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EEG alpha power and creative ideation

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Abstract

Neuroscientific studies revealed first insights into neural mechanisms underlying creativity, but existing findings are highly variegated and often inconsistent. Despite the disappointing picture on the neuroscience of creativity drawn in recent reviews, there appears to be robust evidence that EEG alpha power is particularly sensitive to various creativity-related demands involved in creative ideation. Alpha power varies as a function of creativity-related task demands and the originality of ideas, is positively related to an individuals' creativity level, and has been observed to increase as a result of creativity interventions. Alpha increases during creative ideation could reflect more internally oriented attention that is characterized by the absence of external bottom-up stimulation and, thus, a form of top-down activity. Moreover, they could indicate the involvement of specific memory processes such as the efficient (re-)combination of unrelated semantic information. We conclude that increased alpha power during creative ideation is among the most consistent findings in neuroscientific research on creativity and discuss possible future directions to better understand the manifold brain mechanisms involved in creativity.

Keywords

EEG; ERD; ERS; Synchronization; Alpha; Creativity; Divergent thinking; Internal attention; Top-down control

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1. Introduction

1.1. Creativity and neuroscience: the status quo

Creativity is commonly defined as the ability to produce work that is both novel (original, unique) and useful within a social context (e.g., Flaherty, 2005; Stein, 1953; Sternberg and Lubart, 1996). Besides other classic mental ability constructs such as intelligence,[1] creativity appears to be crucial or even indispensable in many areas of our everyday lives, leading some authors to conclude that creativity is "…a good attribute for people to

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[1]Throughout the history, many definitions of intelligence have been proposed, and it has been sometimes criticized that there are as many definitions of intelligence as there are researchers attempting to define this construct (Neubauer and Fink, 2009, p. 1005). Meanwhile, some consensus about the core elements of intelligence has been achieved and many scientists (e.g., Jung and Haier, 2007; Neubauer and Fink, 2009) refer to Neisser et al.'s (1996) definition: "Individuals differ from one another in their ability to understand complex ideas, to adapt effectively to the environment, to learn from experience, to engage in various forms of reasoning, to overcome obstacles by taking thought" (p. 77).

possess…" (Simonton, 2000, p. 151). It is sorely needed in culture, science and education, likewise in the economical or industrial domain. As a matter of fact, creativity is becoming increasingly attractive not only in the popular domain but also across a broad variety of different scientific disciplines. Meanwhile it has been approached in the cognitive sciences (e.g., Smith et al., 1995; Ward, 2007), in pedagogy or in the educational domain (e.g., Sawyer, 2006), from the perspective of social psychology (e.g., Amabile, 1983; Hennessey and Amabile, 2010), in the context of mental illness (e.g., Kaufman, 2005; Fink et al., 2011b) and most recently also in the field of neurosciences (see e.g., Arden et al., 2010; Dietrich, 2004, 2007; Dietrich and Kanso, 2010; Fink et al., 2007; Jung et al., 2010a,b). Though relevant research in this burgeoning field is rapidly growing it seems nevertheless noteworthy that, compared to other mental ability constructs such as intelligence, this field is only at the beginning of a long search for potential cognitive and neural mechanisms underlying this multifaceted mental ability domain. Up to the present, a comparatively low number of approx. 550 scientific publications is available which deal with brain correlates of creativity (Source: Thomson Reuters © WEB of KNOWLEDGE; Topic: "*Creativity*" AND "*Brain*"), while there are approx. 19.300 published papers dealing with the brain-intelligence relationship (ibid.).

