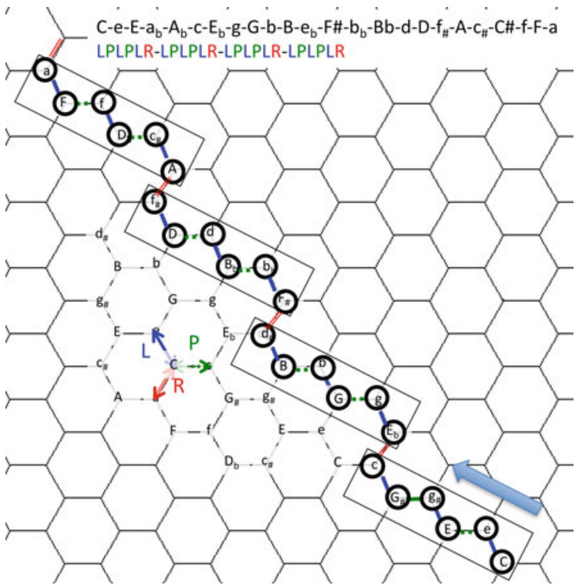

Fig. 20 Hamiltonian cycle underlying a *Ballade-Marabout* written collectively by students of Paris Sciences and Lettres (PSL). The cycle involved here is listed as #9 in Fig. 18; it is comprised of four periodic blocks of six chords each

achievable than, for example, the elusive *heteropangram* which the Oulipo list has spent decades striving to achieve: a sentence of 26 letters where no letter is used more than once… and that still makes sense.

Melodic Generation and Transformations

Beyond their apparent simplicity, some melodies can prove to be fairly complex objects as soon as one attempts to describe them in rational or procedural terms. This has been one of Tom Johnson's fields of study long before he became a member of Oumupo, from his *Rational melodies* (1982) to more recent works (Johnson 1996).

Such experiments, needless to say, have existed for many centuries; to name but one, examples of **canons** are found as early as the fourteenth century (and probably even predate musical palindromes, which we mentioned previously). Numerous composers, including the well-known J. S. Bach, have proven that a melody can act as a counterpoint to itself, when either shifted by a certain duration, reversed ("crab canon") or played simultaneously at different tempos. More recently, the study of canons has gained new traction following Dan Tudor Vuza's work on their rhythmic structures (Vuza 1991–1992). A relatively new field in musical composition, the so-called tiling canon is of particular interest to Oumupo, and with some help from the Oulipo list, we have even tried to account for the possibility of multi-layered lyrics, whose meaning evolve when additional syllables are interpolated between different voices.

Another example of structures that are both melodic and "potentially" polyphonic is provided by **self-similar melodies**, i.e. melodies that replicate themselves at different timescales (not unlike fractals in the mathematical realm).

Concretely, the melody re-articulates itself by only playing one note out of every *n* notes (see Fig. 21). In the most complex cases, *n* can change but the melody remains invariant. This property has notably been explored by Tom Johnson in his 1998 octet *La Vie Est Si Courte* (Fig. 22).

The whole point of Ou*x*po schools of thought is to restrict the number of possibilities, thereby limiting the author's reliance on arbitrary choices or, *horrescimus referens*, "inspiration". Which does not exonerate authors of any control nor responsibility: some choices still have to be made (the least of which is indeed not *which* formula to choose in the first place); furthermore, musical composition has always been a point of tension between artistic freedom and formal determinism.

With this in mind, one can notice that where forms such as canons and self-similarity define a set of criteria that allow us to choose between multiple possible melodies (or even to adapt a pre-existing melody by somehow making it fit, more or less artificially, inside the requisite frame), they still do leave a lot of room for many "potential" solutions to the problem at hand. Hence the need for

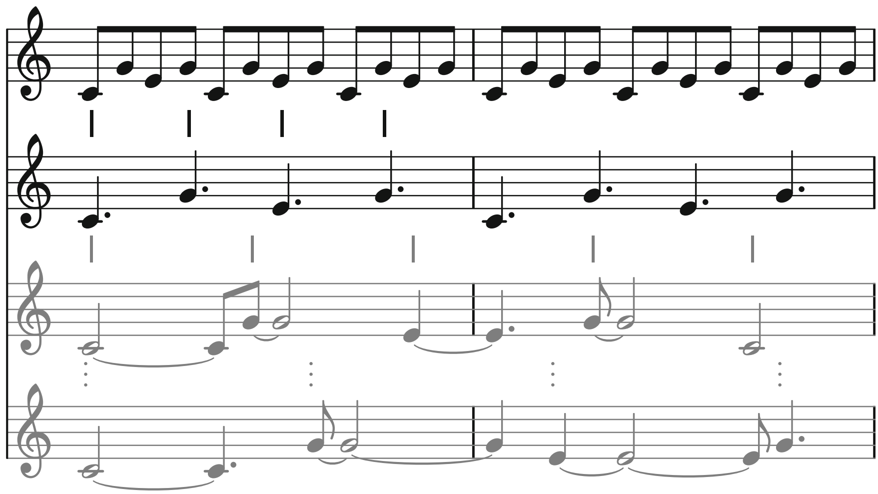

Fig. 21 So-called Alberti bass happens to be a self-replicating loop: one can find the exact same melody when playing only every third note, but this property is also verified with other ratios such as 5 or 7

Fig. 22 *La Vie Est Si Courte*, T. Johnson (1998)

another kind of tools: "generative" constraints, where one can let an algorithmic automaton roam free and generate the *whole melody*.

An example of such a process is as simple as it is fascinating: the **Dragon Curve**, first described by Martin Gardner in a 1967 issue of *Scientific American* (Gardner 1967), has become a familiar and popular entry into mathematical concepts… but few have applied it to the creation of a musical score.

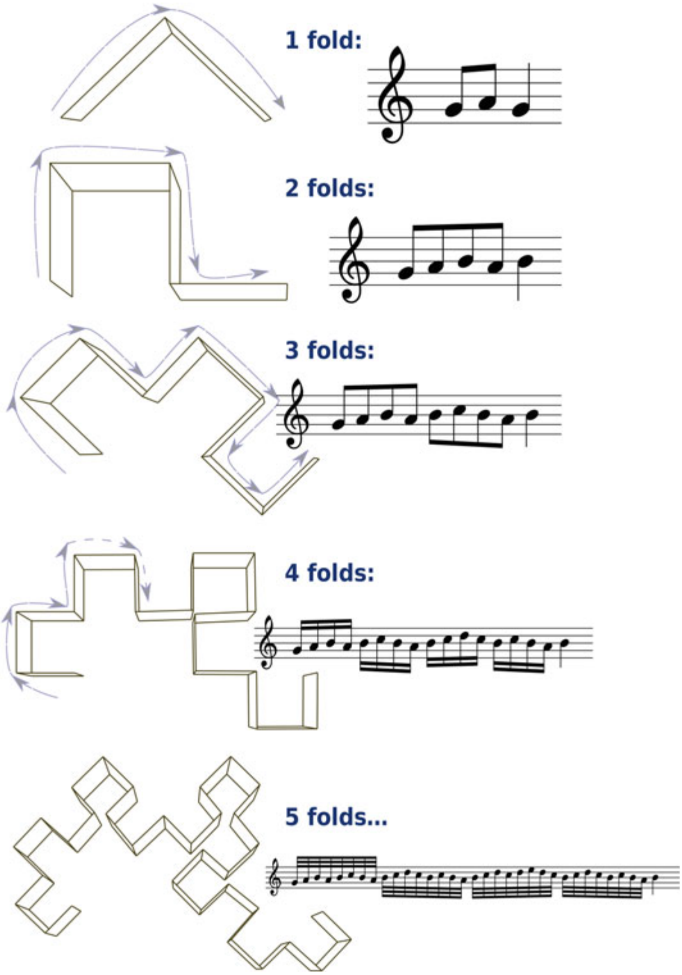

Fig. 23 How to tuck your dragon

We all know the simple game of folding a slip of paper n times in the same direction and then unfolding the paper to see the final form. The complexity of the exercise increases according to the number of folds (as demonstrated in Fig. 23). This "Dragon Curve" possesses several interesting properties (fractal, self-similar, symmetric but non-periodic, etc.). The curve can also be read as a series of melodic movements: for each "bump" in the paper, go up one note; for each dip in the paper, go down by one note.

One can hardly fail to notice that for every extra fold, the melody becomes more and more complex, but also more and more maze-like and mysterious—even more so if a specific, non-standard scale has been chosen in the first place, for example a modal scale such as C D♯ E F G A♭B for a somewhat exotic effect. This goes to

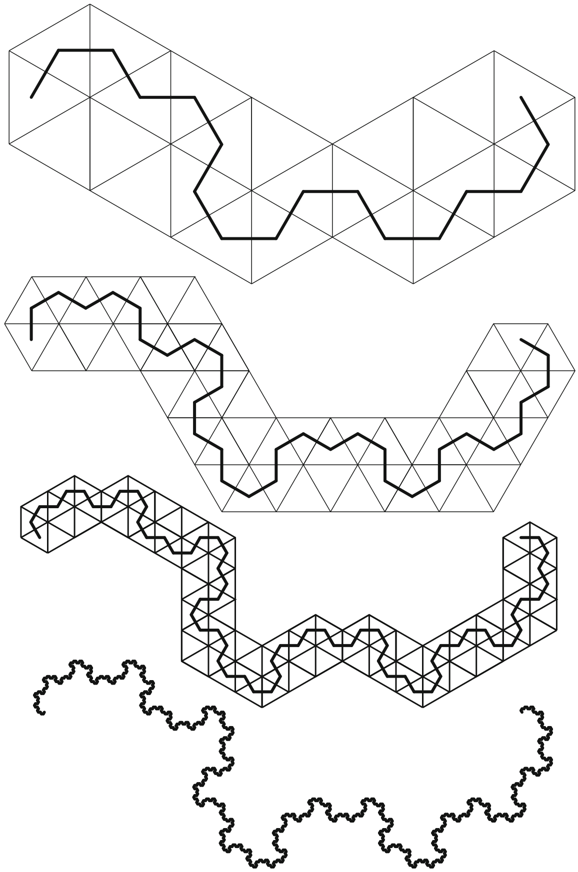

Fig. 24 How often do you get to see a dragon in a honeycomb?

illustrate the tension stated above between freedom and determinism: different composers will make different choices, and therefore get different musical outcomes.

This recreational game was the basis of a piece written by Tom Johnson in 1979 for a student orchestra, *Dragons in A*. The simplicity of its procedural engine allows children to understand the experiment, reproduce it and possibly make it their own, which highlights an essential aspect of Oumupo's pedagogical subtext: by demystifying musical composition and turning it into an accessible game that is both logical and playful, we hope to reconcile the broadest, most diverse audience with contemporary artistic creation.

The Dragon Curve has been happily adopted by several other Oumupo contributors in new, unforeseen ways. Figure 24 shows an example where the curve has been given additional dimensions by iterating 120° angles instead of right angles, and then running it through a *Tonnetz*.

Melodies and harmonies generated by the Dragon Curve are yet another case where music, through its breathtaking and hypnotic beauty, allows one to "hear" mathematical constructs and to comprehend them in exciting new ways.

A Potential Conclusion?

Starting with the assumption that music is much more flexible than literature with respect to the combinatory potential of its own material, we have presented some of the ideas that Oumupo has set out to explore in recent years.[6]

Although mathematics are an integral part of our activity (and the same could be said of any musician), we have also made it a point to engage as much as possible with other languages, especially by exchanging with Ou*x*po groups that apply similar tools and methods to other expressive media—to begin with Oulipo, our historical common reference.

Much like Oulipo does not define itself as a literary movement, all Oumupo members pursue a creative career of their own by taking inspiration from our collective reflection on constraint-based writing, and in turn influence ongoing projects with their own research field and interests. Far from being felt as limiting, these constraints are a source of freedom and artistic courage to all of us. To paraphrase Georges Perec: "At the end of the day, I give myself constraints in order to be entirely free".

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All musical examples were typeset using GNU LilyPond (http://lilypond.org), an integral tool in many of our experiments and daily creative activities.

Like all our collective publications, a version of this article is available under a free license on Oumupo's web site (https://urldefense.proofpoint.com).

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Martin Granger is a writer, comedian, musician and performer. After a brief stint as a journalist, he has engaged in a multifaceted and never-predictable artistic career. He has been part of several bands a singer, musician and songwriter, but also co-wrote and starred in shows that ally music and theatre. In various cultural and socio-educational settings, he also teaches creative writing, songwriting and musical workshops.

Tom Johnson was born in Colorado in 1939. He studied music at Yale University and composition privately with Morton Feldman. After 15 years in New York, he moved to Paris, where he has lived since 1983. A rigorous minimalist, he builds upon limited material using logical and mathematical processes; many of his works involve some level of conceptualism or theatricality. His abundant catalogue includes operas, instrumental pieces, radio creations, as well as numerous reports and essays.

Valentin Villenave is an author and musician, although he may rather describe himself as an activist (promoting free, universal access to culture and knowledge, through the use of "libre" licenses in software and art). He mainly spends his time teaching and writing; in addition to dozens of essays and music scores, he has written hundreds of pedagogical short pieces. He has founded the current Oumupo group in 2011.

Edith Piaf, Billie Holiday, and Elisabeth Schwarzkopf Making Music Together

Georges Bloch and Jérôme Nika

Abstract Billie Holiday, Edith Piaf, and Elisabeth Schwarzkopf are three great musical ladies, born in 1915. Could we make them singing together? This was the goal of a performance made for a music festival in L'Aquila (Italy) in 2015. This raises musical questions: what kind of sound could link Billie Holiday to Schwarzkopf, Schwarzkopf to Piaf? What kind of musical structure? With the help of the software ImproteK, the three ladies eventually sang together *Autumn Leaves* and *The Man I love*. ImproteK allowsmony of the used material (called "memories") to the harmonic progression of the reference song (called "scenario"). The machine can also include into its "memory" what is currently played during the performance. This process raises fascinating questions about musical notation and style: the chosen common notation will define how the improvisation will follow the reference scenario, where the chosen memories inds and character interacting with this structure. The result can be arresting, surrealistic, kitsch; it is often fun.

Introduction

What is Schwarzkopf doing here? Having Edith Piaf and Billie Holiday singing together is crazy enough, but why add Elisabeth Schwarzkopf? Because she was also born in 1915? When the "Three Ladies Project" was born, the main question was: how to deal with Schwarzkopf? Giving a tribute to three ladies meant finding common points and differences between them. As an artistic project, an approach based on "hybridization" was chosen: we tried to find points of resonance in the repertoire and style of the three singers. The climax of the project was to have the three ladies singing together by the means of the ImproteK software. ImproteK is a part of the family of stylistic re-injection systems in the line of the OMax software

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and is to generate musical phrases planned on a relatively large scale and defined by reference to a piece called "scenario."

A "scenario" is a structural notation of this reference piece. The vocabulary (symbols) used for this notation can be adapted to the style of music used. In theory, ImproteK can use any pieces of recorded music to generate a new musical material matching this scenario (as long as the recordings are annotated with the exact same notation). All these recorded pieces, time-stamped with the same vocabulary, constitute a repertoire called "memory." Of course, ImproteK finds solutions more easily either with bigger memory or when the structure of the memory is similar to that of the scenario. Practically, the usual notation for ImproteK is very similar to the harmonic notation of jazz standards (although very different descriptions have recently been used).

In this project, the question of notation was crucial, since, even for jazz standards, a common musical notation is not obvious. The jazz notation is not strictly standardized. Moreover, most pieces sung by Schwarzkopf can hardly be related to jazz; notating the harmony of a Mahler song using a jazz notation, for instance, can become very tricky. The use of a functional notation was preferred, but strong aesthetic choices had to be made in notating all the pieces used, whether as reference (scenario) or as memory.

In dealing with hybridization, this paper discusses two different but complementary topics. One is a description of the relevant features of ImproteK software regarding musical hybridization. The other one relates the musical path followed by Hervé Sellin and Georges Bloch, in order to explore hybridization processes. First, they composed hybrid pieces "by hand" (without the use of any machine); this work explored what could be a reference piece (called "scenario" in ImproteK environment), and of how a notation could imply some kind of style or structure. Then, with the help of Jérôme Nika, they actually set up ImproteK performances, with Sellin improvising with the three ladies, based on two "scenarios," *Autumn Leaves* and *The Man I Love*. The "memories" consisted of five to six annotated pieces chosen from the ladies' recordings.

The choice of the notation, the playing mode, the variable emphasis on the reference or on the memory will be discussed. The result was often arresting, with some surrealistic edge, in any case very enriching.

"Three Ladies": An Hybrid Anniversary

It Should Have Been Maria Callas

In 2015, Luisa Prayer, the artistic director of *le pietre che cantano*, a yearly music festival happening in L'Aquila (Italy), asked Georges Bloch about a concert–conference celebrating the centenary of the birth of Billie Holiday, Edith Piaf, and Elisabeth Schwarzkopf. She told him: "these are three of the greatest female singers of the twentieth century. In addition, Billie Holiday and Piaf were, in some ways, very independent women in times and professional worlds in which it was very hard to be. Although we could argue about the relevance of a term like ‘the greatest’ in any art form, it is perfectly plausible to think of Billie as the greatest jazz singer, of Piaf as the greatest popular singer, in any case very great ones. Of course, for opera, it should have been Callas. A small problem: she was not born in 1915!”

Therefore, Schwarzkopf was chosen, quite a contrasting personality! Moreover, (and this goes for Callas as well) in opera and art songs, basic forms are generally longer: for broadcasting reasons, a song or a jazz standard is generally shorter than opera arias, which are also often through-composed. Furthermore, large orchestras are much more frequent in opera than in jazz or popular music. Like for all general remarks, in all cases there are numerous exceptions. Luisa Prayer asked Georges Bloch because she knew of the work in Institut de recherche et de coordination acoustique/musique (IRCAM), Paris, and École des Hautes Études en Sciences Sociales (EHESS), Paris on computer-assisted improvisation and stylistic re-injection.

Rapidly nicknamed the “Three Ladies,” this project was an interesting challenge in stylistic hybridization. Bloch decided to concentrate the performance on this subject, hybridization, and immediately contacted Hervé Sellin. Sellin, a jazz pianist, teaches also at the Conservatoire National Supérieur de Paris.[1] For his teaching, he sets up joint ventures mixing jazz and classical piano students on transversal concerts, generally based on one composer (Debussy, Messiaen, Bartók, Ellington). Not only do these ventures involve a professor in jazz (Sellin) and classical piano (like Georges Pludermacher, Bruno Rigutto, Yves Henri) but also music analysis and history professors (like Alain Mabit and Jean-François Boukobza). Sellin was an obvious candidate to address the question of hybridization.

The climax of the performance was to get the three ladies singing together with Sellin at the piano. It was also an interesting musical challenge to seek for an even thin stylistic bridge between the three ladies’ huge repertoire, whether using a machine or not. The planned performance was a kind a concert-conference, in which were presented:

- actual recordings of the three ladies,
- one song by Gustav Mahler: *Revelge* performed live by Bloch and Sellin,
- two compositions by Sellin for piano solo, exploring hybrid versions of *Revelge*, one inspired by Piaf, one by Billie Holiday, performed by Sellin,
- one composition for piano and voice by Bloch, where a tribute to the three ladies uncovered a jazz standard, performed by Sellin and Bloch,
- two performances with ImproteK, with piano live and recording of two or three ladies, based on two jazz standards, with Sellin at the piano and Bloch as computer operator.

[1] A full biography of Hervé Sellin can be found on inter-jazz.com.

Hybridization: Style, Structure, Notation

From the start, ImproteK was to be used. Therefore, if different types of hybridization composed "by hand" were to be heard during the performance, they had to be related to those offered by the software in the other pieces of "human–computer co-improvisation." It means that the whole work process in building a hybrid performance had to rely on the same concepts for hybridization.

In a Given Style, On a Given Style

ImproteK (Nika et al. 2017a) belongs to the OMax group of softwares (Assayag et al. 2006; Lévy et al. 2012). The first version of OMax was conceived around 2002. OMax is a music co-improvisation system based on the Factor Oracle automaton, conceived for on the fly pattern matching developed in 1999 by Allauzen and Crochemore (Allauzen et al. 1999). The Factor Oracle algorithm builds a graph in real time and on the fly of the repeated patterns in a symbolic sequence. The early Oracles were built with MIDI information, and the pitches were readily available with MIDI instruments. Later, sound was added through pitch detection and, later on, alphabets of spectral descriptors were used (Bloch et al. 2008; Lévy et al. 2012).