This article attempts to show how neuroscientific studies on creative ideation using human electroencephalography (EEG) can help us to learn more about the manifold ways of how creative thought might be manifested in our brains. Motivated by the increasing availability of new neuroscientific methodologies, creativity has become increasingly attractive in the neurosciences, and in the meanwhile a considerable number of studies has been published in this emerging field. These studies investigated brain activity during a broad range of different creativity-related tasks (ranging from divergent thinking, over insightful problem solving to artistic or musical creativity) by means of a variety of different neuroimaging methods. Taken together, these studies have produced a large diversity of findings and existing review articles on the neuroscience of creativity (e.g., Arden et al., 2010; Dietrich and Kanso, 2010; Sawyer, 2011) draw rather disappointing conclusions. For instance, in reviewing EEG, ERP and neuroimaging studies of creativity and insight, Dietrich and Kanso (2010) recently came to the conclusion that "… creative thinking does not appear to critically depend on any single mental process or brain region, and it is not especially associated with right brains, defocused attention, low arousal, or alpha synchronization, as sometimes hypothesized …" (p. 822). In a similar vein, Arden et al. (2010) found "little clear evidence of overlap" (p. 143) in the findings obtained in different neuroimaging studies of creative cognition. These two reviews have covered a large amount of studies involving a variety of creativity tasks investigated by means of a variety of different neurophysiological methods. At this, it should be noted that creativity is usually not considered as prime example of a homogeneous construct. Creativity can be variably defined either as a cognitive state or event, as a cognitive potential or personality disposition, by creative expertise, or even by life time creative achievement (e.g., Kaufman and Beghetto, 2009).

In addition, a large number of tasks have been conceived which are thought to capture relevant cognitive processes related to creativity. They include such different tasks as creative ideation tasks asking participants to come up with original ideas for open problems (e.g., alternate uses task), insight tasks involving misleading problem representations which need to be restructured (e.g., matchstick problems), remote associates problems which require loose associations to find non-obvious semantic relations, or the production of creative stories, metaphors, paintings, or melodies (Arden et al., 2010; Dietrich and Kanso, 2010). Moreover, there are so many different ways such tasks can be realized, particularly with respect to task instructions (e.g., stressing more strongly the fluency or the originality facet of creativity), timing (duration of stimulus presentation, etc.), response modalities (e.g. button press, verbal response, etc.), control conditions and so on. This diversity in defining and measuring creativity as well as the diversity of experimental procedures (e.g., stimuli, control conditions, timing, response mode, etc.) may well have contributed to the difficulties in identifying reliable and replicable brain correlates underlying creativity so far. In addition to this, the broad diversity of neurophysiological measures and parameters that were used in this field might be also assumed as being responsible for the fact that no conclusive picture about potential neural mechanisms underlying creativity has been achieved yet. Even if we concentrate on EEG studies on creativity, there are so many different measures or parameters, ranging from event-related potentials and oscillatory brain activity (in a broad range of different EEG frequency bands), over coherence or functional connectivity indicators between different cortical areas (which are also analyzed in a broad range of different frequency bands), to measures of dimensional complexity, etc., with each of them having different functional meanings–that makes it notoriously difficult to compare and integrate findings across different studies.

The undertaking of finding consistent brain mechanisms underlying creativity, therefore, requires above all a clear conceptual definition of what aspect of the multi-facetted construct of creativity is actually looked at (Dietrich and Kanso, 2010). Moreover, it is probably beneficial to focus on specific tasks and specific methods and only extend the scope of research and interpretations as soon as the initial findings are well understood. In this article we aim to specifically focus on brain correlates of the well-established process of creative ideation (or more generally on divergent thinking, respectively). The generation of creative ideas to open problems can be considered as key component of creativity, and the creative ideation approach has already been adopted in a considerable number of neuroscientific studies of creativity (see following section for further definition). As will be shown in this review, recent studies in this field have yielded evidence that brain activity in the EEG alpha frequency band is sensitive to various creativity-related demands involved in creative ideation, thereby revealing a quite consistent and replicable picture about some promising brain mechanisms relevant for creativity.

1.2. Creative ideation

Creative ideation denotes the process of creating a number of different original ideas to given open problems. It is conceptualized as a cognitive process involving “both the retrieval of existing knowledge from memory and the combination of various aspects of existing knowledge into novel ideas” (Paulus and Brown, 2007, p. 252). Creative ideation tasks are commonly called divergent thinking tasks pointing at the notion that thought “goes off in different directions” (Guilford, 1959, p. 381). Accordingly, for divergent thinking

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tasks there exist many possible solutions which may differ in their quality. This stands in contrast to convergent thinking tasks which only have one correct solution. The Guilford tests which were developed based on the divergent production component in his structure of intellect model (Guilford, 1967) include a number of such divergent thinking tests. A typical example is the alternate uses (AU) task which requires participants to think of many different creative uses for a conventional object (e.g., “brick”). A possible creative response would be to use it as a “business card that surely will be remembered”, whereas an uncreative response would be to use it “for building houses”. Besides ideational fluency (i.e., number of generated ideas), and flexibility (i.e., number of different categories), creative task performance is often quantified with respect to the originality of ideas, as assessed by external ratings (similarly to the Consensual Assessment Technique proposed by Amabile, 1982).