With an input recorded on the fly (or pre-recorded), OMax improvises in the style of the performer by navigating along the graph of the Oracle, and human and computer can perform a duet in real time. By triggering how often the machine "jumps," that is, departs from the recorded performance, or by selecting recorded regions of the Oracle, a computer operator can also influence the ongoing performance. Therefore, one could speak of stylistic re-injection. However, in a duet situation, the machine learns from what is currently played, but does not listen. These features have been taken into account in further developments, notably through the project SoMax (Bonnasse-Gahot 2014). But a clever re-injection of the material played by one same performer is generally sufficient to create a perception of stylistic continuity.

From the start, the OMax software was also pursuing another goal than this kind of free improvisation. Following his work on jazz chord sequences generated by Steedman's grammar (Chemillier 2004), Marc Chemillier developed a version called OMax-Beat, where the recombination of the original improvisation was carried out according to the position of the current beat in the jazz harmonic progression. This concept was enhanced through the use of audio and came to a real achievement through the ImproteK project, particularly through Jérôme Nika's Ph.D. work (Nika 2016).

In theory, we are no more dealing with stylistic, but more with style-driven re-injection, since the machine improvisation is supposedly driven by the stylistic requirements brought about by the harmonic progression of the scenario. Moreover, the original material can follow a different structure and be from a different performer. In this case, we should rather speak of style-driven injection: although possible, the feedback loop through a re-injection of the same material is not mandatory anymore.

Style: Sound or Structure?

Even in something as defined as a jazz standard, is its chord progression enough to define its style? Or, more modestly, its structure? Defining a chord progression from a common denominator, a kind of perfect, ideal *Real Book*,[2] is primarily a structural idea. It means we take this structural chord progression for a stylistic notation of a piece like *Autumn Leaves*.

This is not self-evident: many jazz musicians can be recognized by their use of specific chords. However, it does not necessarily mean that they play from a different book. They just have a personal way of realising a given chord progression. Let us imagine we have solo recordings of Ellington, Monk, and Taylor playing *Autumn leaves*.[3] By writing down carefully the actual recorded chords, we would obtain three different "scenarios" of the same piece. The chords would be different, to the point, perhaps, that even the chord collections themselves would be distinct. And, probably, only the Ellington example would correspond (in part) to the *Real Book*.

It is commonplace to note that the sound of a musician relies, in part, on his/her way to deal with harmonies. Choosing a common denominator for harmonic notation implies a preference for the most general structural description, knowing that, in exchange, the distinctive sounds of the individual performer will be lost. By giving primacy to the general structure defined (in theory) by the progression of an ideal *Real Book*, we aim at a structure-driven improvisation.

In their original conception, with OMax-Beat and later ImproteK, the effect of style-driven improvisation actually relied as much on sound re-injection than on its structural drive. The reason was simple: before working on different projects focusing on hybridization, the used material often came from a single player or group. One of the first and most regular users of OMax, OMax-Beat, and ImproteK, the jazz pianist and percussionist Bernard Lubat, used to say about machine-generated improvisations using his own musical material "it sounds really bizarre, but it is still me." The early experiments of "hybridization" he carried out with the ImproteK software consisted in making the system improvise on jazz standards using some choruses he had played on different tunes. Bernard Lubat called "étrange étranger" (strange stranger) the choruses generated by the system, and valued the fact that he did not recognize his own harmonic language in these improvisations (Chemillier and Nika 2015). Indeed, the "strangest" part came from the different character of the quoted piece and the "scenario." Yet, what we could call his "sound" (i.e., his articulation, uses of dynamics and chord colors, etc.) was preserved, and because of these consistent sound characteristics, one could still find a similarity of style.

Therefore, the real ultimate of "style-driven" machine improvisation will be achieved by mixing performers with different identities and musical genres. Only in this case can we check how a scenario could to impose, through its structure, a given "style." Of course, a more realistic and more interesting goal is to aim for some kind

[2]The *Real Book* is a popular compilation of lead sheets for jazz standards.

[3]It is a virtual example since, as far as we know, neither Monk nor Taylor did record the piece, and Duke Ellington did not play it in solo.

of compound style, mixing the structure of the “scenario” *and* the various sounds of the “memories.” It was the founding principle of the “Three Ladies” project.

Notation and Structure: la macchina infernale

But could a perfect *Real Book* exist? The first problem is that of vocabulary, that is, the collection of symbols used to notate the chords. A simple example: in a chord progression where the same performer could alternatively play A7 or A7b9, which one should be notated? Moreover, with ImproteK, but also when comparing repertoires, one must refer to similar symbols for defining both the pieces of structural reference, or scenarios, and the one we are allluding to, or memory (see section “Building the Repertoire”).

Two reason made us consider the harmony and, consequently, the chord notation, from a functional point of view. One was our search for a cross-repertoire vocabulary of chord notation (fitting, at least, for the repertoires of the three ladies). The other one was its power in defining a scenario as a complete structural entity, rather than a specific instance; because, more than the sound-texture, it is the chord progression that is notated. For *Autumn leaves*, the functional progression can be inferred from the original composition by Kosma. In the end, it does not matter that, for Ellington, C maj7 will be c-e-g-b, when it will be c-b for Monk, and when Taylor, perhaps, will play c-e-g#-a#-b. By deciding that all three pianists play the same progression, we impose the functional structure of *Autumn leaves* as our scenario.

But this virtual example is probably too easy: we *know* that the three pianists are playing the same piece. Deciding on a notation with varied repertoires is harder: the common notation becomes less obvious. Therefore, the choice of a scenario defined by structural harmony can also be preferred for its relative versatility among musical genres. It corresponds to a relatively common but very dynamic view of notation: what is notated is where we are going. Structural functions could be applied to jazz, popular music and classical music repertories.[4]

ImproteK imposes a written “scenario,” adding to the OMax paradigm some structural constraints. Therefore, we speak of “structure-driven” improvisation. But, with the fact that “real” chunks of sound are used within the system, some sound-injection takes place. These sounds still carry some, often many clues of their origin. When using improteK, a very interesting task is finding a balance between structural constraints induced by notation and sounds attached to the idiosyncrasy of the original material. What we call ‘sounds” includes the distinctive features of the individual performers and of the original material. This kind of balance could only be chosen by ear, determining what kind of “infernal machine” (to take Hervé Sellin’s words) we chose ImproteK to be.

[4]The precise chord vocabulary is described in section “Functional Notation”.

Hybridization by Hand: The Mahler Track

First, Sellin, and Bloch tried to find, if not a common sound, some common ground between the three ladies. With this knowledge, they composed pieces about the three ladies, all displaying on some kind of hybridization.

There is an obvious common feature between them, which is a direct consequence of their being born in 1915: all three women lived the generation of the booming recording industry.[5] This exceptional development of recording industry was definitely something which happened during the lifetime of the three ladies, and in which they played no minor role. All three made many recordings; Walter Legge, Schwarzkopf's husband, was one of the most famous record producers of the past century. Also, the modern microphone invented in 1933 brought about important transformations in vocal techniques, even for classical singers who did not use it for performances, but only for recording sessions.

Using Mahler as a Model

The reason for our first concentration on Gustav Mahler, a composer chosen in the very broad repertory of Mrs. Schwarzkopf, was that some of his music heralds the popular ballads of the 1930s and 40s. It is still tonal music, but its harmonic gestures are at the same time obvious (with overtly banal bass lines) and original (the voices above do rarely correspond to the implied bass).

During the concerts, Sellin and Bloch performed a Mahler Lied, *Revelge*, presented as a primary material.[6] The text of this Lied is based on *Des Knaben Wunderhorn*, a collection of pseudo popular texts collected (or written) by Arnim and Brentano at the beginning of the nineteenth century. It tells the horrendous story of a drummer, who, after marching before the house of his beloved, is, very fast, fatally wounded on the battlefield. The next day, followed by his dead comrades, his ghost wakes up to parade again in front of the house of his beloved. Not only it is very moving and effective but it also has some of the character of a popular song, and the irony of its refrain: "Trallali, Trallala" is just bloodcurdling.

For these works composed in the traditional manner, "by hand," there is a reference piece, *Revelge*, which provides a sort of scenario; it is also naturally associated

[5] Actually, we should speak about the second boom of the recording industry: audio recordings were already quite popular in the middle class at the turn of the twentieth century. In his Ph.D. dissertation, Chamoux (2015) found that more than 100 millions records were sold in France between 1900 and 1914. However, the first World War and the spread of the radio, made the recording industry collapse; these huge record sales were not equaled before the end of WWII. Other factors played a role in this re-birth, like the use of LPs and, more importantly, the modern microphone technology developed toward the end of the 1930s.

[6] This Lied is written for a male voice and Schwarzkopf never recorded it. However, the composer is obviously associated with her repertory, and several recording of Schwarzkopf singing Mahler were subsequently used with ImproteK.

to one of the ladies, even if not in her repertoire (Elisabeth Schwarzkopf). The compositions sound like versions of it, or rather variations on it, obviously connected with the other (Billie Holiday and Edith Piaf), because they display some of their distinctive gestures.

"Revelge" by Billie and Edith

The first examples of hybridization process consisted in two compositions by Sellin inspired by *Revelge*: *Revelge-Billie* and *Revelge-Piaf*. As we just said, just before hearing these compositions, the audience had heard a live performance of the original Lied by Mahler.

The effect of the original Mahler song, and even the argument of the story fit very well with Piaf, whose famous song *Mon Légionnaire* told about a tragic love affair with a soldier. *Revelge-Piaf* is a kind of "Valse-musette," in which the main themes and harmony of the Mahler song could be recognized. Notated as a jazz score, with a melody and a chord progression, its performances implied a quite large part of improvisation, as can be seen in Fig. 1.

The same notation was used for *Revelge-Billie*, shown in Fig. 2, although with a very different atmosphere. No waltz anymore: the mood is of an almost empty nightclub, every, very late, that is very early in the morning. We speak of notation for what were mostly improvised pieces, because the point of departure was a jazz-like notation that Hervé Sellin made from the Mahler piece. However, the same passage does not yield into the same harmonies, although theme and harmonic framework could still be recognized by the audience, especially with the Lied being sung just before.

The compositions made by Sellin for these pieces were stand up as original composition inspired by *Revelge*. This work was also very useful for the subsequent work

Fig. 1 An excerpt of *Revelge-Piaf*, with its Valse-musette rhythm and the relevant original lyrics

Fig. 2 Equivalent passage in *Revelge-Billie* sounds more like a Ballade, in a slower tempo

with ImproteK. First, one reference piece or main scenario: *Revelge*. Second, stylistic sound characters, gestures and effects associated to the music of the ladies, like sound memories of Edith Piaf and Billie Holiday. Sellin kept (more or less) to the scenario, while conveying the idea that this scenario was actually performed, either by Piaf or by Holiday. For the scenario itself, it could be associated the third lady, Elisabeth Schwarzkopf, because of the acknowledged reference to Gustav Mahler and the fact the ladies performed musics of so such different genres.

"Soft Garlic..."

"*Soft Garlic Raymond 1815 Screws*," by Georges Bloch, is another "hybrid" piece, first conceived as an hommage to the three ladies. It is a piece for three-hand piano (two for Sellin and one for Bloch, first introduced by a simple percussion), bass-baritone (Bloch), and spoken voice (Sellin), as shown in Fig. 3.[7]

It is a 6-voice tiling canon: once all voices are playing, two voices never start a note together, and the combined entrances of the voices sound like an ostinato on the smallest note division (here, the eight-note): hence a tiling of the eight-note rhythm. This kind of structure was described by the mathematician Dan Vuza and studied by Andreatta et al. (2002), Andreatta (2003), Bloch (2006). In the excerpt above, the canon structure is easy to detect by comparing both top parts; no voice plays at the same moment of the bar; finally, on all 12 eighth-notes of each measure, one note starts, resulting in a tiling ostinato. However, there is also a running hybridization process, uncovered at the end of the piece, when the piano alone plays the 6-voice canon, as in Fig. 4.

[7]For the people puzzled by this strange title: Soft garlic = *Aïl doux* in French; Raymond alludes to the writer Raymond Queneau; 1815 = Waterloo; Screws = vis; finally, *Aïl doux Queneau Waterloo vis* sounds approximately like *I do know what love is*, enunciated with a terrible French accent.

Fig. 3 *Soft Garlic Raymond 1815 Screws*: a tiling rhythmic canon in which, every eight-note, one voice starts a sound

Fig. 4 *Soft Garlic*: the progression of *You Don't Know What Love Is* gets uncovered

At this point, the canon at the piano is heard as a possible accompaniment of the jazz standard *You Don't Know What Love Is*. The singer hums the tune over the pointillistic accompaniment, and the song is recognized. This piece could be understood as a strictly written-out composition following a given harmonic scenario, in this case the harmonic progression of the standard. Since it follows this "scenario," it can be used as input to an improvisation with ImproteK, and its performance was actually followed by an human–computer improvisation on this standard. This kind of "composed improvisation" setup was experienced before (Bloch et al. 1986), but at a time where the harmonic constraints imposed by the ImproteK notation did not exist:

These musical works made "in a normal fashion," that is "by hand," gave useful informations about hybridization processes, especially when following a kind of scenario. They gave information about the type of sound we were looking for, about what could be extracted from the harmonic structure, and what different sounds could be attached to the harmonic progression of a jazz standard. Some of these fine-tuning details could could look sort of anecdotal, but required much know-how, and all these small adjustments were critical in the success of the project, when the machine was used to create a virtual trio Holiday–Piaf–Schwarzkopf, with Hervé Sellin improvising with them on the piano.

Creating the Virtual Trio with ImproteK

Introducing Scenarios in Human–Computer Improvisation

Scenario and Memory

The ImproteK software (Nika et al. 2017a) combines the "style modeling" approaches mentioned in section "'Three Ladies': An Hybrid Anniversary" with research on automatic chord sequences generation (Chemillier 2004) to address idiomatic improvisation (Bailey 1993) and structured improvisation. It is able to cope with a beat and long-term constraints and takes advantage of prior knowledge of the temporal structure.

ImproteK introduces a temporal specification, called "scenario," in the music generation process. Depending on the musical context, this temporal structure can, for example, represent the harmonic progression of a jazz standard, a profile of audio features, or any formalized structure defined on a user-defined alphabet. As detailed later in section "Final Repertoire," the scenarios used in the "Three Ladies Project" were sequences of chord labels, one chord label representing one beat.

"Improvising" means navigating through an indexed musical "memory" to collect some contiguous or disconnected sequences matching the successive parts of the scenario guiding the improvisation. This musical memory can be learned online (typically the music played by a musician co-improvising with the system during a performance) or offline (an indexed and labeled memory). The musical memories used in this project were different audio recordings of the "three ladies" (see section "Building the Repertoire") with chord labels annotations: one event in the memory consists of a one beat long audio slice and its corresponding chord label.

In a first approach, the consistency between scenario and memory ensures the conformity of the improvisation generated by the machine regarding a required temporal evolution (*e.g.,* conformity of the successive elements retrieved from the memory to a given chord progression). In a second approach, the scenario gives access to prior knowledge which is exploited to introduce anticipatory behavior in the generation process: the generation of a musical slice corresponding to a given label of the scenario takes the future of the scenario into account (see section "Anticipation, Forward Motion, and Hybridization").

Composing Improvisation

The research associated to ImproteK covers several topics in the field of machine improvisation: learning and modeling of musical sequences, the integration of anticipation relative to a predefined structure in a guided generation process at a symbolic level, an architecture combining this anticipation with reactivity using mixed static/dynamic scheduling techniques, and an audio rendering module performing live re-injection of captured material in synchrony with a non-metronomic beat. Finally, it sketches a framework to compose improvised music and extends the initial musical scope of the system. In this framework, musicians can be involved in a meta-level of composition by designing musical scenarios as well as alphabets and their properties.

Hervé Sellin and Georges Bloch worked for six months in collaboration with Jérôme Nika. This collaboration led to two concerts (August 21, 2015, Festival Internazionale "Pietre che cantano," L'Aquila, Italy; February 6, 2016, Conservatoire du sixième arrondissement, Paris, France) and a studio session to record the pieces. The main focus of this transversal project from a technological point of view was on "hybridization," mixing offline and online musical memory, and "music-driven" versus "event-driven" interactions.

Anticipation, Forward Motion, and Hybridization

"Hybridization" means here, for example, being able to make the software improvise on the scenario *Autumn Leaves* using some material which is exogenous to *Autumn Leaves*, such as a musical memory constituted by Elisabeth Schwarzkopf singing Mahler's *Lob des hohen Verstandes*. In the case of a scenario defined as the chord progression of a jazz standard and a memory recorded on different chord progressions, the simple idea is the following: if the scenario requires a *ii-V-I* progression, retrieving a musical event labeled by *ii* located in a *ii-V-I* progression, then a musical event labeled by *V* located in a *V-I* progression... is likely to produce a better result than the concatenation of a *ii*, a *V*, and a *I* independently retrieved in the memory.

The first chapter of the book *Structural functions of harmony* by Schoenberg and Stein (1969) begins with the following considerations about *successions* and *progressions* of chords: "*A succession is aimless; a progression aims for a definite goal*." Indeed, taking advantage of prior knowledge of the temporal structure is crucial if we want models that can address composed or idiomatic music (jazz, rock, blues, pop, etc). A chord progression, for example, is oriented toward its future and carries more than the step-by-step conformity of a succession. The sequentiality of a progression has therefore to be exploited to introduce forward motion at each step of the generation (trivial examples being harmonic anticipation, "going from the tonic to the dominant," "going from the tonic to the tonic," etc.). This can be summarized by this sentence of Hervé Sellin, who formalized his expectations regarding the system at the beginning of the project: "*It should become 'intelligent,' structure itself within chord progressions, and not chose an element for a chord, then another for the following chord....*" Later, during the interviews and listening sessions carried out at the end of the project (Nika 2016), Hervé introduced a distinction between "music-driven" and "event-driven" reaction to describe how the anticipation in the generation process of the system enabled to settle a musical interaction with a long-term horizon in the piece based on *The Man I Love*.

To achieve this, the generative model of ImproteK is conceived to ensure both continuity with the future of the scenario and continuity with the past of the memory. Each generation phase consists of two successive steps:

- *Anticipation*: find an event in the memory sharing a common future with the scenario while ensuring continuity with the past of the memory (when it is possible);
- *Copy or digression*: retrieve the whole sequence or use the regularities in the memory to follow an equivalent nonlinear path (and possibly extend it) and thus digress from the original material.

Continuity with the future of the scenario is handled with a novel algorithm indexing the prefixes of a pattern (the current scenario) in a text (the memory) using the regularities in the pattern (Nika et al. 2017a). Continuity with the past of the memory is provided by the automaton structure chosen to learn the musical memory: the Factor Oracle automaton (Allauzen et al. 1999).

Harmony-Driven Generation with Memories of the "Three Ladies"

Building the Repertoire

In order to select the "scenarios," that is, the reference pieces that would eventually serve as an harmonic model for the performance, Hervé Sellin and Georges Bloch followed at first the same process used in the music they made by ear: look for a a piece which could relate to one or two ladies and find a way to insert the third one.

This was the reason for chosing *Autumn Leaves* (*Les Feuilles mortes*). This French popular song composed by Joseph Kosma in 1945 with lyrics by Jacques Prévert became popular in America with the English lyrics by Johnny Mercer, before becoming a jazz standard. Actually, Piaf recorded a version in which she sang alternatively in English and in French. With its repeated phrases following the circle of fifths, its harmonic structure is somehow intrusive. It was perhaps hard choice to start working with ImproteK; but it did look like a good choice, the very blatant harmonic progressions could really impose a scenario. Since it could relate both to Piaf and to Billie Holiday (as a jazz standard), the point was to have Schwarzkopf singing it or, at least, singing along.

During the first sessions, the pianist reacted to the heterogenous material generated by the system by asserting the original tune, "doing his job" in gluing the whole thing together. Hervé Sellin noticed a problem, feeling torn between the "permanent call to order" regarding the "invasive standard" imposed by the bass line played by the system, and the "free patchwork" of the virtual singer.[8] The chosen "memory" was relatively small; it included pieces by Mahler and Mozart, all accompanied with an orchestra, which contrasted heavily in sound and character, especially by comparison with the original song. It resulted in a patchwork effect. The performance proved to be successful when these discrepancies were openly accepted by the performers. Intentional as it was, it took some time for both pianist and operator to overtly accept the inherent risk of this patchwork aesthetics, to play with it, have fun with it.