Divergent thinking tasks represent the dominant approach in the psychometric assessment of creativity (Kaufman et al., 2008). They are included in most standard tests of creativity and there is increasing interest to use them as supplement to traditional cognitive measures of ability and achievement (Kaufman, 2010). Divergent thinking tests show good reliability but the evidence concerning validity is inconsistent. While it is widely accepted that divergent thinking ability reflects a useful indicator of creative potential (Runco and Acar, 2012), it is sometimes doubted that divergent thinking scores can predict real-life creative achievements. So far, a number of studies have supported reasonable predictive validity of divergent thinking (e.g., Plucker, 1999), but the validity may be limited when it comes to predict outstanding creative achievements which crucially depend on persistence and expertise (Ericsson et al., 1993; Weisberg, 2006).

Neuroscientific studies have also commonly employed divergent thinking tasks which, however, have to be adapted according to the restrictions of neuroscientific methods (cf. Fink et al., 2007). A single divergent thinking task often takes between 2 and 5 minutes during which participants are requested to generate creative ideas to a given stimulus (with open eyes). Brain activation related to creative idea generation is usually assessed by contrasting brain activation during task performance to activation during a pre-task reference period. Moreover, it needs to be taken care to separate the process of thinking about ideas from the actual vocalization of ideas. This can be achieved by defining time periods either reserved for creative thought or by using variable time markers (e.g., requesting participants to push buttons prior and after giving a response). This allows for a proper attribution of the relevant cognitive process and also avoids motor artifacts related to speech.

1.3. EEG methodologies in the context of creative ideation

Neuroimaging techniques such as functional magnetic resonance imaging (fMRI), near infrared spectroscopy (NIRS), the measurement of the brain’s glucose metabolism via positron emission tomography (PET), or the analysis of different parameters in the EEG allow us to investigate the way the brain works when engaged in the performance of different creativity tasks. Each of these measurement methods has its pros and cons in the particular context of the study of creativity. The primary advantage of fMRI lies in its high spatial accuracy, but it does not allow for the study of cognitive processes with high

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temporal resolution (as opposed to EEG techniques). The observed changes in brain activity (e.g., blood-oxygen-level dependent [BOLD] response) occur rather slowly, thereby complicating the analysis of time-related brain activity patterns during the process of creative cognition. EEG techniques, in contrast, show considerably lower spatial resolution but allow for a much more fine-grained temporal analysis of brain activation that could be observed, for instance, in response to a particular cognitive event (e.g., immediately prior to the production of an original idea). Both, fMRI and EEG approaches in this field are challenged to decompose the complex construct of creativity into measureable cognitive processes that can be adequately investigated in the neuro-lab; at the same time, they need to capture “real-life creativity” to the best possible extent. Concerning the latter issue, the EEG environment might provide slightly better conditions for creativity than studies using fMRI, in which participants are required to lie supine in the noisy scanner.