The first reference piece, *Revelge*, hybridized "by hand," referred to Elisabeth Schwarzkopf; the second one, *Les Feuilles mortes*, to Piaf; the third one had to refer to Billie Holiday: it was *The Man I Love*. It allowed us to have a "Bille's track," that is, one improvising instance whose memory consisted of pieces by Bilie Holiday, playing on a memory exclusively based on recordings of this same piece. When, like in this case, both memory and scenario are based on the same piece, solutions are easy to find for the software, the simplest being a straight replay of the memory. However, recombinations can still be triggered, between different versions, and between similar parts of the piece, like verses, or recapitulation and exposition.

Billie's track was sparsely used. Let's face it: we enjoyed having the three ladies singing "Someday he'll come along, the man I love," with Billie as a reference point.

Building the Memory

The construction of the "memory" is a time-consuming task. The prerequisite is that a vocabulary of harmonic notation for both scenario and all pieces of the memory has been found. Then, for all pieces used into memory, one must:

- first, label the piece according to this notation,
- then, create a file (or several) containing beat markers (in milliseconds) labeling the recording(s) of the piece.

The harmonic problem relates to both scenario and memory pieces. For finding the date of the beat, one could resort to automatic or semiautomatic beat-tracking systems, for instance by marking the measure as the recording is playing. For the memory repertoire, we started with Mahler for Schwarzkopf and then added some

[8] All quoted explanations by Sellin come from the interviews of Jérôme Nika for his Ph.D. dissertation (Nika et al. 2017a), in which they are quoted at length.

opera excerpts by Mozart and Puccini. After some sessions, we were aware that some of our favorite songs had very little harmonic compatibility with the pieces chosen as scenario. They were also rhythmic incompatibilities: for instance, a piece in 3/4 like *Les Amants d'un jour* can hardly fit with harmonic scenarios in 4/4 or 2/4. The absence of songs in 3 beats in Billie Holiday's repertoire made us eventually discard any scenario, or memory, in such a rhythm.

Tempo is another matter, but much more flexible: a fast song can be used in a slow environment and vice-versa. For example, Mozart aria from *Don Giovanni*, "Mi tradi quell'alma ingrata," in 4/4 and marked *Allegretto*. It is generally played around 130–150 for the quarter-note. It was used as a 4/4 for *Autumn Leaves*, and as a 2/2, at the same speed but with a twice slower tempo, for *The Man I Love*. Non-musicians should be reminded that, even if both pieces sound relatively slow, the harmonic and notated rhythm of the first piece is much faster than the rhythm of the second one. Therefore, the Mozart aria could be used for both memories, but not with same value for the beat. The original 4 beats by Mozart perfectly fit for *Autumn Leaves*, and a version with 2 beats per bar was used for *The Man I Love*.

What Notation?

The problem of notation was already addressed in the works composed by hand. Sellin devised a jazz notation for *Revelge* to conceive his own version inspired by Billie Holiday and Piaf. Although we are speaking about compositions that were mostly improvised, he actually wrote a harmonic conductor in a jazz-like notation.

With the computer running ImproteK, the rule is simple: a chord from the scenario fits a chord from the memory if, and only if, it is the exact same one within the transposition range. To take a simple example, if the scenario is a popular March -like song starting with C-G7-C-G7 in the first four measures, and your memory is another similar song with C-G7b9-C-G7b9, the software will not find any match longer than one measure! By contrast, if the memory song is D-A7-D-A7 and a transposition of 2 semitones is allowed, it *will* perfectly fit, since ImproteK is able to transpose. The G7/G7b9 problem resumes the question already examined in section "Hybridization: Style, Structure, Notation," when we considered different pianists performing *Autumn Leaves*. In the "Three Ladies Project," very different kinds of music were used: the choice of a common vocabulary was crucial.

There is powerful reason for preferring a restricted collection of chords: it yields more solutions. It is much easier to match words (or parts of words) written with an alphabet of 3 letters than with an alphabet of 26. However, the musical relevance of the vocabulary has to be thoroughly examined. In our given repertoire, two important decisions had to be made:

- first, to decide if we would notate the bass note independently of the chord, since it happens frequently in jazz notation and corresponds more or less to classical notation (where the bass is the actual bass note and the chord degree is deducted from the figure); another reason was the frequent use by Mahler of unrelated chords and basses

- second, how to notate the chord color (as exemplified by the 7/7b9 problem).

We tried to use a notation with an independent bass line but did not get enough solutions: perhaps it could have worked with a much bigger repertoire. For the chord color, it rapidly became irrelevant for our project: a piece like "Tu che del gel sei cinta" from *Turandot* by Puccini keeps the same Eb minor chord for almost the whole aria, and we are speaking of the whole triad, not of a tonic pedal. This is part of his style, enhanced by a lush orchestration, and part of the fun was to be able to impose this kind of sound on a jazz standard. Therefore, as we said, we resorted to a strict functional notion of harmony, where the chord notation primarily describes the functional degrees in the scale. This already was the default notation used by Chemillier for OMax-Beat but within stylistically much tighter repertoires.

Functional Notation

Therefore, the choice of functional notation had to be mastered. Let's first give a summary with 4-notes chords on a C-major scale:

- first degree (c-e-g-b), fourth degree (f-a-c-e): major 7th chord, notated *maj7*
- second degree (d-f-a-c), third degree (e-g-b-d), sixth degree (a-c-e-g): minor 7th chord, notated *m7*
- fifth degree (g-b-d-f): 7th chord, notated *7*
- seventh degree (b-d-f-a): b5minor 7th chord, notated *m7b5*

We add the diminished chord, present in minor mode (ascending seventh degree b-d-f-a flat), and notated *dim*.

We will notice immediately that our March—like popular songs alternating tonic and dominant will be notated C maj7-G 7-C maj7-G 7. It does however *not* imply that a *b* is played or has to be played on the first degree. It just means that we have a perfect cadence in major mode. We should insist on the fact that functional harmony is a horizontal conception of harmony, based on functional progressions and not on individual textures. However, even by strictly keeping to these simple rules, the notation can be tricky. In several chromatic progression by Mahler or Puccini, the choices made to adapt the score to our functional jazz standards relied on what we heard. It was the occasion for heated discussions between Sellin and Bloch!

Figure 5 shows a relatively simple example, which resulted in the notation shown in Fig. 6.

The first chord is notated Bb7, although there is no a-flat; in addition, there is a a-natural. Therefore, why not Bb maj7? Because this chord functions more like a dominant, and the a-natural is just a passing note creating tension, as is the c-flat, the minor 9th eventually removed from our chord vocabulary.

Fig. 5 First measures of Gustav Mahler: *Das irdische Leben*

Fig. 6 ImproteK notation used for the first measures of Gustav Mahler: *Das irdische Leben*

Final Repertoire

In addition to the pieces composed by Sellin and Bloch based on *Revelge* and *You Don't Know What Love Is*, two improvised pieces using ImproteK were played by Hervé Sellin and a virtual trio: Edith Piaf, Billie Holiday, and Elizabeth Schwarzkopf. The chosen reference pieces, or "scenarios," were *Autumn Leaves* and *The Man I Love*. In addition to the live music played by Hervé Sellin, the musical memory of the system was constituted by the following recordings:

- Billie Holiday: *The Man I Love*; *The End of a Love Affair*; *I'm a Fool to Want You*(*); *Saint Louis Blues*.
- Edith Piaf: *Mon Dieu*; *La Vie en rose*; *Milord*; *Les Amants d'un jour*(*).

- Elisabeth Schwarzkopf:
  - Mahler: *Symphony No. 4*, fourth movement: “Das himmlische Leben”; *Des Knaben Wunderhorn*:“Lob des hohen Verstands”; *Des Knaben Wunderhorn*: “Das irdische Leben.”
  - Mozart: *Don Giovanni*: “Mi tradi quell’alma ingrata”; *Le nozze di Figaro*: “Porgi amor” (*).
  - Puccini: *Turandot*: “Tu che del gel sei cinta.”

All these musical memories were used during repetitions and will be exploited in future work. For the two above-mentioned concerts, the pieces marked with “(*)” were not used.

In the interviews he had with Jérôme Nika after the recording session at IRCAM, Hervé Sellin summarized the different approaches for the two pieces:

> Somehow, *Autumn Leaves* is more of a chord sequence whereas *The Man I Love* is more of a story. That’s for sure, even from an historical point of view. First the history is not the same, for *The Man I Love* there is a context, it has been written for a reason. *Autumn Leaves* went through all the colors of the rainbow. Of course, at first, it was a song, but it is not approached like that anymore, and the chord sequence we use is not exactly that of the original song. It is the chord sequence that the jazzmen seized. *The Man I Love* is different, it is another canvas which ties harmony together in a different way. So it generates other elements at every level. (Nika et al. 2017a)

Therefore, the approach was to see the improvised piece based on the scenario *The Man I Love* as a “horizontal story,” and the improvised piece based on the scenario *Autumn Leaves* as a “vertical patchwork.” **Video 1** and **Video 2** (see Appendix) show recordings of improvisation sessions based on *The Man I Love* and *Autumn Leaves*.

Scenario-Driven, Memory-Driven

Hervé Sellin introduced a distinction between “music-driven” reaction (“réaction à l’élément musical”) and “event-driven” reaction (“réaction à l’élément événementiel”) to define his attitude regarding *The Man I Love* and *Autumn Leaves* respectively, and valued the “music-driven” reactions that the system triggered in his own playing in the case of *The Man I Love*:

> Here, my reactions are ‘music-driven’, and not really’event-driven’. [...] A’musical element’, here, is for example when a piano plays something and I play something which is complementary, and then a singer arrives and she sings to me at least 8 bars so I know where to place myself... (Nika 2016)

Hervé discovered in the last sessions of the piece on *Autumn Leaves* that the system could be used to achieve hybridization “in the other sense,” that is, by immersing the scenario into the sound universe of the memory. According to him, the interesting way to push on the experiment would be to play with the material itself, and the “strange harmonies” produced by the hybridization: “We should forget *Autumn*

Leaves and say at the end ‘It was *Autumn Leaves*’ !”. His conclusion on this piece was the following:

> I think it would be worthwhile to go through with this intention, including the’patchwork’ aspect. [...] We have to remove everything that does not help to go to an optimal result on the pretext of providing a false security [*e.g., the bass line*]. It is now obvious to me. (Nika et al. 2017a)

Discovering a scenario (or a reference piece) at the end of a composition, like in Bloch’s “*Soft Garlic Raymond 1815 Screws*,” is relatively old hat in Western music. Basically, it is like taking backwards the process of musical variation. One famous example is Schumann’s *Fantasy in C major*, Op. 17: when the most memorable theme of Beethoven’s *An die ferne Geliebte* is quoted at the end of the first movement, the listener discovers that the whole music he heard was based on this theme (Rosen 1998). This was achieved in the last recorded versions of *Autumn Leaves* with ImproteK. Not only did the memory take the power, but the effects of its sound went much beyond the “strange harmonies” produced by the hybridization process. These versions enhanced the craziness of the material and the actual sound of the memory, because of Sellin’s wonderful reactions to it, yielding to this sound and accepting its clashing against the affect usually associated with *Autumn Leaves*.

Event-Driven? Music-Driven? Sound-Driven? In such a project, the hybridization power of the system becomes self-evident:

- notation: the notation always relate to the scenario, since the goal of ImproteK is to align the memory to the scenario. The notation defines what is considered as relevant.[9] If the choice of a notation common to scenario and memory is vital, it bears mainly to the importance of the musical discourse of the scenario. Generally, by Music-Driven or Structure-Driven, *Scenario-Driven* is intended. It is even the case when the scenario becomes “invasive,” like in the first versions of *Autumn Leaves*. It is Scenario-Driven, but the scenario is so obnoxious that it impedes the existence of other materials.
- sounds or events: whatever the consistency between memory and scenario, the memory always proposes another sound. Even if the “étrange étranger” of Bernard Lubat is only a “strange cousin,” it is still strange, and even stranger when it comes from a completely different musical world, as in this project. Therefore, by Sound-Driven or Event-Driven means *Memory-Driven*. It is very obvious in **Video 2**, when the creaking sound of Mahler’s Lied takes the precedence on the scenario.

Music-driven? Generally, Scenario-Driven. Event- or sound-driven? Generally, Memory-Driven. As performers, we have to chose which one of these driving force we chose to follow or enhance. The resulting style will be a careful (in)balance between both.

[9]We should keep in mind that this is not necessarily a harmonic notation, since it could use, for instance, categories of spectral descriptors.

Further Research

The current developments of ImproteK are part of the collaborative research and development project DYCI2 (Nika et al. 2017b). This project explores the creative dynamics of improvised interactions between human and artificial agents, featuring an informed artificial listening scheme, a musical structure discovery and learning scheme, and a generalized interaction/knowledge/decision dynamics scheme.

The ongoing research focuses on the versatility of the digital musical agents and their capacity to adapt to different musical settings, with or without prior knowledge on the musical context. The main goal is to merge the usually exclusive "free," "reactive," and "scenario-based" paradigms in interactive music generation to adapt to a wide range of contexts of human–computer music improvisation, capitalizing on the models OMax (free), SoMax (reactive), and ImproteK (scenario-based). This requires to design a range of strategies going from a floating musical coordination on different musical dimensions (e.g., energy, harmony, melody, timbre) with live musicians and/or other digital agents, to the conformity to a predefined structure (e.g., a chord progression, a long-term profile of audio features).

Another direction is that of the inference of short-term scenarios. The models proposed in ImproteK are queried by successive "partial scenarios," i.e., subsequences of a scenario *defined before* the performance. The idea is to enrich the reactive listening introduced in SoMax so that it discovers underlying structures in what the musician plays to infer possible continuations of this underlying structure. This model inferring short-term scenarios for the future (e.g., sequence of chroma, chord progression) to feed a scenario-based music generation engine in real time will enable the agents to generate anticipative improvisations from an inferred (and not only predefined) underlying structure.

The adaptive audio renderer implemented in ImproteK has been generalized to become a control unit to pilot multimedia rendering of sequences generated from offline or online inputs. Georges Bloch could thus link the video player already used in OMax (Bloch et al. 2008) to the system: in this case, the renderer module associated to each voice played by the system does not only send control messages to audio modules to pilot audio rendering, but also to video units to pilot video rendering through simple messages: indexes of frames and speed coefficients. This way polyphonic video improvisations following a given scenario can be created using preloaded video clips or online recorded video as memories, while being reactive to the same controls than that described for audio (see **Video 3** in Appendix).

Conclusion: Surrealism, Kitsch, Fun

In his book *Psychologie du Kitsch* (Moles 1976), Abraham Moles lists several modes of esthetic relationship between human and object. For instance, according to Moles, the "Surrealist mode lies on a strangeness factor." The strangeness depends on the fact that the subjective probability of the occurrence of the object is small (like a sewing machine on an operating table), and there are as many dimensions as they are objects at the same time.

Undoubtedly, there is something surrealistic in the performance of the three ladies with Hervé Sellin. The strangeness factors, to stick to the term used by Mole, are several:

- the mere fact they are singing together
- and one of its consequence, the effect of anachronism. Since most people suspect that they never sung together, the performance emphasizes the shift in time, and not only because it uses recorded performances (although one could find some irony in imagining Schwarzkopf singing with Billie Holiday in 1945)
- the emergence of very distinctive sounds, connotative but strange to one another: for instance, the solo saxophone in Billie Holiday's rendering of *The Man I Love*, the very soapy chorus accompanying Piaf, and the very dense Puccini or Mahler orchestras
- the fact the sources of the memory could be recognized, the scenario also, and their possible inadequacy, inadequacy between sources and between any source and the scenario.

The degree of surreality depends on all these factors. When heterogeneous material is used, as in this case, Memory-Driven performance will tend to be more surrealistic. The coming up of all these different sounds and their overt contradiction, even if it is eventually solved, is undoubtedly of surrealistic nature.

However, in the case of *The Man I Love*, the last "recognition" factor is not that strange. Billie Holiday was heard singing the piece from the start; [10] therefore, the program is known. We are in a Scenario-Driven, with a not too invasive scenario, thanks to its Ballad character. Of course, the interventions of Schwarzkopf, then Piaf, then two ladies, then the piano solo and finally the three ladies in a sort of Grand Finale are somewhat strange, but, in some sense, are piling-up in an amusing manner.

Is it Kitsch? In the same book, Moles makes a tentative typology of groups of objects, form a Kitsch point of view; he lists four distinctive characters: heterogeneity is one, but, contrary to the surrealistic mode, it is generally not intentional. The three other criteria are the piling-up of objects, the refusal of functionality and the sedimentation aspect. The piling-up heard in *The Man I Love* could be sensed as Kitsch. Furthermore, the mixing of all these masterpieces can undoubtedly be considered bad taste. Interestingly, at first, the most creative performances are considered too complex, because the listeners want to hear achievement of the machine, a machine playing a jazz tune with Piaf and Schwarzkopf. This desires for comfort resorts very much to Kitsch. Only later is it possible to grasp the real fun of the machine, and the musical power featured in the notation constraints and the multiple possibilities of sound-events.

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[10] The videos listed in Appendix just show excerpts of performances.

Several months before the conference, Hervé Sellin was reading a biography of Schwarzkopf. At that time, we rehearsed only *Autumn Leaves*, with an extensive memory exclusively of Schwarzkopf: two Mozart arias, four Mahler pieces including a whole symphonic movement and one Puccini aria. One day Hervé came to the rehearsal and said:

> It is strange. I read that book, and most of her accompanists are listed. I don't know why they forgot me!

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Appendix: Videos listed in the article

Video 1: Hervé Sellin Playing "The Man I Love" with Billie Holiday, Edith Piaf & Elizabeth Schwarzkopf

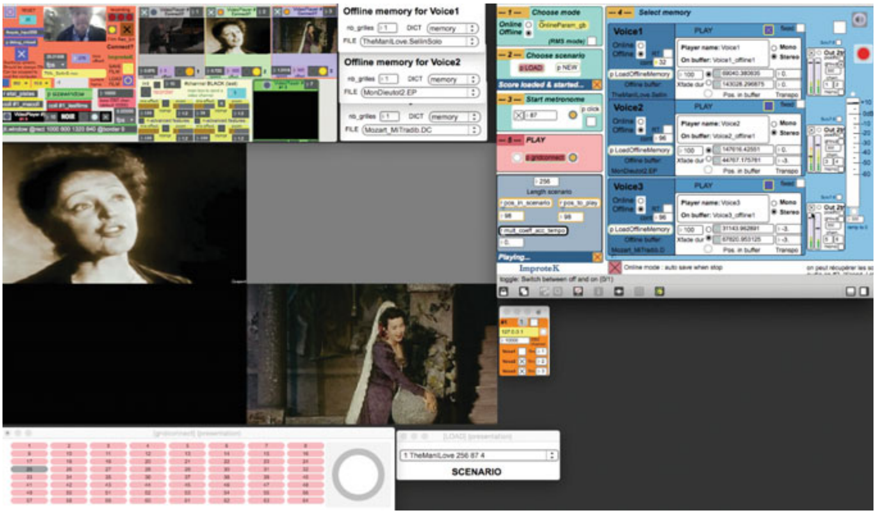
https://www.youtube.com/watch?v=fyW4A3L7kBo
The Man I Love #1 improvisation by Hervé Sellin (piano) and Georges Bloch (using ImproteK). The scenario provided to the system is the chord progression of the song, and its musical memory is:

- Hervé Sellin playing *The Man I Love*,
- Billie Holiday singing *The Man I Love*,
- Edith Piaf singing *Mon Dieu* and Milord,
- Elisabeth Schwarzkopf singing Mozart, *Don Giovanni*: "Mi tradi quell'alma ingrata," and Puccini, *Turandot*: "Tu che del gel sei cinta."

Video 2: "Autumn Leaves" by Sellin, Bloch, Mahler, Mozart, Puccini

https://www.youtube.com/watch?v=dNcK3bRnbv8
Autumn Leaves #2: improvisation by Hervé Sellin (piano) and Georges Bloch (using ImproteK). The scenario provided to the system is the chord progression of the song, and its musical memory is constituted by recordings of Elisabeth Schwarzkopf singing Mahler, Puccini, and Mozart.

Video 3: Example of Video Improvisation



https://www.youtube.com/watch?v=UUXDkdt76J8
Example of video improvisation. ImproteK is chained to a video player (Bloch et al. 2008) and improvises by re-injecting videos, transformed and reorganized to match a given scenario. In this example, the scenario provided to the system is the harmonic progression of *The Man I Love*, and its memory is constituted by several videos:

- Lisa della Casa singing Mozart, *Don Giovanni*: "Mi tradi quell'alma ingrata,"
- Edith Piaf singing *Mon Dieu*,
- Billie Holiday singing *The Man I Love*,
- Hervé Sellin playing *The Man I Love*.