EEG activity can be quantified in many different ways and many techniques have already been successfully employed in the study of creativity (cf. Bazanova, 2012; Bhattacharya and Petsche, 2005; Mölle et al., 1999; Srinivasan, 2007). These methods include various parameters such as the assessment of changes in spectral power in different EEG frequency bands, the method of event-related potentials (ERP), or the analysis of functional connectivity (or functional coupling, respectively) between different cortical areas. The present article focusses on the analysis of task- or event-related changes in spectral power. The EEG signal represents oscillations observed across a wide range of frequencies which are commonly divided into distinct frequency bands (e.g., alpha band: 8–12 Hz, beta band: 13–30 Hz). Spectral analyses of the EEG can be used to compute the band-specific frequency power for given periods of time. Additionally, task- or event-related power changes can be quantified by contrasting the power in a specified frequency band during a cognitive task (e.g., a creativity task) with a preceding reference interval. Event-related power decreases from a reference to an activation interval are commonly referred to as event-related desynchronization (ERD), while power increases are referred to as event-related synchronization (ERS; Pfurtscheller, 1999). ERD/ERS of the alpha band has been found to be especially sensitive to cognitive task performance and higher cognitive abilities (e.g., Neubauer et al., 2006; Neubauer and Fink, 2009). To date, the ERS/ERD method has been employed in a variety of studies covering a broad range of different cognitive task demands (excellent reviews are given in Klimesch, 1999; Klimesch et al., 2007; Neuper and Klimesch, 2006). Just to illustrate the broad range of application of this method, Jaušovec et al. (2006) measured ERS/ERD during spatial rotation, Karrasch et al. (1998) during the performance of auditory lexical matching tasks, or Bastiaansen and Hagoort (2006) investigated ERD effects during language processing or comprehension. In other studies, the ERD method was used during visual information processing (Pfurtscheller et al., 1994), reasoning (Fink and Neubauer, 2004) or in the context of memory processing (Doppelmayr et al., 2005; Grabner et al., 2004; Krause et al., 2000; Stipacek et al., 2003).

Research on alpha ERS/ERD reveals evidence that different patterns of alpha (de-)synchronization can be observed when the broad alpha frequency range (approximately in the range between 8 and 12 Hz) is subdivided into different alpha sub-bands (see Klimesch, 1999). Specifically, lower alpha ERD (~8–10 Hz) has been found as being more likely to reflect general task demands such as attentional processes (basic alertness,

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vigilance or arousal). ERD in the upper alpha band (~10–12 Hz), in contrast, has been observed as being more sensitive to specific task requirements (e.g., semantic memory processes; see e.g., Doppelmayr et al., 2002, 2005; Klimesch et al., 2000). Finally, the ERS/D method has been found to warrant a high psychometric quality (i.e., re-test reliability, internal consistency; cf. Burgess and Gruzelier, 1996; Krause et al., 2001; Neuper et al., 2005), therewith substantiating its valuable role in the context of neuroscientific individual differences research (Neubauer et al., 2006). Hence, in applying this measurement method we are well equipped for the complex study of creative ideation.

2. Empirical findings on the relationship between creative ideation and EEG alpha power

2.1. First findings

The American psychologist Colin Martindale was one of the first who related EEG alpha wave activity to creative ideation. He showed that highly creative individuals were more likely to exhibit higher EEG alpha wave activity than less creative individuals while performing the alternate uses test (Martindale and Hines, 1975). In a subsequent study, Martindale and Hasenfus (1978) observed a higher level of alpha activity while participants were instructed to think of a story (i.e., inspirational phase) than during an analogue of creative elaboration (i.e., writing down the story). In a second experiment of that study (cf. Martindale and Hasenfus, 1978), half of the participants were instructed to be as creative and original as possible (originality instruction), while such an instruction was omitted for the other half of the participants. Interestingly, creative participants who received the originality instruction exhibited more alpha during inspiration than creative control subjects (receiving no originality instruction).

Since these early findings of Martindale and colleagues, EEG research on creativity came to rest for a comparatively long period of time. Only approx. a quarter of a century later, a revival of relevant research activities in this field can be detected, initialized by a couple of highly relevant publications such as those by Jaušovec (1997, 2000), Mölle et al. (1999) or Razumnikova (2000). By now, a considerable number of EEG studies have yielded consistent evidence hinting at a particular role of EEG alpha oscillations in the context of creative ideation. These studies have approached this topic from different perspectives. They can be roughly categorized into studies that looked at (1) the effects of creative (vs. non-creative) task demands, (2) the originality of ideas, (3) individual differences in creativity, and (4) creativity enhancing interventions. In the following we will review evidence in these fields.

2.2. EEG alpha power as a function of creative task demands

As initially suggested by the pioneering work of Colin Martindale (cf. Martindale and Hasenfus, 1978), EEG alpha wave activity appears to be sensitive to different creativity-related task demands. Meanwhile this observation has been corroborated in different studies using varying task demands (e.g., Fink et al., 2007; Jauk et al., 2012; Jaušovec, 1997; Krug et al., 2003; Mölle et al., 1999). Jaušovec (1997) compared alpha power (7.5–13 Hz) related to problem solving of well-defined vs. ill-defined problems. In the well-defined problem

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task participants had to find the correct solution to the missionaries and cannibals task, whereas in the ill-defined task participants were instructed to find explanations for the shapes of the numbers 1–9. He found that solving the ill-defined problems was related to higher alpha power in posterior regions of the brain than solving the well-defined task. He also noted that this pattern was reversed during an initial phase of reading and planning, and it was not evident in another experiment which did not discriminate these problem solving stages.