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Georges Bloch (born in Paris, 1956), composer and researcher, graduated in engineering before studying composition in U. C. San Diego (Ph.D., 1988). Now Associate professor at Strasbourg University and associated to Ircam in Paris, he works on OMax, a computer-assisted improvisation system. He also works on opera dramaturgy. His compositions count "musical visits" (Beyeler Foundation, Salines of Arc-et-Senans) and pieces with machine improvisation on a written material played by a live performer. Currently, he is working on a book linking opera, novel and film music.

Jérôme Nika is a postdoctoral researcher in the Music Representations team at Ircam (UMR STMS 9912 CNRS). His Ph.D. work "Guiding human-computer music improvisation: introducing authoring and control with temporal scenarios" was awarded the "Young Researcher Prize" by the French Association of Computer Music, and the "Young Researcher Prize in Science and Music". Through the development of the software ImproteK and within the DYCI2 project, his research focuses on the integration of temporal specifications in music generation processes, and on the dialectic between reactivity and planning in interactive human–computer music improvisation.

Part IV
Evolutionary Aesthetics
(Julien Renoult)

Expertise Affects Aesthetic Evolution in the Domain of Art

Evidence from Artistic Fieldwork and Psychological Experiments

Jan Verpooten

Abstract An unmade bed. A cigarette glued to the wall. A replica of a soup can box. Drippings on a canvas. Can an evolutionary approach help us understand the production and appreciation of, sometimes perplexing, modern and contemporary art? This chapter attempts at this by investigating two hypotheses about the evolution of human aesthetics in the domain of art. The first hypothesis, commonly called evolutionary aesthetics, asserts that aesthetic preferences, such as those for particular faces, body shapes and animals, have evolved in our ancestors because they motivated adaptive behavior. Artworks (e.g., those depicting facial beauty) may exploit these ancestral aesthetic preferences. In contrast, the second hypothesis states that aesthetic preferences continuously coevolve with artworks, and that they are subject to learning from, especially prestigious, other individuals. We called this mechanism prestige-driven coevolutionary aesthetics. Here I report artistic fieldwork and psychological experiments we conducted. We found that while exploitation of ancestral aesthetic preferences prevails among non-experts, prestige-driven coevolutionary aesthetics dominate expert appreciation. I speculate that the latter mechanism can explain modern and contemporary art's deviations from evolutionary aesthetics as well as the existence and persistence of its elusiveness. I also discuss the potential relevance of our findings to major fields studying aesthetics, that is, empirical aesthetics, and sociological and historical approaches to art.

Keywords Evolutionary aesthetics • Prestige bias • Coevolutionary aesthetics
Art appreciation • Artistic research • Expertise • Cultural evolution theory

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Introduction

Everyone will recognize the uncomfortable experience of being confronted with some piece of modern or contemporary art you cannot wrap your head around. To me at least it happens once every while. For example, I recently visited an exhibition in a reputed gallery and one of the less minimalistic works was an ordinary filter cigarette glued to the wall. The gallery owner asked me what I thought about the exhibition. I decided not to be intimidated by the fanciness of a professional art gallery and admitted I was quite puzzled by it. To my surprise, she said she was puzzled too but that she was not supposed to actually say this as a gallery owner. This anecdote illustrates the fact that even art experts are sometimes perplexed by modern and contemporary art.[1] Regardless of the consequences for the meaning and value of artworks, which I'll touch upon in the discussion, I find this fascinating. Why did we at some point decide to start making art that does not seem to make sense to an expert audience, let alone to the general audience?

The issue is also intriguing from an evolutionary standpoint. Evolutionary psychology predicts that aesthetic preferences are shared among all people and evolved in our evolutionary past under natural (and sexual) selection. For example, it has been suggested that faces we find more attractive indicate higher biological fitness. A preference for such faces is adaptive because it enhances our social and sexual partner choices. All else being equal, you would therefore expect that a picture of a beautiful face is appreciated to a greater degree than a portrait of a less attractive face. But, as shown by the studies I will discuss next, it appears that a contemporary art expert is no longer supposed to simply follow the dictates of our ancestral aesthetic preferences.

One possible explanation for experts' and modern and contemporary art's deviation from ancestral preferences may be provided by cultural evolution theory. Cultural evolution theory predicts that when an individual is uncertain about which cultural habits (such as art preferences) it should adopt, it will copy those associated with prestige because prestige may indicate quality. So, maybe, "prestige-biased learning," as this mechanism is referred to, has taken over the role of ancestral aesthetic preferences, at least among art connoisseurs. Prestige bias implies that the individual copies preferences without actually knowing why; it simply trusts in the reliability of prestige. Thus, if all art experts (which includes the artists themselves) apply prestige bias, it might explain why modern and contemporary artworks often deviate from ancestral preferences and why elusive art persists.

In this chapter, I will first briefly discuss our artistic fieldwork that illustrates this issue. Then I will explain in more detail what evolutionary psychology and cultural evolution theory predict about human art preferences. Next, I summarize empirical findings that support our contention about deviant expert appreciation and the

[1]Modern art includes artistic work produced during the period extending roughly from the 1860s to the 1970s and denotes the style and philosophy of the art produced during that era, while more recent artistic production is often called contemporary art (or postmodern art).

elusiveness of modern and contemporary art. I conclude with a discussion of how all of this relates to empirical aesthetics and to sociological and art historical approaches of art.

Art Observation Post

It is conventional practice among primatologists to avoid interfering with the behavior of wild primates while observing them in their natural habitat. The idea behind this custom is simply that primatologists want to measure primates' *natural* (i.e., undisturbed) behavior. However, this is not always easily achieved. For example, I did field work on the social behavior of spider monkeys (*Ateles geoffroyi yucatanensis*) in their natural habitat in Yucatan, Mexico, as a field assistant. As I was with the monkeys, day after day, months on end, they started to recognize me and greeted me in the mornings with their typical whinny vocalization. As a lonely gringo far from home, it was hard to control myself and not greet these cheerful monkeys in return.

Later on, I studied a primate species that has been called "*Homo aestheticus*" or "the artful species" (Davies 2012; Dissanayake 1995). These names are well deserved since "art behavior," or producing and appreciating art, is an integral part of its behavioral repertoire (Dissanayake 1988). For the sake of maintaining a certain distance and avoiding any disturbance to the behaviors under scrutiny, I asked Gert Verpooten to build an observation post. As you can see in Fig. 1 its design was not intended to be aesthetically pleasing or recognizably artistic, it was purely functional (easily disassembled and watertight).[2] I used it for the first time during a biennial art event in Amsterdam organized by the Sandberg Institute. Despite its non-aesthetic camouflage, some visitors approached my post and greeted me. They inquired: "Studying Dutch art monkeys?" Again it was hard to control myself and not greet these primates, this time *Dutch art monkeys*, in return.

Another opportunity for collecting data arose with the first edition of the Canvascollectie, a Belgian national art contest. Participation in this contest enabled me to observe a professional art jury while they were making judgments. Despite the camouflage, the post survived several selection rounds and was one of the 250 works (out of an initial 14,000) that made it into the final exhibition at the BOZAR (the center for fine arts in Brussels) (Fig. 1b). The BOZAR exhibition lasted three weeks and offered another opportunity to collect data on the art behavior of the hordes of visitors. Since I was unable to keep watch for the entire period, I organized a crash course in measuring behavior at an art center (Monty, Antwerp) in

[2]To be clear, whether something is aesthetic or not, depends on the concept of the aesthetic, naturally. Does the concept also comprise the possibility of *conceptual* beauty in addition to the more traditional perceptual beauty? For instance, someone might find an "anti-aesthetic" statement, such as Duchamp's influential artwork "Fountain" (an ordinary urinal) intellectually quite beautiful, in a similar way as someone might find a mathematical proof beautiful.

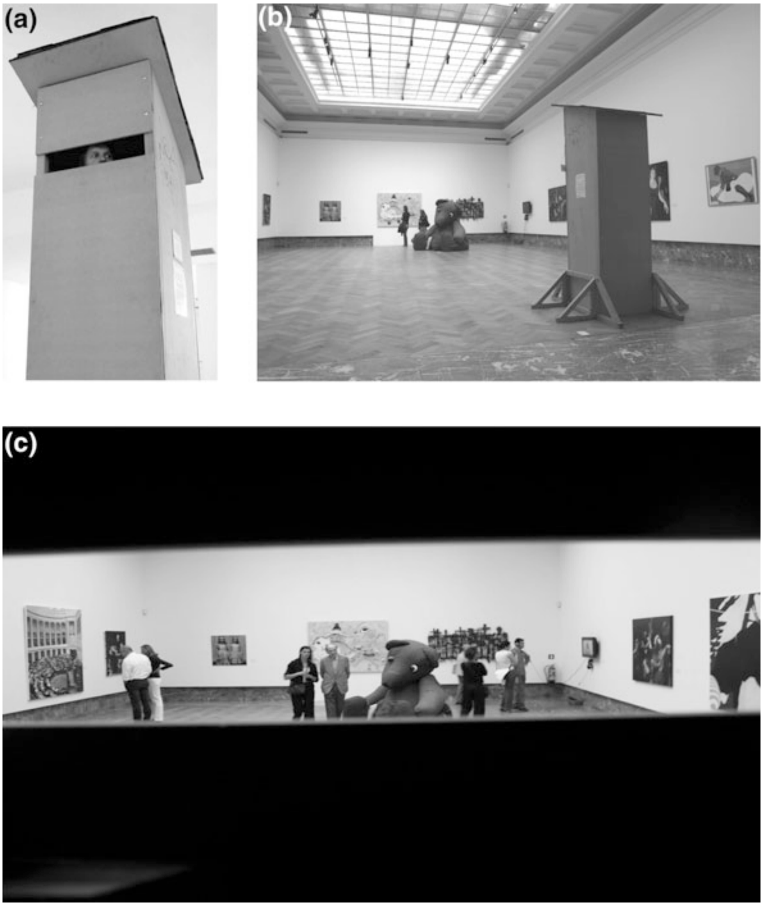

Fig. 1 Fieldwork with the art observation post. **a** Front view during a preselection round at M HKA (the contemporary art museum of Antwerp, Belgium), **b** back view, and **c** inside view during the final selection of the Canvascollectie, a Belgian national art contest, in the BOZAR (the center for fine arts in Brussels)

order to recruit volunteers. About ten of them took turns in observing art from inside the post. They collected data on the interaction of visitors with the artworks in sight. The post looked out on a room exhibiting a giant teddy bear, a conceptual video installation, abstract artworks, and figurative paintings (Fig. 1c).

I have not statistically analyzed any of these collected data (yet), but two observations already stood out during the BOZAR exhibition. Firstly, we had the impression that, of all the artworks within our view, the teddy bear achieved by far the longest average viewing time. Secondly, the study was informative in another, perhaps unusual way. The fact that our observation post was *itself* selected by the professional jury conferred on it the status of art, despite its purely functional design. As I will discuss in the next section, the popularity of the teddy bear is consistent with evolutionary psychology's predictions about art preferences. In contrast, the fact that an observation post—in its purely functional and non-aesthetic appearance—was selected by the contest's jury can barely be explained by this account. In contrast, I will argue in the following section that cultural evolution theory is well suited to explain the appreciation of artworks that deviate from ancestral preferences such as our observation post.

Evolutionary Psychology

Evolutionary psychology seeks to identify which human psychological traits are evolved adaptations—that is, the functional products of natural selection and/or sexual selection in human evolution. Evolutionary psychologists have employed this "adaptationist approach to the evolution of the human mind" to explain the evolution of aesthetics as well (Renoult 2016). Evolutionary psychological theories in which the aesthetic preferences of *Homo sapiens* are argued to have evolved in order to enhance survival and reproductive success are the subject of a research program dubbed "evolutionary aesthetics" (Dutton 2003; Voland and Grammer 2003). Hereafter I refer to it as *standard evolutionary aesthetics* to distinguish it from other evolutionary approaches to aesthetics. Standard evolutionary aesthetics hypothesizes that beauty experiences, evoked by particular elements of the human environment, are unconsciously realized avenues to high fitness in human evolutionary history (Thornhill 2003). In support of this view, research is often cited that suggests that aesthetic preferences for certain landscape, animal, and human features may have been selected to guide, respectively, habitat choice, hunting and predator avoidance and peer and mate choice (Barrett 2015; Falk and Balling 2010; Little et al. 2011; New et al. 2007; Orians and Heerwagen 1992; Windhager et al. 2011; Yang et al. 2012). While hypotheses about evolved landscape preferences appear somewhat controversial, at least in the form of the savanna hypothesis (a naturally selected preference specifically for savanna-like environments in which *Homo sapiens* is thought to have evolved; Joye and De Block 2011; Renoult 2016), the universality of attentional biases and preferences in humans toward particular human and non-human animal figures and features is empirically well supported and seems theoretically sound (Altman et al. 2016; Verpooten and Nelissen 2010; Windhager et al. 2011; Yang et al. 2012). The claim that these preferences are ancestral and biological rather than cultural in origin is further evidenced by the fact that humans and animal figures appear as dominant themes in prehistoric rock art and sculpture around the globe, some of which have been dated to be around 40,000 years old (Hodgson and Watson 2015). Moreover, (personalization disabled) Google image searches with the terms "drawing" and "sculpture" illustrate that these very same themes have remained prominent to the present day (see Fig. 2). More systematic, cross-cultural evidence of the present prominence of these themes comes from several large polls, conducted by the conceptual artists

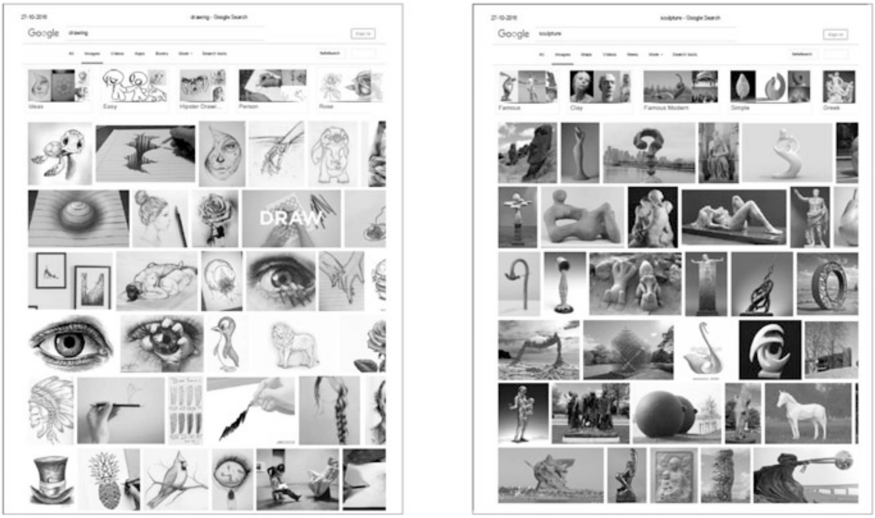

Fig. 2 Google image searches with terms "drawing" (left) and "sculpture" (right) demonstrate that even today (October 27, 2016) human and animal figures feature as the most popular artistic themes

Melamid and Komar. They assessed what people want to see in art, as part of the artists' so-called People's Choice series 1994–1997. Their findings demonstrate—inadvertently, because they were not testing evolutionary hypotheses—that across cultures people's art preferences tend to converge on the very same aesthetic preferences predicted by evolutionary psychology. In particular, their surveys showed a near-universal preference for pictures of lush landscapes with greenery, blue skies, and water, as well as for human and animal figures (Dissanayake 1998; Dutton 2009; Pinker 2002). This was illustrated by the "Most Wanted" paintings the artists made based on their findings per country and which looked surprisingly similar across countries and continents (Dissanayake 1998).

At present, it remains unclear and therefore hotly debated whether art has evolved as a mere by-product of these ancestral aesthetic preferences or whether it has served any evolutionary functions in itself. However, it is clear that the "proper" functions of ancestral aesthetic experiences and motivational systems are not preserved when they are elicited by artworks (Sperber and Hirschfeld 2004). After all, we cannot mate with a portrait or seek refuge in a painted landscape. Therefore, it has been argued that the most parsimonious explanation for the evolution of art is that it has evolved as an evolutionary by-product of these ancestral aesthetic preferences (Verpooten and Nelissen 2010). Thus, I will hereafter refer to this hypothesis as the *by-product hypothesis* (Pinker 2002).

The relative popularity of the giant teddy bear we observed during our artistic fieldwork is consistent with the suggestion that aesthetic preferences result from natural/sexual selection in the past, in this particular case, an evolved preference for animal figures.[3] But what about our observation post itself and its selection by a professional jury? What about a cigarette glued to the wall of a highly reputed gallery? What about an unmade bed ("My bed", Tracey Emin 1998)? Or a replica of a soup can box ("Campbell's Tomato Juice Box", Andy Warhol 1964)? Or an urinal ("Fountain", Marcel Duchamp 1917)? These are just a few examples of an abundance of modern and contemporary artworks which have been produced in the last 100 years or so that seem to defy the rules of standard evolutionary aesthetics. Does this mean that modern and contemporary art fall outside the scope of the study of the evolution of human behavior? Some evolutionists seem to think so. Pinker (2002), for example, considers modern art a "denial of human nature" because it does not appear to appeal to our ancestral aesthetic preferences. However, modern art is only a denial of human nature if human nature is considered to be restricted to ancestral psychological adaptations, as standard evolutionary psychology asserts. Yet, another, less well known (possibly because more complex) but upcoming evolutionary approach to human behavior has a somewhat different and perhaps less narrow view on human nature. It takes into account both past and current selective forces and acknowledges the role of culture in shaping human evolution; it considers culture as an integral part of human biology. This approach is called cultural evolution theory. In the next section, I will explore whether cultural evolution theory can provide an evolutionary framework for understanding how and why modern and contemporary art often deviates from ancestral aesthetic preferences or standard evolutionary aesthetics.

Cultural Evolution

Cultural evolution theory (aka dual inheritance or gene–culture coevolution)[4] is a growing body of theoretical and empirical work that seeks to explain the evolution of human behavior. In that sense, it is not unlike evolutionary psychology, and indeed, they are largely overlapping research areas (Lewens 2015). However, unlike evolutionary psychology, its focus lies on how individuals acquire "cultural information" (mostly adaptive behaviors, skills, preferences, etc.) by social learning, that is, learning from conspecific. While evolutionary psychology typically leaves culture out of the "evolutionary equation," cultural evolution theory posits that the non-genetic transmission of information significantly impacts human evolution and behavior. Therefore, it is argued that culture should be considered conjointly with genetic influences. Thus, cultural evolution theory considers the

[3]This is not to say that other aspects might have played a role in the popularity of the bear as well, such as its monumentality.

[4]Next to the dual inheritance or "Californian" school, there is a "Paris" school of cultural evolutionists (i.e., cultural attraction theory) (Sterelny 2016). While the focus of the Paris school also lies on explaining the evolution of human behavior and culture, their ideas are closer to standard evolutionary psychology than the Californian school. Here I focus on the Californian school.

human behavioral phenotype as the outcome of both genetically and culturally inherited information. A classic case in point demonstrating that culture and genes interact during human evolution is the selection for alleles enabling the adult capacity to digest milk (lactose tolerance). Adult lactose tolerance has been selected several times and independently in human evolution in response to independent instances of the cultural innovation of dairy farming, while nondairy farming peoples across the world have remained lactose intolerant. This particular process has been called culture-driven gene–culture coevolution and provides convincing evidence of the impact of cultural transmission on human evolution (Richerson et al. 2010).

Even though, generally speaking, genetic and culturally inherited information are thought to interact during human evolution, it should be acknowledged that their relative roles in shaping human behavior depend on the behavioral domain. And this is not specific to humans. Song from songbirds, parrots, and hummingbirds, for instance, is by definition socially learned (without exposure to conspecific song the song does not come to full expression), while calls (such as alarm calls) are typically innate (Fitch 2006). Thus, just as bird calls, human aesthetic preferences for particular human, animal, and landscape features are not socially learned, but likely innate or at least "prepared" (Ohman and Mineka 2001), as discussed in the previous section. However, this does not seem to hold for modern and contemporary art. A lot of the artworks you find in today's reputed galleries are as difficult to grasp as to aesthetically appreciate. Its appreciation requires extensive training and learning; the art world has become a specialized domain of knowledge and skills even with respect to "mere" appreciation of art. Because standard evolutionary psychology pays comparatively little attention to behavior shaped by learning from others, it has a hard time reconciling modern and contemporary art (and its appreciation) with evolution.

Cultural evolution theory, on the other hand, focuses its empirical and theoretical efforts on understanding how learning from others shapes the human behavioral phenotype. Thus, since modern and contemporary art require extensive learning, cultural evolution theory seems, in principle, much better placed than evolutionary psychology to elucidate modern and contemporary art. Cultural evolutionists considers many different kinds of social learning strategies, but one of the most researched—and also possibly the most effective one—is the strategy to preferentially copying the cultural repertoire of influential or prestigious individuals. (Boyd and Richerson 1985; Henrich and Gil-White 2001; Henrich and McElreath 2003). Imagine a hunter-gatherer individual arriving in a new environment, with no knowledge about how to extract food from this local environment. He does not know which local plants are edible, nor how to track down and hunt animals. Probably, the most efficient strategy to quickly acquire adaptive survival skills and knowledge is copying the cultural repertoire of the most successful and admired (prestigious) individuals of the people living in that environment. Thus, the logic behind this strategy is that prestige functions as an indicator of locally "better-than-average" information. Empirical evidence shows that, for instance, individuals in hunter-gatherer societies indeed preferentially learn from prestigious hunters (Henrich and Broesch 2011). Quite relevant with respect to the current issue, cultural evolution pioneers Boyd and Richerson (1985) advanced the hypothesis that this "prestige-biased learning" strategy gave rise to the evolution of aesthetics. Thus, they offered an alternative explanation for aesthetics to the standard evolutionary aesthetics from evolutionary psychology. Their scenario goes as follows. The degree of prestige of a "cultural model" (an individual from whom may be learned) works as an indirect indicator of the quality of cultural information this cultural model has (say hunting or farming skills) to potential social learners. Thus, according to Boyd and Richerson (1985) prestige is analogous to a characteristic of a sexual ornament, such as the length of the peacock tail, which functions as an indirect indicator of the genetic quality of its bearer to the opposite sex (the peahen). However, the indicator trait (i.e., the degree of prestige or the ornament's signaling characteristics, respectively) can seize to reliably indicate "better-than-average" information and hence becomes arbitrary, due to a process that has been called Fisher's runaway process. In this process, preference for the indicator trait remains intact even though the indicator trait does not indicate any quality anymore. It is this latter process that Boyd and Richerson (1985, p. 278) envisioned as driving the cultural evolution of aesthetics: "Much as peacock tails and bowerbird houses are thought to result from runaway sexual selection, the indirect [i.e., prestige] bias runaway process will generate traits with an exaggerated, interrelated, aesthetically pleasing but afunctional form."

A similar proposal—albeit not framed within cultural evolution theory—has recently been made by Prum (2013). This evolutionary biologist also supports the view that Fisher's runaway process can explain the evolution of aesthetics. Specifically, Prum (2013) elaborates on the similarities between runaway sexual selection and Danto's concept of the artworld. Danto (1964) proposed the concept of "artworld," which denotes the social and cultural context within which theories of art[5] evolve (i.e., change), specifically to address the fact that some modern artworks deviated from what was at the time considered aesthetic (which roughly corresponds to the above-mentioned ancestral aesthetic preferences predicted by evolutionary psychology). Prum (2013) recast Danto's concept of the artworld into the Fisher's process, which he dubbed "coevolutionary aesthetics." The resulting framework holds that, within artworlds, artworks coevolve with their evaluations. This means that as evaluations change within a population, artworks change accordingly and vice versa. The coevolutionary framework implies that artists do not create art in a vacuum, inspired by the muses and separated from their audience, but that the audience has a decisive influence on how art changes over time. This makes perfect sense. It has been reported that influential art critics, dealers, or museum directors can have strong selective influences on the directions in which art changes (Thompson 2008; Wolfe 1975). In fact, they might well have stronger impact than most artists themselves. Yet, artists are naturally also part of the

[5]A theory of art is a cognitive structure or capacity that critically affects the outcome of the evaluation of art (Danto 1964; Prum 2013).

audience and as such they significantly influence both their own artistic production and the productions of other artists. As a result, anyone with some influence over others in an artworld, be it an artist or not, may have an impact on artistic change. Modern and contemporary art has evolved in the "international artworld",[6] which is a highly competitive, winner-take-all, environment. For instance, income and influence inequality are exceedingly large in the international artworld. This causes large differences in esteem and prestige. In such a situation, prestige may have a large impact on artistic preferences, beliefs, and opinions of its members, which in turn drive artistic evolution.

Based on Boyd and Richerson's (1985) and Prum's (2013) accounts of coevolutionary aesthetics, we can speculate whether prestige-biased learning might be used by insiders of the modern and contemporary art world to gain access to highly specialized information about art. And if this happens, whether it could account for contemporary and modern art's elusiveness and its divergence from standard evolutionary aesthetics. The general audience basically seems to ignore that art has become a specialized domain. Non-experts seem to go on judging modern and contemporary artworks based on ancestral aesthetic preferences, and because these artworks generally do not satisfy these preferences, they are often disturbed, shocked, or even bothered by them. In contrast, expert insiders of the international artworld are open to its ever changing, diverse aesthetics and want to learn to appreciate those new aesthetic developments every time again in order not to become an outsider. However, due to its diversity and degree of specialization, modern and contemporary art is exceedingly difficult to grasp and appreciate. Understanding and appreciating modern and contemporary artworks may be quite challenging because, due to the premium on originality and innovation, artists are incentivized to produce artworks that each time differ from existing ones. Rarely more of the same is produced. To keep track of relevant artistic developments, it makes perfect sense to use shortcuts to quality for anyone whose career depends on it. Prestige bias could be such a shortcut. As a consequence, an art insider or expert (i.e., professional artists, curators, dealers, critics, museum directors, etc.) would estimate that, all else being equal, an artwork has a higher chance to be of high quality if it is part of a highly prestigious collection, such as the New York Museum of Modern Art (MoMA) collection. The artwork would be definitely relevant for the international artworld *simply* because it is part of a highly reputed collection. The influence of MoMA's reputation on experts' appreciation of artworks is exactly what we investigated in a series of works presented in the next section. But before turning to these studies, I should address one other issue. The reader may have

[6]Also sometimes referred to as the "global art world," the international artworld is an intricate international network of artists, dealers, auction houses, collectors, and institutions, predominantly engaged in modern and contemporary art (e.g., Hart 1995).

concerns about some circularity in my contention above. I predicted that experts, some of them carrying prestige in the international artworld, will themselves use prestige to evaluate artworks. This circularity might seem problematic at first glance. Why someone so skillful or knowledgeable that she carries high prestige in the global art community would use prestige bias herself? You would assume that she does not need a shortcut to the hidden quality that prestige offers, because she already knows what is out there. Yet the reasoning would be illogical *only if* there is an objective artistic quality that prestige reliably indicates. However, if modern and contemporary art largely evolve according to the Fisher process, as Prum (2013) and Boyd and Richerson (1985) both contend, rather than the quality indicator mechanism, then there is no real hidden quality to find, except the prestige itself. In other words, preferences of art experts might be caught up in a self-reinforcing feedback loop as described by the runaway process. Eventually, any evidence that even (top)experts use prestige bias would support dynamics of artworld evolution typical of a runaway version of prestige-biased learning rather than a quality indicator version of prestige-biased learning.

Based on this brief presentation of what evolutionary psychology and cultural evolution theory have brought to the study of aesthetics and the arts, we make several predictions about the evolution of art. First, we predict that the general audience, that is non-experts or laypeople, will conform to the by-product hypothesis of art appreciation. This means that they will appreciate artworks to the degree that the content of these artworks appeal to human ancestral aesthetic preferences. Furthermore, we predict that the appreciation of artworks by experts, whose careers may depend on understanding specialized art, will be positively influenced by the association of artistic prestige with those artworks. Moreover, their appreciation might not depend on the presence of content appealing to ancestral aesthetic preferences.

Experiments

To date, we have conducted three studies to test our predictions about art appreciation. The first two have been published recently (Verpooten and Dewitte 2017). The third study has not been published yet, but we have done preliminary analyses. In all three studies, we measured the participants' expertise to distinguish between experts and non-experts in study 1 and 2 and to zoom further in on experts with different degrees of expertise in study 3. At the end of each experiment, we gave to participants a subjective expertise survey that included questions such as "How often do you go to an exhibition?" (slightly modified from Leder et al. 2012). We also let them take part in a short art quiz as an objective measurement of expertise.

Participants were then presented with pictures of artworks and were asked to express their appreciation of artworks on a Likert scale. The scale pairs numerical values (ranging from 1 to 7 or 1 to 5) with subjective evaluations of liking (ranging from "not at all" to "very much").

In each study, we manipulated two variables among both experts and non-experts: the "biological relevance" of the content of artworks and the artistic prestige of their associated context. Biological relevance refers to the extent to which the content fitted to naturally and/or sexually preferences as predicted by evolutionary aesthetics. We predicted that biological relevance would have a positive effect on non-expert appreciation. Biological relevance was always manipulated *within* subjects. As a result, each participant evaluated pictures that varied in biological relevance. In contrast, we manipulated artistic prestige *between* subjects in order to conceal this manipulation from them. To do so, participants were randomly assigned to two groups: one group was told that the works of art they were going to evaluate were part of the MoMA collection and that the MoMA is one of the most prestigious museums of modern art in the world. The other group received no information relative to the context. They were simply told that they would get to see and evaluate artworks. We predicted that experts' appreciation of a given picture would increase if they were told that it was an artwork from the prestigious MoMA collection. We did not expect any effect from content (biological relevance) on expert appreciation.

Facial Beauty in (Purportedly Artistic) Pictures

In study 1 and 2, the stimuli we used were not actual artworks, but rather pictures of faces that were previously produced for the purposes of research into face perception (Schacht et al. 2008). We presented participants with neutral and attractive faces (based on previous ratings: Schacht et al. 2008; see Fig. 3), thereby manipulating biological relevance given that facial beauty correlates with fitness and is therefore biologically relevant in a peer and a mate choice context (Little et al. 2011). As predicted, and in line with Komar and Melamid's findings, non-experts appreciated the (purportedly artistic) pictures featuring attractive faces more so than those in which the faces were only moderately attractive. Pinker (1997) put forward that art evolved as a by-product by "pushing," so to speak, naturally selected "pleasure buttons." In order to test this hypothesis about the underlying motivational system of non-expert appreciation, we also surveyed participants' aesthetic pleasure while evaluating the artworks, by asking the participants to express how aesthetically pleasing they found the artworks we presented to them (again on a Likert scale, which pairs numerical values of 1–7 or 1–5 with statements ranging from "not at all" at the lowest possible value to "very much" at the highest). Consistent with Pinker's pleasure button hypothesis, we found that aesthetic

Fig. 3 Some examples of portraits that we used as stimuli in study 1 and 2, depicting faces previously rated as being neutral (left) and attractive (right) (Schacht et al. 2008)

pleasure mediates[7] the positive effect of biological relevance on non-expert appreciation. This was not the case for the experts. Furthermore, experts appreciated the portraits with neutral faces even more than those with attractive faces, irrespective of the MoMA manipulation. Hence, as predicted, they clearly diverged from standard evolutionary aesthetics and from preferences of non-experts.

[7]We showed this using mediation analyses. A mediation is a hypothesized causal chain in which one variable affects a second variable that, in turn, affects a third variable. The intervening variable, M, is the mediator. It "mediates" the relationship. In psychology, mediation is commonly used to investigate hypothesized "underlying" mechanisms.

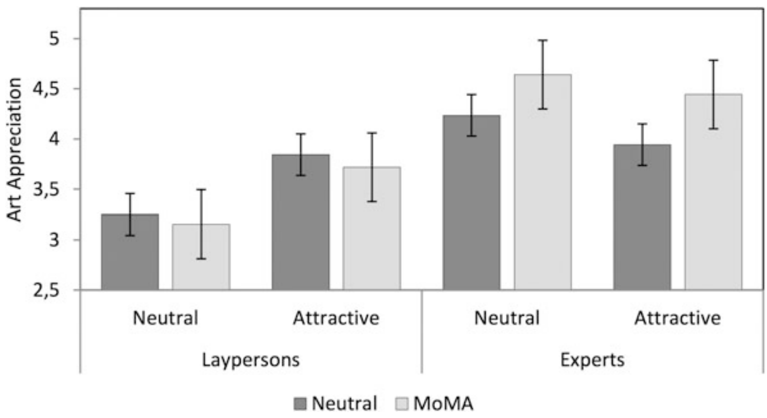

Fig. 4 A histogram showing the effects of depicted facial beauty (neutral vs. attractive) and of prestige (neutral vs. MoMA) on non-expert and expert appreciation in study 2. Non-experts appreciated ostensible artworks exhibiting attractive faces more so than did experts, who preferred neutral faces to attractive faces. Contrary to non-experts, experts were positively affected by prestige. The error bars show the standard error of the mean (from Verpooten and Dewitte 2017)

The predicted prestige effect was observed, as expected, in both studies 1 and 2. The prestigious MoMA context had no effect on non-expert appreciation. In contrast, experts who were grouped in the MoMA condition—and who were therefore tricked into believing that the portraits belonged to the MoMA collection—appreciated the portraits (both the neutral and attractive one's) more than did experts who were not included in the MoMA condition. We also measured admiration for the artist, as prestige biased social learning is associated with social emotions such as admiration, devotion, and respect (Henrich and Gil-White 2001). We asked the participants to express how admirable they found the hypothesized artist who made the purported artworks we presented to them (again on a Likert scale). Our analyses supported our expectation that admiration mediated the effect of prestige on expert appreciation. Consequently, the results of these two studies satisfied quite well our predictions. The main findings are displayed in Fig. 4.

(In)animate Objects in MoMA-Artworks

The third study is again a collaboration with Siegfried Dewitte. We managed to recruit more than a thousand highly experienced participants, mainly via a large European museum. Our second study indicated that people recruited through this European museum scored on average about twice as high on our expertise scales than the general population. We could therefore assume that the majority of them were art experts. Thus, this large sample allowed us to investigate expert appreciation in more detail. In this third study, we manipulated biological relevance in a

Fig. 5 Some examples of artworks that we used as stimuli in study 3. Artworks depicting animals (left) and inanimate objects (right). Retrieved from http://www.moma.org

different way. This time we used real artworks from the MoMA collection as stimuli and selected visual artworks that either clearly pictured animals, such as a pig, or artworks that clearly depicted inanimate objects, such as a chair (see Fig. 5). Since research showed that people exhibit evolved attention and preference for animate entities because they are biologically relevant (Altman et al. 2016; New et al. 2007; Yang et al. 2012), we were confident of being able to manipulate biological relevance in this way. The analyses I here present are preliminary; however, I include them because they indicate some clear patterns that are relevant to the issues discussed in this chapter.

We found a strong main effect of the variable animacy on appreciation such that, overall, participants appreciate the artworks depicting animals to a higher degree than artworks depicting inanimate objects. However, this effect of animacy is moderated by expertise: the more experienced the participants are, the less they are positively influenced by the presence of animals in the artworks. Figure 6 displays these findings. As Fig. 6 suggests, there might even be an inverse effect of animacy on appreciation of the most experienced experts, such that these "top experts" might even prefer artworks depicting non-animate objects. Further analysis will allow us to determine whether this is the case or not. At any rate, the present analyses indicate that biological relevance does not increase top expert appreciation.

As for prestige, we found that situating the artworks in the context of the MoMA produced a positive effect on the appreciation of experts, as in study 2. This effect is not moderated in any way by expertise, which indicates that even top experts are positively influenced by the prestige manipulation. As mentioned, this is consistent with the runaway version of prestige, which Boyd and Richerson (1985) linked to

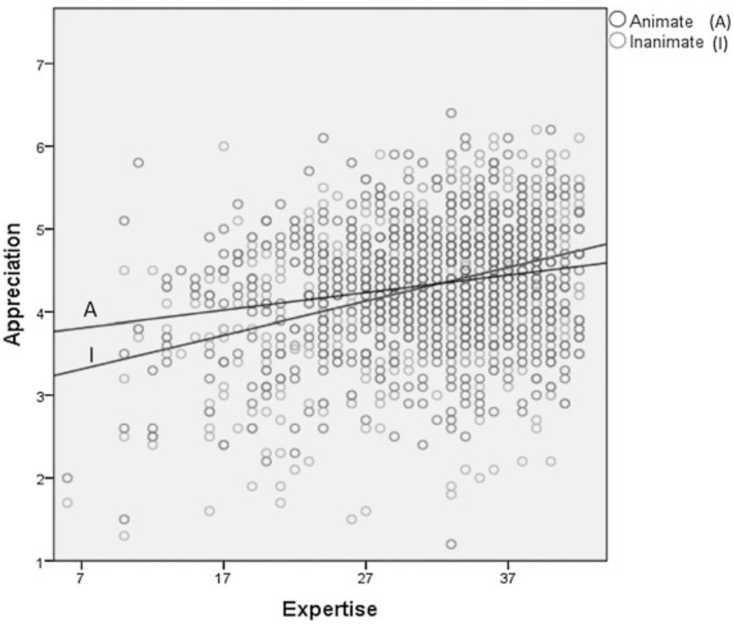

Fig. 6 A scatter plot with fit lines showing the effect of animacy in relation to expertise on the appreciation of artworks in study 3. The fit lines show that as expertise of spectators increases, appreciation of artworks depicting inanimate objects (e.g., a chair) increases relatively to appreciation of artworks depicting animate objects (e.g., a lion) (Verpooten and Dewitte, unpublished data)

the evolution of aesthetics, rather than with the quality indicator version of prestige. Furthermore, our preliminary analyses indicate that prestige moderates the effect of animacy on appreciation, such that it decreases the differences between appreciation of animate and inanimate, possibly by increasing the appreciation of artworks depicting inanimate objects. Moreover, we found a significant three-way interaction between prestige, animacy and expertise that point in the same direction. We have not yet delved into this statistics either, but Fig. 7 already shows that this three-way interaction may be caused by the fact that the overall positive effect of prestige is strongest on the least experienced experts' appreciation of inanimate objects. We did not find any interactions between prestige and biological relevance in the previous studies, yet finding them in study 3 does seem to make sense: inanimate objects are least biologically relevant and require strongest efforts in terms of using prestige-biased learning to be appreciated, especially among the least experienced who tend to appreciate the artworks depicting the animate objects more. Hence, these interactions may provide additional support for our prediction that experts actively use prestige bias to increase their appreciation of artworks that deviate from standard evolutionary aesthetics.

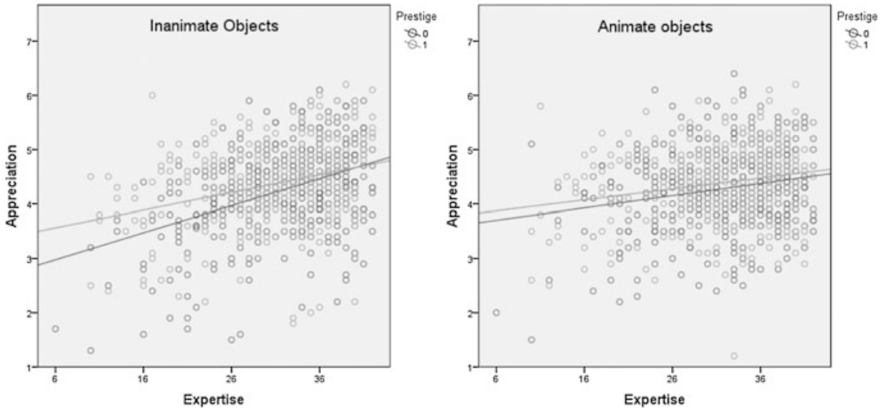

Fig. 7 Two scatter plots with fit lines showing the effect of prestige (MoMA) on appreciation in relation to expertise for artworks depicting inanimate (left) and animate objects (right). The plots' fit lines illustrate three findings of study 3 with respect to prestige. Taken together, they demonstrate the overall positive effect of prestige on appreciation, they show how prestige decreases the difference between the appreciation of inanimate and animate objects and they illustrate that prestige has a particularly large effect on the appreciation of inanimate objects among the least experienced experts (Verpooten and Dewitte, unpublished data)

Apart from the interactions between biological relevance and prestige (and expertise), the reader may have noticed another potential difference between studies 1 and 2 when compared with study 3 with respect to the variable biological relevance. In study 3, less experienced experts' appreciation remains subject to biological relevance, whereas in studies 1 and 2 this was not the case. Several explanations are possible. For instance, it may be that the distinction between inanimate and animate objects in study 3 is a stronger manipulation of biological relevance than the distinction between neutral and attractive faces in studies 1 and 2. As a result, despite the use of prestige (to deviate from evolutionary aesthetics), biological relevance continues to have a positive effect on the appreciation of the least experienced or "regular" experts. Further analysis of the data set in study 3 should allow us to objectify this observation.