Mölle et al. (1999) contrasted EEG brain activity during divergent (e.g., alternate uses task, consequences task) vs. convergent thinking tasks (intelligence test tasks such as mental arithmetic) and they observed evidence that divergent thinking was associated with more alpha power (8–12.1 Hz) than convergent thinking at central and parietal sites. Krug et al. (2003) tested women in two experiments and compared EEG power during divergent thinking in the consequences task (participants had to think of as many unique consequences as possible given the hypothetic scenario that people no longer had to eat) with a convergent thinking task (subtest arithmetical thinking from the Hamburg-Wechsler Intelligence Scale; Wechsler, 1981). In both experiments they found that alpha power (8–12.1 Hz) was higher during the divergent thinking task than during the convergent thinking task. This experiment was actually on the effect of treatments with estrogen or testosterone, but it was reported that these treatments had no effects on the power in the alpha band. Shemyakina et al. (2007) also examined the spectral power related to divergent thinking. Participants were presented with the beginning part of well-known proverbs and had either to make up a different ending for them which would change their meaning (divergent thinking task), or to recite the correct common ending of it (convergent control condition). They found that the divergent task resulted in somewhat higher upper alpha power in posterior regions of the right hemisphere, but these alpha effects were not as robust as the observed power increases in upper beta band or gamma frequency bands.

Similarly, Fink et al. (2007) investigated task- or event-related alpha power changes (creative idea generation vs. reference) while individuals worked on four different types of creative idea generation tasks. Besides the alternate uses (AU) task and the consequences task (here called utopian situation task; US), they also used the insight (IS) task, where participants were confronted with unusual, hypothetical situations that were in need of explanation (e.g., find reasons for “*a light in the darkness*”), and the word ends task (WE), where German suffixes had to be completed by the participants in many different ways. Behavioral analyses of the employed creative idea generation tasks revealed that the employed tasks notably differ with respect to their task demands. This was evident by the finding that performance in the IS, US and AU task (as opposed to the WE task) was more strongly correlated with the big five personality factor “openness to experiences” which is seen in relation to creativity (e.g., Feist, 1998; King et al., 1996). In contrast, completing suffixes (i.e., performance of the WE task) was significantly correlated with verbal intelligence (Benedek et al., 2006; Fink et al., 2006, 2007), while in the IS, US and AU task no correlation with verbal ability was apparent at all. Thus, the IS, US and AU tasks seem to rely more strongly on divergent, free-associative demands, while the WE task rather involves more convergent, intelligence-related demands. Most interestingly, these

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behavioral task differences were also reflected at the neurophysiological level. All tasks were accompanied by comparatively strong alpha synchronization at frontal sites, but they differed significantly at more posterior recording sites (see Fink et al., 2007). Specifically, the AU, IS, and US task were accompanied by relatively strong alpha synchronization in the upper alpha band (10–12 Hz), whereas in the more intelligence-related WE task the lowest synchronization of alpha activity was observed, suggesting that the more creativity-related a task is (e.g., finding original alternate solutions as opposed to completing suffixes) the stronger is the synchronization of alpha activity (Fink et al., 2007).

This notion is further corroborated by recent findings of Jauk et al. (2012), who aimed at discriminating EEG brain activation related to convergent vs. divergent modes of thinking within the same task. In this study, participants worked on the AU task and a word association task and were either instructed to generate common, typical responses (i.e., convergent condition) or uncommon, creative responses (i.e., divergent condition). In both tasks, the convergent response condition resulted in a much stronger task-related desynchronization of alpha activity than the divergent response condition, which rather tended to show synchronization of alpha activity over frontal cortical sites. This indicates that the amount of task-related alpha activity can be directly attributed to the mode of task-processing (convergent or divergent thinking), and that this effect can even be observed at more elementary cognitive tasks such as word association.