Discussion

I began this chapter with our art observation post and described how we used it to do fieldwork. In hindsight, we combined two types of field research from the standpoint of anthropology and the social and behavioral sciences. On the one hand, we collected quantitative data about human art behavior in its natural setting, such as a national art contest. This outsider and top-down method is referred to as the *etic* approach in these research fields. On the other hand, in a way, I simultaneously participated as an artist and was regarded as such by members of the contemporary art world. This enabled me to do what anthropologists call "participant observation" of art experts of all kinds (artists, gallery owners, curators, art critics, etc.). This insider and bottom-up method corresponds to the *emic* approach in which fieldwork privileges viewpoints obtained from within the social group under analysis, that is, from the perspective of the subject (Headland et al. 1990). Next to informative first-hand experiences as an artist, participating in art events created the opportunity to talk to members of the contemporary artworld about their experiences and thoughts about how the contemporary international artworld operates. Based on discussions, experiences and observations, I speculated that appreciation deviated from non-expert appreciation and I also suspected that prestige played a role in this deviation.

To test these hypotheses, we went back to using the *etic* method and conducted studies in experimental psychology probing art appreciation. With respect to non-experts or general audiences, the studies corroborated earlier cross-cultural findings about art appreciation (Dutton 2009): studies 1 and 2 suggested that non-experts appreciate art based on naturally and/or sexually selected aesthetic preferences for facial beauty, which is in accordance with standard evolutionary aesthetics. In contrast, we found that facial beauty and appreciation were negatively correlated among experts. In study 3 we found that animacy is positively correlated with appreciation among experts; however, expertise moderates the effect of animacy on appreciation such that among top experts animacy becomes uncorrelated (or perhaps even negatively correlated) with appreciation. Furthermore, experts, including top experts, increase their appreciation of artworks if they are told that the artworks they are rating belong to the prestigious MoMA, while non-experts are not influenced by the prestige of the context of the artworks. Thus, our findings on expert appreciation lend support to our contention that experts have learned to deviate their appreciation from evolutionary aesthetics by engaging in, most likely among other things, prestige biased social learning. The contemporary artworld consists of communities of art experts who exert influence on the direction in which art changes by selectively preferring art (art critics, artists), literally selecting art (curators, dealers, collectors, etc.) or by selectively producing it (artists). In other words, artworks coevolve with their evaluations and especially with evaluations by prestigious entities such as well-respected experts or institutions such as the MoMA. This is what we have called prestige-driven coevolutionary aesthetics (Verpooten and Dewitte 2017). This implies that expert appreciation could, in principle, explain why modern and contemporary art deviates from naturally selected aesthetic preferences and hence evolutionary aesthetics. But how precisely does prestige-biased learning achieve this effect?

A first possible explanation is that the divergence from standard evolutionary aesthetics is driven by the need of experts to distinguish themselves from non-experts (cf. Bourdieu 1979). For instance, if art expert preferences were to coincide entirely with non-expert preferences, this might undermine their relevance and thus their career. A second possibility is that experts want to resist the easy reward of pleasure based on standard evolutionary aesthetics and instead prefer art based on an indicator of quality, that is, prestige. This mechanism might be comparable, on a generic level, to the resistance of exploitation of sensory biases in sexual selection, which also has been shown to lead subsequently to the quality indicator mechanism to take over (Garcia and Lemus 2012; Garcia and Ramirez 2005). A third possibility is that art experts seek an intellectual challenge and therefore prefer art that is hard to grasp (this mechanism may account for the divergence from biological relevance among experts, but is hard to reconcile with the use of prestige) (Van de Cruys and Wagemans 2011). A fourth possibility is that deviations from standard evolutionary aesthetics among experts result from random outcomes of the runaway version of prestige bias. For example, if a highly reputed institution, say the MoMA, within an artworld promotes art that, for some arbitrary reason, slightly deviates from standard evolutionary aesthetics, members of this artworld are predicted to adapt their art preferences according to MoMA's promotions in order to stay up to date. If, as a result, deviations from previous aesthetic standards become generally preferred, that is, they become the norm, this can lead to new preferences for even further deviations from these initial slight deviations from standard evolutionary aesthetics. Without going into technical details, the essence of the runaway process is thus that initial slight deviations can become really exaggerated in a self-reinforcing feedback loop of runaway prestige-biased learning (cf. Boyd and Richerson 1985). As explained above, our preliminary finding that even the most experienced experts resort to prestige bias supports this final possibility. However, it is conceivable, perhaps even likely, that some of these possible mechanisms operate sequentially or even in tandem. Further experiments could be conducted to determine which of these particular mechanisms are accountable—and to which extent—for the patterns with respect to biological relevance and prestige we found.

In summary, we found that non-expert appreciation is consistent with standard evolutionary aesthetics, while expert appreciation corresponds to prestige-driven coevolutionary aesthetics. The latter mechanism can explain deviations from standard evolutionary aesthetics as well as the existence and persistence of elusive modern and contemporary art. The fact that our art observation post also deviates from standard evolutionary aesthetics, but was nevertheless selected by a professional art jury, is consistent with our contention that coevolutionary aesthetics prevails among art experts.

Relation to Empirical Aesthetics and Social/Historical Accounts of Art Appreciation

Our findings may have relevance beyond aesthetic evolution in relation to art. In a recent paper, Bullot and Reber (2013) discuss the lingering divide between psychological and sociohistorical approaches to art appreciation which hampers scientific progress. The psychological approach focuses on mental (empirical aesthetics) and neural processes (neuroaesthetics) involved in the appreciation of artworks (Leder et al. 2004; Leder and Nadal 2014). Much like evolutionary psychological accounts of art (Boyd 2009; Dutton 2009; Pinker 2002), this approach holds that the appreciation of artworks depends on universal human psychological characteristics. However, the historical approach to art contests psychological methods and views. Its defenders (scholars from aesthetic contextualism, sociology of art, art history, and art criticism) contend that the sensitivity of art appreciators to the contexts of an artwork determines their evaluation of that work. These contexts include individuals associated with the artwork such as the producing artist, curators and dealers (Bloom 2010), the social context (Bourdieu 1979), and the art historical context (Gombrich 1951) or artworld (Danto 1964). Even though the divide between the psychological and historical approaches to art has traditionally been wide (cf. the infamous "Two Cultures" in academia), there is a growing consensus that in order to advance our understanding this divide will need to be bridged (Bullot and Reber 2013).

In order to bridge the divide, psychological researchers should and are starting to acknowledge that appreciation of an artwork does not only depend on the experience of its formal characteristics (which is an idea from modernism which is now considered outdated by contemporary art experts), but also, crucially, on sociohistorical and art historical context aspects. Art experts (art theorists, historians, and philosophers of art), on their part, should acknowledge that art appreciation is not entirely idiosyncratic, as they often assume, but that universal psychological rules exist that do influence art appreciation.[8] Our findings might contribute to the (partial) integration of psychological and sociohistorical approaches. Firstly, our data show that the universal psychological characteristics that are examined by standard evolutionary aesthetics have above all an effect on the art appreciation of *non-experts*. Yet, we find that expert appreciation diverges from this and may even run against standard evolutionary aesthetics. Secondly, traditionally, empirical aesthetics considers the exposure afforded by "daily life" to be a major determinant of non-expert appreciation (Cupchik and László 1992). Yet, our data suggest that this is not the case. We find support for the standard evolutionary aesthetics prediction that ancestral, naturally and/or sexually selected aesthetic preferences play a much greater role in art appreciation than daily life does. For example, in study 3 we find that even regular experts appreciate artworks picturing animals we commonly do not encounter in our daily lives, such as a leopard, more so than artworks depicting objects that are highly relevant in our daily lives such as a building or a chair. Next, I will hone in on artistic understanding, which contextual aestheticians and art historians consider an essential part of art appreciation.

[8]The fact that appreciation varies substantially between individuals does not preclude underlying human universals. Evolutionary researchers stress that human universal psychological characteristics are most often plastic, which means that they can change adaptively in response to particular environments.

Artistic Understanding

Bullot and Reber (2013) argue that artistic understanding of an artwork based on knowledge of its art historical context is a requirement for its appreciation. Our theoretical and empirical work does not necessarily contradict this, but it does suggest some major caveats. Firstly, it seems that being familiar with the art historical context is only important for appreciating art that *requires* you to know its context in order to appreciate it. This may be the case for hard to grasp modern and contemporary art. This kind of art is often hard to understand and appreciate without any context information. Take the prototypical example of Duchamp's Fountain again. To someone who does not know the artist's intentions and the social and art historical relevance of that influential artwork, it is merely an ordinary urinal. Without understanding, there cannot be a proper appreciation of that work. But context information is, logically, much less important to appreciate art that appeals directly to standard evolutionary aesthetics, that is art that depicts, for instance, attractive human or non-human animals, as the majority of popular art, ethnic and prehistoric art does. The things that need to be understood in order to appreciate these latter kinds of art are usually more limited. For example, even though we do not know what the potential cultural significance or symbolism of a prehistoric figurine such as the famous Venus of Willendorf (c. 25,000 BCE) was, we can appreciate it as art nonetheless, thanks to its direct appeal to standard evolutionary aesthetics (Dutton 2009). Thus, it seems that only modern and contemporary art, which has coevolved with expert evaluations, requires artistic understanding to be appreciated. However, the runaway hypothesis about expert appreciation may imply a further caveat concerning artistic understanding. If experts trustingly use prestige to base their appreciation on and if prestige is in fact arbitrary, that is, not referring to any objective quality, as indicated by our finding that even top experts use prestige, then artistic understanding may be illusory. As the gallery owner I mentioned in the intro to this chapter admitted, experts sometimes do not grasp contemporary art, even when they have access to all of the context information. In such a case, appreciation is not based on artistic understanding, but it might be based on an illusion of understanding, which may in turn be based on the runaway version of prestige. It thus remains an empirical question to what extent artistic understanding is real or an illusion of understanding maintained by runaway prestige bias. An interesting development in this respect is that some art experts now seem to prefer art that they do not understand. As artist Pae White quite literally puts it: "My favorite art is the art I don't understand" (Grosenick and Riemschneider 2005, p. 330). Thus, elusiveness seems to have become an artistic quality in itself. This makes perfect sense if you consider that elusiveness indicate some hard to grasp but valuable meaning, as predicted by quality indicator prestige. However, elusiveness is equally consistent with the possibility that the artwork is baked air, as predicted by runaway prestige. Again, the degree to which modern and contemporary art corresponds to the former or latter possibility is an empirical question, albeit one which is probably hard to answer.

Conclusion

In this chapter, I reported research we have conducted in the domain of art. I began with a description of the art observation post that was used to collect data on art behavior in the field. We found that the post itself was considered to be art by art experts even though it did not seem compatible with standard evolutionary aesthetics, a subfield of evolutionary psychology. I then argued that cultural evolution theory, and in particular prestige biased social learning, might be better suited to explain the fact that experts regarded the observation post as an artwork as well as the fact that they appreciate modern and contemporary art that does not correspond to standard evolutionary aesthetics. I summarized and discussed psychological studies that we conducted and that, overall, lent support to the hypothesized role that prestige bias plays in the appreciation of modern and contemporary art, its divergence from standard evolutionary aesthetics and its elusive manifestations. I suggested a number of specific mechanisms that may be associated with this divergence. Their relative roles should be further scrutinized theoretically and empirically. I concluded with a discussion of our findings in relation to empirical aesthetics and to social and historical approaches to art.

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The Evolution of Feminine Beauty

Jeanne Bovet

Abstract If you enter the word "beauty" in a search engine, almost all the pictures you will see appear on your computer screen are of attractive young women. In Western society, the concept of beauty is closely associated with physical attractiveness and especially feminine physical attractiveness. Beautiful women are everywhere: on the walls of our cities, on the screens of our movie theaters, on the glossy paper of our magazines. But is this phenomenon restricted to contemporary societies? It does not seem so, as women's beauty has occupied the minds of painters, poets, philosophers, musicians, and writers for centuries. Indeed, in arts, depictions of idealized female beauty far outweigh those depicting ideals of male beauty. Why are human beings so fascinated by female attractiveness? The aim of this chapter is to show how evolutionary theory can help us to understand this passion for women's bodies and their beauty, and explore what the arts can teach us about human beauty while addressing the question of its universality.

Introduction

Ancient Greeks thought that human beauty could be explained by mathematical rules. According to these early scholars, beauty was defined in terms of right proportions (or "golden ratios"). These principles governed the human face and body, but also dictated what was beautiful in architecture, music, and painting (Swami and Furnham 2008) and was later adopted during the Italian Renaissance (see Fig. 1). This view of beauty is outdated, but it demonstrates that the search to understand human beauty is old. Apart from its central place in the arts, physical attractiveness has an impact on many aspects of our everyday lives, as people tend to behave differently with attractive people. Indeed, beautiful people are judged more positively on a variety of dimensions and treated better than less attractive

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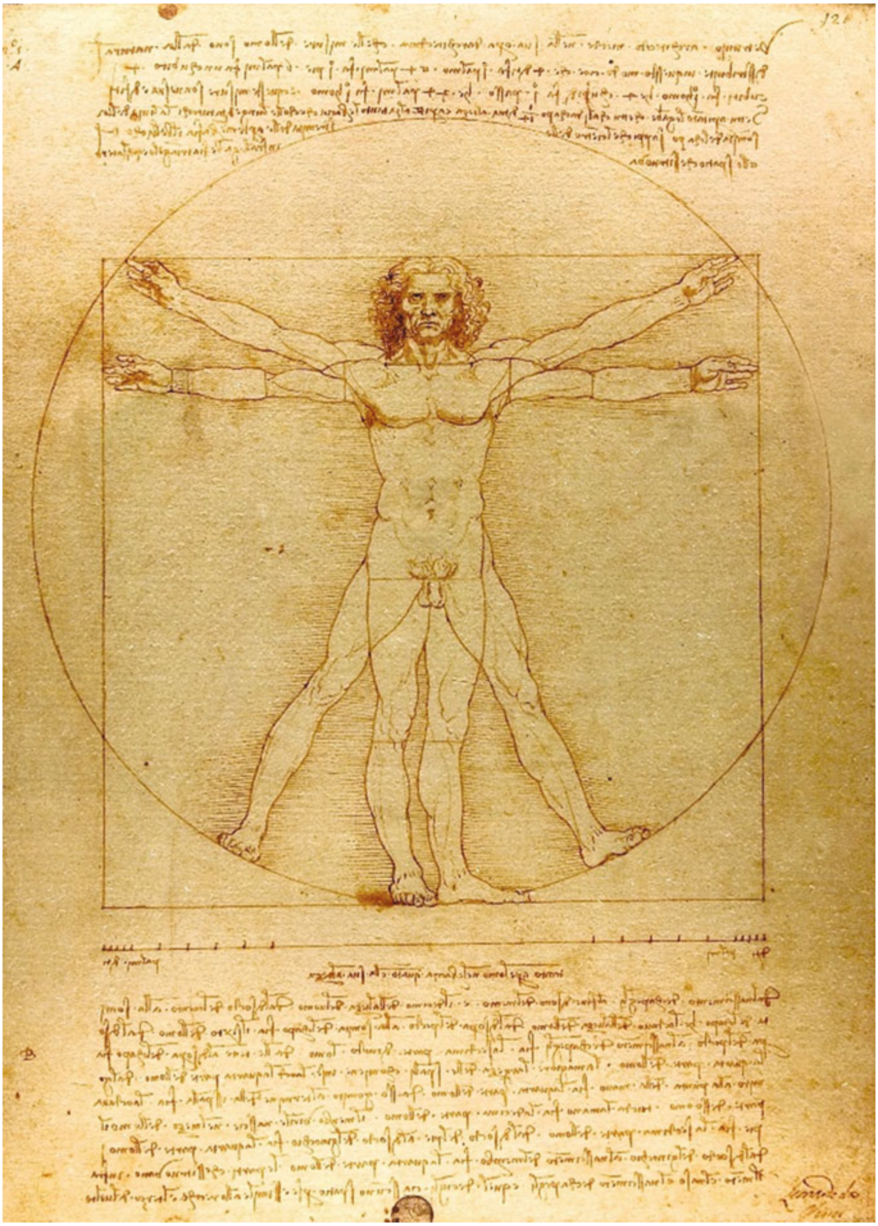

Fig. 1 Leonardo da Vinci's Vitruvian Man (c. 1492) combines a reading of texts from ancient Greece and his own observations of human bodies

ones (Langlois et al. 2000). For instance, physically attractive individuals are judged as more socially and intellectually competent, more successful, and happier than less attractive individuals (Dion et al. 1972; Eagly et al. 1991). Attractive people are also more likely to be hired for jobs (Dipboye et al. 1975, 1977; Watkins and Johnston 2000), receive higher salaries (Roszell et al. 1989), and benefit from more lenient sentencing in the courtroom (Stewart 1985; Mazzella and Feingold 1994). However, the aim of this chapter is not to explore the various effects of physical attractiveness on an individual's life, but rather to explain which features are considered attractive and why. To do so, I adopt an evolutionary psychological approach that seeks to understand human behaviors in an evolutionary framework. I will show that preferences for some physical features are likely the result of sexual selection. The list of physical features linked to attractiveness presented in this chapter is not exhaustive, and I will focus on the evolutionary mechanisms behind our preferences for beauty.

Evolution, Preferences, and Mate Choice

The Adaptive Value of Preferences

We make choices all the time, in a wide variety of contexts, such as where to live, what to eat, who to be friends with, who to avoid, and who to marry. Some options are better or more adaptive than others for the individual choosing them. For example, our ancestors had to choose what to ingest among various elements present in their environment, like fruits, nuts, roots, mushrooms, but also leaves, soil, stones, feces, carrion, etc. An individual picking his food randomly will not survive very long, simply because there are many non-edible and toxic elements in the environment. This is where preferences come into play. Preferences can be defined as psychological mechanisms motivating individuals to adopt beneficial behaviors. In our example, taste preferences help individuals to choose non-toxic and healthy food over items that may be poisonous or have little nutritional value. Individuals who found that sweet fruits and honey tasted "good" survived better than individuals without any preference or than individuals who liked the taste of rotten meat. Many of these preferences are heritable (biologically or by cultural transmission) and so are transmitted from parent to offspring and so on, until us.

Similarly, during mate choice, individuals have to choose between a variety of potential partners with different mate values, defined as the degree to which an individual would promote the reproductive success of another individual by mating with him or her. Here again, preferences can help in choosing a mate that will increase reproductive success compared to other options. This phenomenon—mate choice—is a major mechanism through which sexual selection influences evolution (Andersson 1994). Sexual selection refers to differentials in reproduction rates among individuals, independent of advantages resulting from differential survival.

One way this occurs is through intrasexual competition where same-sex individuals compete against each other, resulting in adaptations of traits useful during confrontations between same-sex conspecifics like size, strength, weapons, and aggression. Another way consists in attracting opposite-sex individuals through mate choice, which can drive selection for extravagant traits like ornaments or complex courting behaviors. Some of these traits indicate the underlying health and genetic quality of individuals. For instance, the peacock's tail is thought to indicate the quality of the individual even though it does not directly help the individual to survive (in fact, it may even be detrimental to survival by increasing the individual's conspicuousness to predators) (Zahavi 1975; Petrie 1994). Traits that indicate underlying mate quality may come to be preferred, as individuals having these traits will confer benefits to those choosing them. Benefits can be direct (protection or material provisioning for example, but also number of descendants) or indirect (fitness of the descendants) (Kokko et al. 2003). Over time, selection favors psychological mechanisms allowing the identification, assessment, and integration of cues of high mate value and motivating individuals to be attracted to conspecifics exhibiting these cues, because these preferences likely led to more successful reproduction than alternative designs. The sum of these assessments contributes to our perception of a potential mate's "physical attractiveness" (Sugiyama 2015).

Individuals are mostly not conscious of the ultimate, evolutionary reasons of their preferences, whether they are for sweet and fatty foods over bitter and starchy foods, or for attractive potential mates. A human being, as well as a chimp or a cat, can have a preference without being aware of the factors that caused this attraction (Zajonc 2000; Berridge 2003). Even if an individual is aware of the factors affecting his choice (e.g., he may know that he prefers sweet over bitter food), he will not necessarily be aware of the underlying quality linked to the preference (sugar represents a source of energy for the organism, while bitterness is often linked to toxicity, see Scott and Mark 1987; Glendinning 1994). Thus, humans can have preferences for certain types of physical features because they indicate some underlying quality, without being conscious of the evolved reasons for these preferences.

The evolution of adaptive preferences for cues of underlying mate value is not the only mechanism occurring in sexual selection. Fisher described a process called the "runaway sexual selection" (Fisher 1930). It consists in an evolutionary positive feedback loop between female preferences for certain male features and the male features in question. Let us assume a male trait—for example the color red—and female preference for this trait that are both genetically determined and genetically linked to each other (e.g., the genes coding for these traits are located closely on the same chromosome). Females who mate with red males will thus produce red male descendants and female offspring with a preference for red mates. At the next generation, these red "sexy sons" will have higher mating success as females prefer red partners, and females will have successful red sons themselves. Another theory known as the "sensory bias" model (Endler and Basolo 1998; Payne and Pagel 2001; Fuller et al. 2005) stresses that a preference for a given characteristic in a mate can derive from a preference that has selective advantage in another domain than mating. For example, a general preference for the color red can evolve to spot mature fruits and then applies to a mate choice context and biases preference toward red sexual colors. In that case, the color red is not a signal of a mate underlying quality, and the preference for red mates is a by-product. Importantly, these different mechanisms of sexual selection (runaway selection, sensory bias, and cues of mate quality) are not mutually exclusive, and they surely work together (Kokko 2001; Kokko et al. 2003, 2006). For example, sensory biases have been proposed to explain the initial association between a trait and a preference from which a runaway process can take place (Kokko et al. 2003). In this chapter, we focus on features that are cues of underlying mate value and do not consider runaway selection and sensory bias.

Women's Mate Quality

Components of human mate value include sex, age, degree of relatedness, health, status, kindness, intelligence, and willingness and ability to invest in offspring (Sugiyama 2015). The features linked to a high mate value in men are not necessarily the same as the features that women value and the criteria for male and female attractiveness will often differ (Symons 1980; Buss 1989a). A major feature of women's mate value is fertility, defined as the probability of present reproduction. Indeed, to be reproductively successful, ancestral men had to mate with women able to have children, and this capacity varies among women (more than it varies between men, as it requires a larger investment). Thus, ancestral men would have the greatest likelihood of having children if they mated with women who were fertile and more likely to bear children than other women. As a woman's fertility is largely determined by her physical and physiological condition, men value physical cues in prospective mates more than women (Buss 1989a). Women appear to be sensitive to this preference and frequently try to amplify these cues, as indicated by the highly lucrative cosmetics and associated beauty industries. Male mate value includes traits associated with genetic quality, health, and physical strength, as well as traits associated with ability and willingness to invest in a woman and her offspring (Symons 1980). In the following, I will focus on men's preferences, even if some of the characteristics described here are considered attractive to both men and women. I will also focus on fertility, even if mate choice obviously implies many other aspects (personality traits for instance, see Botwin et al. 1997).

Two obvious elements of fertility are youth and health: Older and unhealthy women cannot have as many children as young, healthy women. As a consequence, ancestral men who were able to detect and prefer young and healthy women had more descendants, who inherited these preferences. Women's fertility increases from puberty, peaks during the twenties, and decreases after the late twenties until menopause (around fifty on average) (Menken and Larsen 1986; Dunson et al. 2002). After thirty, the probability of becoming pregnant decreases, and risks of complications, miscarriages, and mortality (of both the mother and the baby) increase (Naeye 1983; Amarin and Akasheh 2001). The average mean age at last birth for women in hunter-gatherer societies is 34.9 years (Sugiyama 2015). Thus, women's capacity for reproduction is limited to a fraction of their life, and cues associated with advancing age are expected to be negatively correlated with female sexual attractiveness. Indeed, cross-cultural research shows that men prefer partners younger than themselves (Buss 1989b; Kenrick and Keefe 1992). Marriage patterns in these cultures are in accordance with this preference: Wives are, on average, 3 years younger than their husbands (Buss 1989b; Kenrick and Keefe 1992). In fact, the age difference preferred by men increases with their own age, showing that, whatever how old they are, men are sexually attracted by women with an age close to their fertility peak (Buunk et al. 2001).

Health is also a critical criterion in mate choice (Tybur and Gangestad 2011). Not only it is dangerous to copulate with an individual with a contagious disease, but health can also affect an individual's reproductive capacity and especially female fertility. Pregnancy and lactation are demanding and usually require being in good health: For women of normal BMI, pregnancy increases energetic requirements by roughly 90, 300, and 466 calories a day during the first, second, and third trimesters, respectively. Breastfeeding increases energy requirements by about 450–500 calories per day in healthy Western women who are not particularly active (Butte et al. 2004). The mean weaning age in hunter-gatherer societies averages 30.9 months (Sugiyama 2015), followed by years of investment where the child is still dependent of care and food provisioning. Moreover, many diseases can limit or disrupt the ability to become pregnant, the course of pregnancy, or the health of the baby. Finally, individuals differ in their susceptibility to parasites because of genetically determined host resistance, and sexual selection for healthy partners would provide choosy individuals with resistant offspring (Fink and Neave 2005). As a consequence, healthy individuals should be judged as more attractive than unhealthy individuals. This is confirmed by research showing for example that attractive faces are considered healthier than less attractive faces (Grammer and Thornhill 1994; Kalick et al. 1998).

Not all young and healthy women have the same fertility, and this individual variation in fertility is closely linked to sexual hormones. Levels of sexual hormones vary during women's life course and ovarian cycles, but they are also variable between women, and high levels of feminine hormones are closely linked to fertility. The two main hormones that impact women's fertility are estrogen and progesterone. Their levels of production during menstrual cycles have been demonstrated to be good predictors of conception's success (Roumen et al. 1982; Dickey et al. 1993; Stewart et al. 1993; Lipson and Ellison 1996; Baird et al. 1997; Santoro et al. 2000). Reproductive status and parity (i.e., the number of previous pregnancies) are also important factors. Pregnant and lactating women are momentarily infertile, and, independently of age, each pregnancy decreases future reproductive potential: With each birth, the average hunter-gatherer woman loses a sixth of her reproductive value (Sugiyama 2015). Thus, cues associated with sexual hormone levels, reproductive status, and parity are all expected to be correlated with female sexual attractiveness. Between-women differences in estrogen and progesterone levels are indeed linked to ratings of facial attractiveness (Law Smith et al. 2006), and some studies even suggest that men are capable of detecting ovulatory cues, with men preferring women's odors, faces, and voices during their fertile phase (Haselton and Gildersleeve 2011).

What Is Beauty Made Of?

A Beautiful Face

Multiple studies have shown that cues of aging are present in the face and that men use them to judge a woman's attractiveness (Korthase and Trenholme 1982; Alley 1988). Facial features that indicate youth are more attractive to men (Furnham et al. 2004; Fink et al. 2006; Matts et al. 2007; Kwart et al. 2012), and the decline of facial attractiveness with age is stronger for women than for men (McLellan and McKelvie 1993; Maestripieri et al. 2014).

Skin quality is also an important element of physical attractiveness as it does not only give information about an individual's age, but is also an indicator of his or her current and past health. First, there is a direct link between some illness, infection, and skin lesions or scars (Buss 2005). Skin condition also provides a window on the strength of immune functioning, indicated by ability to heal without infection (Singh and Matthew Bronstad 1997; Sugiyama 2004a). Some skin issues like dermatoses or acne can also be correlated to hormonal disorders (Steinberger et al. 1981; Schiavone et al. 1983; Held et al. 1984; Lucky 1995). As a consequence, homogeneous and smooth skin are judged as healthier, younger, and more attractive (Fink et al. 2001, 2006; Jones et al. 2004; Matts et al. 2007; Fink and Matts 2008). The color of the skin is linked to nutrition, health, and fertility: The yellowness of the skin is linked to the carotenoids (Alaluf et al. 2002; Whitehead et al. 2012b), which play a role in immune activity and protection from oxidative stress damage (Sies 1993; Hughes 1999). Redness of the skin is associated with vascularization and oxygenation of blood, and women's estrogen levels (Stephen et al. 2009). Several studies show that an increase in redness or yellowness enhances both apparent health and attractiveness of the face (Stephen et al. 2009, 2011; Whitehead et al. 2012a, b; Lefevre et al. 2013; Lefevre and Perrett 2015; Kandrik et al. 2016). Finally, women tend to have lighter skin than men in various populations (Jablonski and Chaplin 2000), possibly to increase vitamin D absorption for calcium needs during pregnancy and lactation (Jablonski and Chaplin 2000). Skin darkens with age and pregnancies (Byard 1981; Jablonski 2013), such that comparatively light skin is predicted to be attractive in females, as a cue of youth and nubility.

Although human faces approach symmetry, developmental events and defects can disrupt its developmental course (Moller 1999). Symmetry is thus hypothesized to reflect resistance to pathogens and developmental stress, thanks to an efficient use of resources during development and a healthy immune system (Moller 1999; Grammer et al. 2003). Asymmetry can also indicate genetic anomalies (Grammer et al. 2003). Consistent with symmetry being a signal of good health and underlying immune and genetic quality, a preference for symmetrical faces has repeatedly been shown for both sexes (Grammer and Thornhill 1994; Rhodes et al. 1998; Mealey et al. 1999; Scheib et al. 1999; Rikowski and Grammer 1999; Perrett et al. 1999; Hume and Montgomerie 2001; Penton-Voak et al. 2001). The importance of symmetry is not confined to modern Western societies: Even early forms of human art, and especially face and body paintings, emphasized symmetry (Swami and Furnham 2008).

During puberty, the level of sex hormones in the blood increases and faces of women and men start to differ: For boys, androgens stimulate growth of the jaw, cheekbones, and brow ridges, while estrogens inhibit the development of these features among girls, which may also increase lip size (Thornhill and Møller 1997). These sexually dimorphic traits signal sexual maturity and reproductive potential (Johnston and Franklin 1993; Thornhill and Gangestad 1996; Law Smith et al. 2006) and influence facial attractiveness (for a review see G. Rhodes 2006). Multiple studies using various techniques found that facial femininity increases the attractiveness of women (e.g., see Jones and Hill 1993; Perrett et al. 1994, 1998; Rhodes et al. 2000; Koehler et al. 2004; Komori et al. 2009; Platek and Singh 2010).

An Attractive Body

Body shape also contains cues of age, health, hormonal status, and parity. Let us first consider the weight—or more specifically the body mass index (BMI), which is the weight divided by height squared. Having a very low or high BMI can have an impact on a woman's capacity to reproduce (Zaadstra et al. 1993). If a woman is too thin (because of a lack of food or a disease), she will stop ovulating or will not have enough resources to carry out a pregnancy or lactation (Frisch and McArthur 1974; Frisch 1987). On the other hand, overweight or obesity are linked to disorders of the ovarian cycle and to a greater risk of miscarriage (Rogers and Mitchell 1952; Hamilton-Fairley et al. 1992; Clark et al. 1998). Thus, we expect individuals to be sensitive to the BMI of prospective partners because it reflects potential reproductive outcomes. Indeed, multiple studies using different types of stimuli show that BMI drastically influences female body attractiveness (Singh 1993a, b, 1994, 1995a; Swami et al. 2006a; Crossley et al. 2012; Faries and Bartholomew 2012). Eye-tracking technique, which enables researchers to follow and record eye movements of an observer, highlights too the major role of BMI when people judge attractiveness of female bodies (Cornelissen et al. 2009).

As for the face, body shape is also influenced by sexual hormones. Indeed, feminine hormones like estrogens have the effect of directing fat storage to the hips, while masculine hormones (testosterone) stimulate fat deposit in the abdominal region (Bjorntorp 1991; Singh 1993a). Fat distribution can be measured with the waist-to-hip ratio (WHR) defined as the waist circumference divided by the hips circumference. This ratio is sexually dimorphic, with women having, in average, a lower WHR (i.e., a thinner waist on wider hips) than men. Among women, WHR is correlated to hormone levels and to fertility: A woman's WHR decreases during puberty and increases during pregnancy and with the number of pregnancies, and after menopause (Furnham et al. 2001; Sohn and Bye 2012). Women with a low WHR have fewer cardiovascular issues (Spies et al. 2009), less irregular menstrual cycles (van Hooff et al. 2000), more frequent ovulations (Moran et al. 1999), and higher luteal progesterone levels (Jasienska et al. 2004). Notably, the WHR is linked to the ability to conceive for women under artificial insemination and in vitro fecundation (Zaadstra et al. 1993; Wass et al. 1997). Many studies showed that men find women with a low WHR more attractive than women with a higher ratio (Singh 1993a, b; Henss 1995, 2000; Buunk and Dijkstra 2005; Dixson et al. 2009, 2010b; Singh and Singh 2011; Crossley et al. 2012; Bovet et al. 2016), suggesting that men could use the WHR when choosing a mate. Finally, one study found that women with a low WHR reported sexual intercourse at an earlier age and more sexual partners (Hughes and Gallup 2003).

This section could not be comprehensive without discussing the topic of breast beauty. Women are the only mammal with permanent breasts, and women's breasts are particularly large compared to other female primates (Montagna 1982). Breast shape is linked to a woman's age, current condition, and parity: High, firm breasts are associated with nubility, engorged breasts indicate lactation, degree of breast "sagginess" increases with age and parity (Buss 2005), and breast symmetry is positively linked to fertility (Moller et al. 1995; Manning et al. 1997). On the other hand, breast size does not seem to be directly associated with fertility or lactation, although one study showed that women with large breasts and a narrow waist had higher fecundity as assessed by levels of feminine hormones (Jasienska et al. 2004). What about men's preferences? If men prefer breast shape linked to youth and nulliparity (Havlíček et al. 2017), results are unclear concerning breast size and several studies report conflicting findings. For example, Furnham found that men have a preference for small breasts (Furnham and Swami 2007), while several studies have demonstrated a male preference for medium to large breasts (Gitter et al. 1983; Thompson and Tantleff 1992; Singh 1995b; Dixson et al. 2011), or no clear preference (Furnham et al. 1998, 2006; Dixson et al. 2009; Swami et al. 2009). Finally, one study confirms the link between breast symmetry and attractiveness in a Caucasian sample (Singh 1995b), but this result has not been replicated yet.

Is Beauty Universal?

One core question about beauty concerns its universality. Darwin himself noticed striking cultural differences in beauty standards and ornamentations: "*It is certainly not true that there is in the mind of man any universal standard of beauty with respect to the human body*" (Darwin 1871). Since then, this issue has been explored in numerous studies, in particular in the field of evolutionary psychology. Are preferences for mating the result of ancestral adaptations shared by all humans, or are they linked to cultural, historical, and ecological conditions that vary across populations? Are preferences for specific beauty features culturally dictated, or are they biological products of sexual selection?

Geographical Variations

Some preferences appear to have little variation between populations. For example, large cross-cultural studies consistently find that men prefer a mate younger than themselves (Buss 1989b; Jones and Hill 1993). This can be explained by the fact that the link between age and female fertility is very similar in all human societies. There is also a high intercultural consensus for judgments of facial attractiveness suggesting the existence of universal preferences—and thus universal beauty standards—challenging the idea that beauty is purely subjective (Jones and Hill 1993; Perrett et al. 1994, 1998; Jones et al. 1995; Cunningham et al. 1995, 2002; Langlois et al. 2000; Rhodes et al. 2001; Dion 2002). These results are enhanced by the fact that infants, who are less likely to have been influenced by cultural norms, prefer looking at faces also found attractive by adults (Kramer et al. 1995; Slater et al. 1998; Rubenstein et al. 1999), and they do so independently of the faces' ethnic origin (Langlois et al. 1991).

However, cross-cultural analysis of men's preferences for the female body provides mixed results. Let us first consider male preferences concerning body weight. Men prefer relatively thin women (preferred BMI around 20) in the USA (Singh 1993a, b; Puhl and Boland 2001; Rilling et al. 2009), UK (Tovée et al. 1998; Swami and Tovée 2005; Smith et al. 2007), Canada (Wilson et al. 2005), Finland (Swami and Tovée 2007b), Poland (Rozmus-Wrzesinska and Pawlowski 2005; Koscinski 2013), Greece (Swami et al. 2006a), Spain (Swami et al. 2007c), Portugal (Swami et al. 2007c), Uganda (Furnham and Baguma 1994), Malaysia (Swami and Tovée 2005), Thailand (Swami and Tovée 2007a), Japan (Swami et al. 2006b), and Hong-Kong (Fan et al. 2004). But other studies seem to indicate a preference for a higher body weight (BMI between 22 and 30) in Uganda (Furnham et al. 2002) and in rural or traditional societies in Tanzania (Wetsman and Marlowe 1999), South Africa (Tovée et al. 2006), Peru (Yu and Shepard Jr. 1998), Ecuador (Sugiyama 2004b), Malaysia (Swami and Tovée 2005), Thailand (Swami and Tovée 2007a), Finland (Swami and Tovée 2007b), Samoa (Swami et al. 2007b), and Bolivia (Sorokowski et al. 2014). Clearly, then, there are cross-cultural differences in what is perceived as an attractive female body weight. Interpretations for this phenomenon and evolutionary implications will be discussed later, in the section "Why Do Preferences Vary?".

Geographical variation in preferences for WHR is smaller than for BMI. As WHR is linked to a woman's fertility, men should prefer a WHR value associated with the highest reproductive value. The value of 0.7 has been proposed as the "ideal" WHR, corresponding to the optimal fat distribution for high fertility and health, and so this shape should be universally highly attractive (Singh 1993a, b, 2002). Indeed, a preference for a low WHR (0.6 or 0.7) has been found in large number of societies, in the USA (Singh 1993a, b, 1994, 1995b; Singh and Young 1995; Streeter and McBurney 2003; Forestell et al. 2004; Singh and Randall 2007; Dixson et al. 2009; Platek and Singh 2010), in several European countries (Henss 1995, 2000; Furnham et al. 1997, 1998, 2001, 2002, 2003, 2005, 2006; Dijkstra and Buunk 2001; Rozmus-Wrzesinska and Pawlowski 2005; Buunk and Dijkstra 2005; Swami et al. 2006a, 2009; Crossley et al. 2012; Koscinski 2013; Bovet et al. 2016), in Africa (Furnham et al. 2002, 2003; Marlowe et al. 2005; Swami et al. 2009; Singh et al. 2010), in Asia (Swami et al. 2006b; Swami and Tovée 2007a, 2007c; Dixson et al. 2007a; Singh et al. 2010), in Oceania (Connolly et al. 2004; Dixson et al. 2009, 2010a, b; Singh et al. 2010; Sorokowski and Sorokowska 2012), and in Central and South America (Sugiyama 2004b; Sorokowski et al. 2014). Some of these studies concern traditional and isolated populations (Sugiyama 2004b; Marlowe et al. 2005; Dixson et al. 2010b; Singh et al. 2010; Sorokowski and Sorokowska 2012; Sorokowski et al. 2014). However, a few studies showed no effect of WHR on attractiveness or a preference for a higher WHR in some traditional societies in Peru (Yu and Shepard Jr. 1998), Malaysia (Swami and Tovée 2005, 2007c), Thailand (Swami and Tovée 2007a), Cameroon (Dixson et al. 2007b), South Africa (Tovée et al. 2006), and Tanzania (Wetsman and Marlowe 1999; Marlowe and Wetsman 2001; but see Marlowe et al. 2005). In conclusion, preference for a low WHR is predominant around the world, but we cannot exclude some variation toward a higher WHR in some traditional and rural populations. Further research is needed to confirm this phenomenon, as results tend to vary according to the visual stimuli used (some studies used drawings of figures, other used manipulated photographs, 3D software or pictures of women before and after plastic surgery, with ranges of WHRs varying between studies). Some studies also underline the interdependence between WHR and BMI, which results in difficulties to disentangle between these two physical components when making visual stimuli and challenges the part of the variance explained by the WHR in attractiveness (Tassinary and Hansen 1998; Wilson et al. 2005; Swami et al. 2006a; Holliday et al. 2011).

Historical Variations

While it is relatively easy to compare men's preferences between different geographic areas, it is difficult to analyze the evolution of these preferences with time and to make inferences about the preferences of historical populations. Indeed, attractiveness judgments cannot be directly observed in past populations, and only indirect evidence of past preferences remains. One way to overcome this limitation is through the examination of women's depiction in the media as a mean to observe the historical changes in beauty standards. Several studies have done so analyzing the measurements of women who won beauty contests (e.g., *Miss America, Miss Korea, Miss France*), or women who were chosen as models for magazines with a large masculine audience (e.g., *Playboy*). These women can be considered as representative of beauty standards at a particular point in time, and several studies have shown a certain variability of their features across time (Garner et al. 1980; Mazur 1986; Singh 1993b; Freese and Meland 2002; Pettijohn and Jungeberg 2004; Byrd-Bredbenner et al. 2005). These studies show that the BMI of beauty contest winners and *Playboy* models declined over time. The general trend for the idealized WHR was to move from a less curvaceous body shape in the early part of the twentieth century to a more curvaceous shape at mid-century and returning back to a less curvaceous shape at the end of the century (see Fig. 2).