However, there are also studies that appear to be at odds with the notion that creative ideation is related to task-related increases of alpha power. Razumnikova (2000; for a similar study see Razumnikova, 2004) analyzed spectral power during a convergent thinking task (mental arithmetic task: mentally add subsequent numbers) and a divergent thinking task (the snake problem: “There are hundreds of poisonous snakes in a zoo. How will it be possible to measure the lengths of each snake?”). Both cognitive tasks were performed with closed eyes for 5 minutes and were compared to an initial 5 minute rest period. She found that lower and upper alpha power were significantly lower during the cognitive tasks than during the rest period. This result was interpreted in terms of alpha desynchronization which would oppose the reported findings of task-related alpha synchronization. It should be noted that this study (and the 2004 study) differed from the other task-related power studies in the aspects that a very long initial rest period was used as reference for both tasks (rather than short reference periods preceding every single task; cf. Fink et al., 2007, 2009a; see also original ERD approach by Pfurtscheller and Aranibar, 1977; Pfurtscheller, 1999) and that the tasks were performed with closed eyes. It is possible that alpha power during the divergent thinking task was quite high but not as high as during a five minute rest period. The different results may thus possibly be due to the different realization of reference and task conditions.

Another reason could be assumed in the employed task itself. Razumnikova and colleagues recently used association tasks requiring participants to find an original association to single words or triads of words (e.g., Razumnikova, 2007a,b; Razumnikova et al., 2009). These tasks were generally reported to be associated with alpha decreases relative to a long pre-task reference period. One study provided detailed topographic analyses, revealing that desynchronization was actually restricted to central and posterior regions of the brain but

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was not found in frontal regions (Razumnikova, 2007a). This finding is in line with the study by Jauk et al. (2012) showing that simple association tasks generally show lower alpha power than more demanding creative idea generation tasks. Moreover, they also observed no desynchronization at frontal brain regions but only at central and some posterior areas.

In another study, Jaušovec and Jaušovec (2000) contrasted verbal and figural divergent production tasks which were adapted from creativity tests (e.g., name all things you can think of that will make noise; alternate uses of a mobile tire; thinking creatively with uncompleted pictures, etc.) with dialectic problems (e.g., thinking about an essay on the Livian war). Both tasks required open solutions, but they differed with respect to the level of creativity needed to solve them. The authors observed that alpha power effects in the lower and to some extent in the upper alpha band were merely related to stimulus modality (higher alpha power for verbal than for figural tasks) and less strongly to the problem type (divergent production vs. dialectic problems). A possible explanation for not finding alpha power differences between both problem types could be that both require open solutions, as it is typically the case in creativity tasks.

2.3. EEG alpha power as a function of originality of generated ideas

Rather than merely focusing on divergent and convergent modes of thinking, relevant research in this field has also addressed the research question as to how brain states during the production of more original ideas might be differentiated from those observed during the production of less original ideas. In doing so, Fink and Neubauer (2006) were able to demonstrate that more original (as opposed to less original) ideas (as assessed via external ratings; cf.Amabile, 1982) were accompanied by a stronger alpha synchronization at centroparietal recording sites.

Grabner et al. (2007) extended the findings of Fink and Neubauer (2006) in two important ways. First, EEG activity was assessed in relation to self-rated originality of ideas. For this reason, participants were requested to evaluate each single idea they gave during the experiment with respect to its originality subsequent to the recording session. And second, as creative ideation presumably requires functional cooperation between different brain areas, Grabner et al. (2007) calculated event-related functional coupling or the phase locking value (PLV) between selected pairs of electrodes (cf. Lachaux et al., 1999). Several findings of this study appear to be noteworthy: First, similar to Fink and Neubauer (2006), creative idea generation was generally accompanied by an event-related alpha synchronization. Second, and more importantly, the obtained findings also suggest that the production of ideas that were subjectively rated as more original was reflected in a different activity pattern of the brain than the production of less original ideas. Analyses revealed that the production of more original ideas exhibited a larger right-hemispheric alpha synchronization than the production of less original ideas, whereas in the left hemisphere no differences in relation to self-rated originality of ideas were found. This effect was significant for the lower alpha band but not in the upper alpha band. In addition, more original ideas were associated with stronger functional coupling of anterior cortices of the right hemisphere, while in the left hemisphere no significant PLV differences between more and less original responses emerged.