Nevertheless, studies based on data from *Playboy* and beauty contests concern the recent past, as the oldest measurements come from the 1920s. For the more distant past, indications about physical preferences come from artworks such as paintings and sculptures. References to ancient artworks are often made to illustrate the debate over the evolution of female beauty standards, but conclusions are inconsistent. References to artworks are sometimes made to underscore the changing ideals of attractiveness in Western societies (Garner et al. 1980; Swami et al. 2007a) and sometimes to prove the invariability of preferences (Singh 2002, 2006; Singh et al. 2007; Hudson and Aoyama 2007). But these conclusions mostly refer to a small number of artists or sometimes only one (often Rubens) or use very different artworks in terms of cultural origins or subjects.

To overcome these limitations, we used a large sample of Western artworks depicting nude women, collecting more than two hundred artworks from 500 BCE to the present. The following part is a description of this study (Bovet and Raymond 2015). These artworks represent women considered as beautiful, such as Aphrodite or Venus (Greek or Roman goddess of love, beauty, pleasure, and procreation), Graces (Greek or Roman goddesses of beauty, charm, nature, human creativity, and fertility), and Psyche (a mythological young woman so beautiful that she was compared to Venus). As a control, art representing women not specifically famous for their beauty, such as Eve (according to the creation myth of Abrahamic religions, the first woman created by God) and Susanna (a biblical Hebrew woman falsely accused by lecherous voyeurs), was also included. As women were depicted from various views (e.g., front view, back view) and in a variety of postures (e.g., standing, lying, sitting), it was impossible to make a direct, objective, and

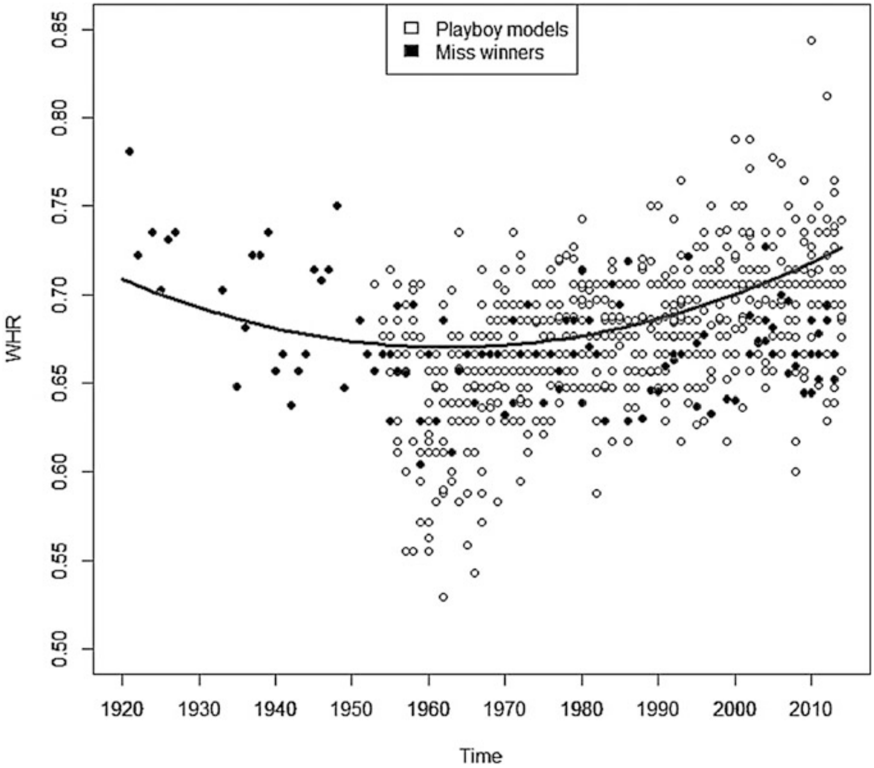

Fig. 2 WHR values for playboy centerfold models (in white) and winners of 4 Miss pageants (Miss America, Miss World, Miss Earth, and Miss Universe, in black) by time of magazine appearance or victory. The data were fit by a linear regression that includes a quadratic term (in red, $\beta = -0.083$ and $\beta = 2.12 \times 10^{-5}$ for time and time^2, respectively, $P < 0.0001$, from Bovet and Raymond 2015)

standardized measure from the artwork picture. To overcome this issue, we used a very efficient tool to judge and compare human bodies: the human brain. We asked a large sample of observers to estimate the body shape of the women represented in the artworks by comparing them to drawings of female silhouettes (see Fig. 3). A mean estimated WHR was computed for each female figure evaluated from all the participants' estimations.

First, we found a significant difference between women representing beauty (goddess of love, beauty, desire, etc.) and the women less known for their physical attractiveness (Eve and Susanna): Beautiful women had a lower—thus more feminine—WHR. This underlines the importance of knowing the intentions of an artist (i.e., what he wanted to represent) before interpreting his/her artwork. Likewise, the so-called paleolithic Venus figurines (often referred to when feminine beauty standards are addressed, see Fig. 4) were not included in our study, because the intended representation remains unknown (see Jennett 2008 for the variety of

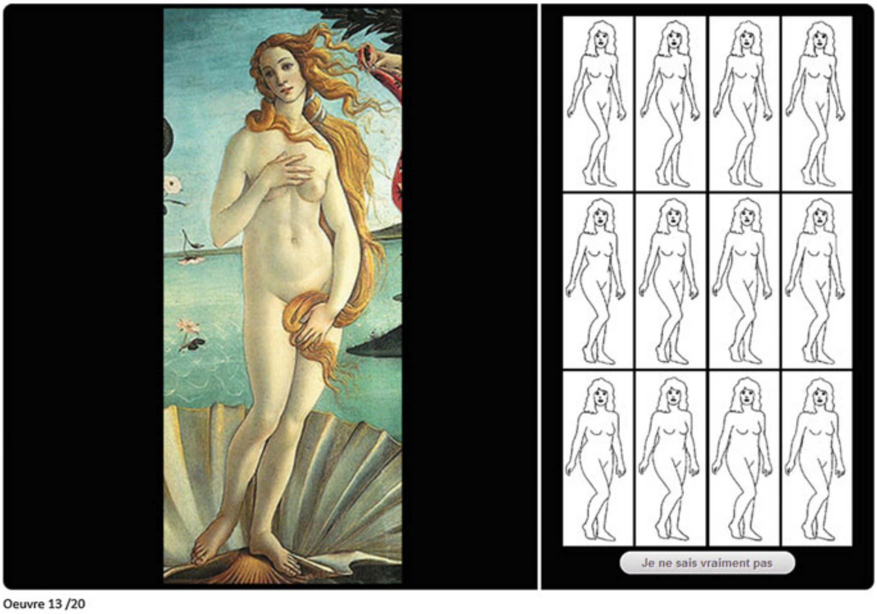

Fig. 3 An online test was developed that randomly presented works of art to participants. On the right part of the screen, 12 drawn figures of women were displayed, representing three different weight categories and four WHRs within each weight category (from Singh 1993a). For each piece of art, the participant had to click on the figure that most closely resembled the woman depicted on the artwork (Bovet and Raymond 2015)

possible interpretations, spanning from goddess to dolls to symbols of fertility and female power).

The WHRs of *Playboy* models, *Miss America*, *Miss Universe*, *Miss World,* and *Miss Earth* pageant winners, were also added to the art dataset. The WHR depicted as beautiful was remarkably constant from 500 BCE to 400 CE, with a mean WHR of 0.74 (slightly higher than the preferred WHR generally found in contemporary societies). Then, the WHR considered as ideal decreased from ca 1400 to the present, suggesting that the ideal of beauty changed during, at least, the last 500 years (see Fig. 5) (due to a ban from the Christian church to depict nude women in art (Beugnot 1835; Todorov 2000), it is difficult to infer exactly when this decrease began and if other variations occurred during this millennium gap). Thus, in contrast with the assertion that the preference for WHR is universal and invariant (Singh 1993b, 2002, 2006), the WHRs of icons of beauty have changed over time. Moreover, contrary to the common claim that the ideal shape for women has dramatically changed in the last 20–50 years with the occurrence of mass media, the shift of beauty standards (at least for the WHR) seems to be older, as the preferred WHR began to decrease since the fifteenth century. Nevertheless, it is important to notice that, during the whole period studied here, the preferred WHR remained close to the value of 0.7 usually indicated as the ideal WHR in the

Fig. 4 The Venus of Willendorf or other Upper Paleolithic statuettes are often taken as examples of the variability of beauty standards. However, the exact purpose of these figurines is unknown (Rice 1981; Jennett 2008)

literature (Singh 1993a, b, 2002, mean for artworks in our study: 0.73) and remained within the normal and fertile range of feminine WHR.

Why Do Preferences Vary?

According to the indicator quality hypothesis of evolutionary theory, men should prefer characteristics corresponding to the optimal value of a particular quality (e.g., the WHR linked to maximum fertility). However, multiple studies show that preferences for BMI and WHR vary between geographical regions and across time. Does this suggest that preferences for female body shape are arbitrary? Not necessarily, as these preferences are not randomly distributed, and these differences can be explained in terms of adaptations to different environmental pressures.

Looking at men's preferences for BMI, we see that they are correlated to an environmental variable that could explain these variations: the availability of resources. As fat represents caloric storage, a high body weight/BMI can be advantageous in environments where availability of food is low and/or unpredictable. As quantity and predictability of food provisioning vary between populations, we can expect that preferences for body size will vary accordingly (Sugiyama 2004b). Nutritionally stressed populations with unpredictable access to

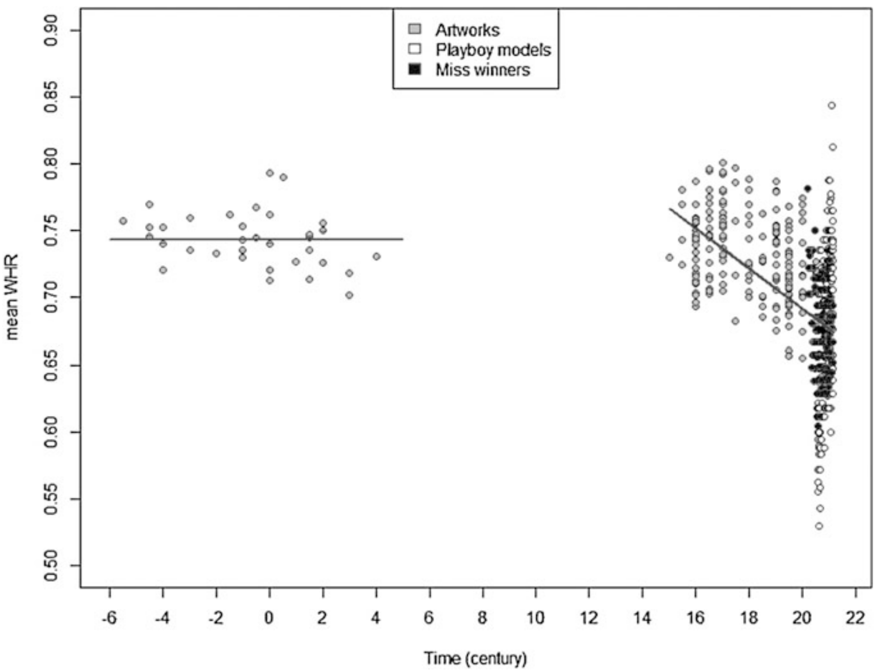

Fig. 5 Plot of WHR values for artworks (in gray), Playboy centerfold models (in white), and winners of Miss pageants (in black) by century. Nude women were absent from artwork during millennia due to a ban from the Christian church. From (Bovet and Raymond 2015)

food may be expected to prefer signals of regular resources or of the ability to resist the next scarcity, and these could be indicated by high BMI. Indeed, the populations where a preference for a high BMI has been observed are those that have low and unreliable access to resources (Yu and Shepard Jr. 1998; Wetsman and Marlowe 1999; Furnham et al. 2002; Sugiyama 2004b; Swami and Tovée 2005, 2007a, b; Tovée et al. 2006; Swami et al. 2007b; Sorokowski et al. 2014). These preferences may be further reinforced by a high prevalence of infectious diseases in these societies. The health consequences linked to serious diseases often include significant weight loss, which may be reflected in the perception that a lower BMI signals potential disease infection. In such environments, therefore, a higher female body weight may be perceived as reflecting affluence, high status, and good health (Brown and Konner 1987; Sobal and Stunkard 1989; Anderson et al. 1992). Although high BMI is also linked to a range of health problems (Manson et al. 1995), under nutritionally limited conditions the advantages of a high BMI may outweigh these problems. This idea is reinforced by studies showing that the socioeconomic status (SES) of a group is a stronger determinant of body weight ideals than ethnicity (Swami and Tovée 2005, 2007a, b; Tovée et al. 2007). In contrast, in populations where a preference for a low BMI has been observed (Singh 1993a, b; Furnham and Baguma 1994; Tovée et al. 1998; Puhl and Boland 2001;

Fan et al. 2004; Swami and Tovée 2005, 2007a, b; Wilson et al. 2005; Rozmus-Wrzesinska and Pawlowski 2005; Swami et al. 2006b, 2007c; Smith et al. 2007; Rilling et al. 2009; Koscinski 2013), food resources are easily available and less subject to variation, and the prevalence of infectious diseases is comparatively low. In these wealthy and industrialized societies, the BMI is negatively associated with SES, and thus, thinness is not necessarily a cue of lack of resources (Sobal and Stunkard 1989; Molarius et al. 2000; Ball and Crawford 2005). In this context, having a high BMI is not a fitness advantage because of the health risks linked to obesity, and a preference for thin women can even be adaptive because a low BMI is here associated with general long-term health, high fertility, and high status (Anderson et al. 1992).

Some studies suggest that a similar link between environment and men's preferences might exist for WHR, with men living in harsher environments preferring a higher WHR (Yu and Shepard Jr. 1998; Marlowe and Wetsman 2001). This theory suggests that in harsher environments men could prefer cues indicating high resource acquisition potential over high fecundity (Marcinkowska et al. 2014). Female hormones and femininity are associated with lower physical performance (Manning and Taylor 2001; Rickenlund et al. 2003; Hönekopp et al. 2006), aggressiveness, and dominance (Dabbs Jr. et al. 1988; Cashdan 1995, 2003; von der Pahlen et al. 2002), qualities which can be useful in resource acquisition and holding. This trade-off could explain why we observe a preference for a higher (i.e., less feminine) WHR in hunter-gatherer or forager groups. Similarly, a change of environment in Western societies during the last 500 years could explain the change of men's preferences for WHR observed in our study (Bovet and Raymond 2015). Indeed, during this period, the life expectancy, food availability, and gross domestic product increased in Western populations (Roser 2014a, b, c). With the environment becoming relatively less harsh, and greater access to resources and better health, men's preferences could have evolved toward a lower—hence a more feminine—WHR, favouring cues of fecundity over resource acquisition potential. Alternatively, the variation of the preferred WHR (between geographic areas and timescale) could result from another phenomenon: The preference for the WHR may depend on the local distribution of the WHR in the population. The cognitive rule would not be a preference for a low WHR (absolute value), but rather a preference for a WHR lower than the average (Sugiyama 2004b). A change of the preferred WHR is then expected when the mean or range of WHR in the population varies. The recent increase in women's average WHR in Western populations (Lissner et al. 1998; Lahti-Koski et al. 2000) could explain the increase in the ideal WHR since the 1960s. Similarly, indirect evidence suggests that the mean WHR in the population could have changed since the fifteenth century. For example, the number of pregnancies—which increases WHR—decreased during the demographic transition, and a change in diet or parasite loads could also have impacted the average WHR. However, data on WHRs of the population before the 1960s are required to further evaluate this hypothesis.

Plasticity of Preferences, Environment, and Media

Migration between populations presents a unique opportunity to evaluate the plasticity (i.e., the ability of an individual to change in response to environmental variations) of mate preferences. Studies show that people born in a different population than their parents or grandparents usually express the same preferences as individuals from the new population in which they were born (Tovée et al. 2006; Swami et al. 2009). Similarly, people who moved from one population to another during their lifetime express preferences which are intermediary between the population of origin and the host one (Tovée et al. 2006; Swami et al. 2009). These results indicate a certain plasticity of preferences. The perception and evaluation of physical attractiveness can also be modified by the prior presentation of specific visual stimuli. When participants are exposed to faces or bodies with a certain trait, they tend to prefer new faces or bodies having this characteristic (Rhodes et al. 2003, 2004; Leopold et al. 2005; Bestelmeyer et al. 2008). For example, a visual habituation to faces with experimentally enlarged features will make new faces with enlarged features appear more normal and attractive (Rhodes et al. 2003, 2004), and exposure to thin bodies make people prefer thinner bodies (Winkler and Rhodes 2005). This type of residual effect could reflect a recalibration of preferences, in order to make them correspond to the mean of the individuals recently encountered. However, it seems that this recalibration can be biased by attractiveness or other positive characteristics linked to the individuals that are encountered (Jones et al. 2008; Boothroyd et al. 2012).

The influence of recent visual stimuli on judgments of attractiveness has obviously important consequences concerning the effects of the media on preferences. Individuals presented in the media never exactly correspond to individuals of the population: Among other things, they are generally more attractive than the average. As expected, exposure to the media has an effect on preferences. In one study, men previously exposed to women pictured in *Playboy* magazine judged "ordinary" young women as less attractive (Kenrick et al. 1989 but see Balzarini et al. 2016). Studies show that access to television or Internet also has an effect on preferences (Batres and Perrett 2014; Boothroyd et al. 2016). For instance, in El Salvador, people without Internet access prefer more feminine men's faces, more masculine women's faces, and women with higher facial adiposity than people with Internet access (Batres and Perrett 2014). In Nicaragua, people from villages with very limited television access prefer higher BMI than people with established television access (Boothroyd et al. 2016). Thus, the media—and more generally culture—influences preferences. But traits presented in the media or emphasized by culture are not arbitrary. For instance, women represented in the media exhibit characteristics which have an adaptive value (e.g., cues of fertility). Consequently, the overrepresentation of attractive women in the media has a feedback effect on the perception of attractiveness of individuals in the population.

All these results show that preferences are far from static and unchanging and can be influenced by the environment and culture, including local socioeconomic, demographic, and individual conditions. Variable and plastic preferences can be more beneficial than rigid ones, as they enable individuals to learn from their environment and then adapt their preferences to the local potential partners and changing conditions (e.g., access to resources or harshness of the environment). In support of the adaptiveness of malleable WHR preferences, several studies have shown that temporary states like hunger and financial satisfaction can produce individual variation in physical attractiveness preferences. Participants who were hungry or not satisfied with their personal resources (induced by the experiment) preferred heavier women than did satiated or satisfied men (Nelson and Morrison 2005; Swami and Tovée 2006), a phenomenon which mirrors patterns found at the population level.

Conclusion

In this chapter, we saw that some physical features of a woman's body are linked to her reproductive potential and that men use these cues to assess feminine attractiveness. Yet beauty is not fixed and men's preferences for some features vary between geographical regions and according to time. If the results presented here refute the Platonic view of an absolute or objective beauty, they also show that there is more than the general maxim "beauty is in the eye of the beholder." A complete understanding of beauty must combine both the objective and subjective accounts of beauty.

The list of physical features involved in female beauty addressed in this chapter is far from exhaustive (for instance, hair, facial averageness, or leg length are also known to have an effect on attractiveness). And there are a myriad of ways in which an individual's physical attractiveness can be enhanced: In almost every culture, dress, jewelery, tattoos, or makeup are used to enhance beauty, and some of these techniques are very ancient (Rubin 1988; Caplan et al. 2000). Moreover, when choosing a mate, men also use non-physical features, such as voice, smell, movements, and behaviors, which can be linked to physical or physiological conditions, as well as personality, psychology, and social background, traits also linked to mate quality. The features involved into mate choice such as physical features, smell, or personality traits are not all equally weighted in mating decisions, but they all likely contribute to the general evaluation of a potential partner.

To conclude, sexual selection influences human preferences for female physical features. But human behavior cannot be understood outside the environment and the cultural norms of the society they occur in, just as culture cannot be fully understood without considering the evolutionary forces which shaped the human mind. Many preferences for features that humans find attractive appear to be the result of evolution and occur because these traits represent reliable cues about potential mates, such as future fecundity indicated by age, health indicated by skin complexion, nutritional status indicated by body weight. However, our preferences are also plastic, and cultural values influence what we find attractive. Culture and art can tell us about how our preferences vary across geography and time and can reveal rich information about our evolutionary-driven preferences.

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Correction to: Gesture: A Transsubjective Tool to Understand a Work of Architecture

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The original version of this chapter unfortunately contained a mistake. Jorge Tavares Ribeiro was not listed among the authors. This has been corrected.

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