2.4. Individual differences in creativity

The studies presented so far used a within-subjects approach comparing tasks with varying creativity-related task demands or more vs. less creative ideas. Beyond that there also exist a number of studies which related inter-individual differences in creativity to EEG alpha power. The studies by Martindale and colleagues (1975, 1978) already revealed some evidence that higher creativity was related to higher alpha power. In a later study, Martindale et al. (1984) reported evidence that high creative participants (as operationalized by higher scores in the AU task and the remote associates task) showed lower alpha power in the right hemisphere during creative task performance which was interpreted in terms of higher activity of the right hemisphere. This was, however, only true for participants who scored high in both tasks, whereas for all other participants the general activation pattern involved higher alpha power in the right hemisphere (see experiment I and II, but not experiment III, which involves a drawing task).

Jaušovec (2000) compared alpha power measures of high and low creative people (based on performance in the Torrance Test;Torrance, 1966) in a number of divergent thinking tasks and also considered the role of intelligence. He found that high creative people showed much higher alpha activity across the entire scalp in the lower and upper alpha band while working on divergent production problems than less creative people, whereas there was no effect in these tasks related to intelligence. Similar findings were obtained by Fink and Neubauer (2008), who showed that more creative people (and especially those who were also more extraverted) showed higher alpha power during creative ideation in two divergent thinking tasks.

In Fink et al. (2009a) participants were divided into a group of lower and higher originality based on the originality/creativity of ideas they generated during the AU task. As shown in Fig. 1, creative idea generation was generally associated with comparatively strong task-related synchronization of alpha (10–12 Hz) at frontal sites, while at more posterior recording positions even small alpha desynchronization was observed. Interestingly, in comparing both originality/creativity groups, we observed that more original individuals (i.e., those who performed well on the AU task) exhibited a comparatively strong hemispheric asymmetry with respect to alpha activity, with stronger task-related alpha synchronization in the right than in the left hemisphere. For less original individuals (who generated ideas of lower originality), however, no hemispheric differences with respect to alpha activity emerged (see Fig. 1). In another study, Fink et al. (2009b) found that a group of professional dancers with perennial professional experience in improvisation dance showed stronger task-related alpha synchronization (10–12 Hz) during AU performance at posterior (i.e., centroparietal, parietotemporal and parietooccipital) recording sites than a group of novices. Moreover, professional dancers showed higher upper alpha synchronization than novices also during the imagination of an improvisation dance which was not evident during imagining of a standard dance involving a monotonous sequence of steps and movements.

Similar findings were also reported by Razumnikova (2007a) and Razumnikova and colleagues (2009). Razumnikova (2007a) observed evidence that more original individuals (operationalized via the originality of responses in a RAT-like association test) showed

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higher amplitudes in the lower alpha band (8–10 Hz). And in a later study, Razumnikova et al. (2009; article in Russian, only abstract in English available) found that highly creative individuals exhibited a higher level of lower alpha power (8–10 Hz) during verbal creative ideation. With respect to the upper alpha band (10–13 Hz), high (vs. low) creative individuals showed more power mostly at anterior and parietal cortical sites.

2.5. Effects of creativity enhancing interventions

The particular sensitivity of EEG alpha activity to creative cognition is also nicely substantiated by evidence that alpha power increases as a result of a verbal creativity training. Fink et al. (2006) reported a study in which participants received a computerized training of creativity composed of different creativity problems such as inventing names, finding slogans or finding nicknames (for details see Benedek et al., 2006). The training, which could be installed and performed on any home-PC, took roughly about two weeks to complete and participants were requested to exercise about half an hour per day. In applying a pretest-posttest design with the training in between, we observed a higher originality of ideas in the trained (as compared to the control) group. Moreover, this training effect was also reflected in stronger alpha synchronization at frontal sites (in the lower alpha band but not in the upper alpha band) in the training than in the control group after completing the training. Based on this promising evidence, Fink et al. (2011a) recently investigated whether alpha activity is also sensitive to more short-lasting creativity interventions. Participants performed the AU task while the EEG was recorded and were exposed to three different experimental conditions. In the cognitive stimulation condition, participants worked on the AU task subsequent to a short intervention in which they were – as it is the case in classic group-based creativity techniques such as brainstorming – confronted with creative ideas of other people (cf. Dugosh et al., 2000; Dugosh and Paulus, 2005). In the affective stimulation condition, participants had to generate creative ideas after the presentation of sound clips of merrily laughing people. Relevant experimental studies demonstrated that positive affect is contagious and can be elicited by short auditory stimuli presenting human vocal affect expressions such as laughter (Hietanen et al., 1998; Meyer et al., 2005; Warren et al., 2006). In the control condition no intervention was applied. In each experimental condition, participants were instructed to respond as creatively and as originally as possible. Creative cognition generally elicited alpha synchronization, most prominent in the prefrontal cortex and in the right hemisphere. In addition to this, it was also shown that stimulating creativity via the exposure to other people's ideas and via positive affect was associated with stronger alpha increases at prefrontal cortical sites as compared to the control condition (no intervention).

2.6. Summary of empirical findings

The preceding sections reviewed existing findings on the relationship between EEG alpha power and creative ideation. In a nutshell, the majority of reviewed studies reveals evidence that the process of creative idea generation can be characterized by increases in alpha power (i.e., task-related alpha synchronization or at least absence of alpha desynchronization, respectively), particularly apparent at prefrontal and (right) posterior parietal sites. Additionally, there is also convincing evidence which suggests that task-related power changes in the EEG alpha band are sensitive to certain creativity-related factors.

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Specifically, on the basis of existing findings in this field it can be concluded that EEG alpha power varies as a function of the creativity-related task demands (the more creative a task, the higher the level of alpha; Fink et al., 2007; Jauk et al., 2012; Jaušovec, 1997; Krug et al., 2003) and the originality of ideas (Fink and Neubauer, 2006; Grabner et al., 2007). Also, EEG alpha power has been observed as being related to an individuals' creativity level (more alpha in higher creative individuals; e.g., Fink and Neubauer, 2008; Fink et al., 2009a, b; Jaušovec, 2000; Martindale and Hines, 1975; Martindale and Hasenfus, 1978). In addition, research in this field also suggests that alpha band power increases as a result of interventions aiming to enhance creativity (Fink et al., 2006, 2011a). The available findings thus strongly suggest that creative cognitive processes are reflected by increased alpha power levels in the brain.

Concerning the potential specificity of lower and upper alpha power for creativity there appears to be no clear evidence. Some studies reported higher sensitivity of the lower alpha band (e.g., Fink et al., 2006; Grabner et al., 2007; Razumnikova, 2007a), while some reported higher sensitivity of the upper alpha band (e.g., Fink et al., 2009a,b, 2011a; Shemyakina et al., 2007). A larger number of studies, however, did either not differentiate between lower and upper alpha band power (e.g., Krug et al., 2003; Mölle et al., 1999) or observed findings according to which any creativity-related effects do not strongly depend on a discrimination of lower vs. upper alpha band but rather apply to the entire alpha band (e.g., Fink and Neubauer, 2008; Jauk et al., 2012; Jaušovec, 2000; Razumnikova, 2000; see also Benedek et al., 2011).

3. The potential meaning of EEG alpha oscillations in the context of creative ideation

3.1. Alpha synchronization and cortical idling

As outlined in Neuper and Pfurtscheller (2001), the ERD of alpha band activity presumably reflects an increased excitability level of neurons in the involved cortical areas, which could be related to an enhanced information transfer in thalamo-cortical circuits (Pfurtscheller and Lopes da Silva, 1999). Relevant findings in this field clearly demonstrate that alpha band ERD could be seen as functional correlate of brain activation (Klimesch et al., 1999). In contrast, event-related synchronization (ERS) of alpha band power (i.e., increases in alpha power from the pre-stimulus reference to the task performance interval) has traditionally been thought to reflect a state of reduced active information processing in the underlying neuronal networks (Pfurtscheller and Lopes da Silva, 1999) or "cortical idling" (Pfurtscheller, 1999; Pfurtscheller et al., 1996). This notion was derived from the common observation that most cognitive tasks usually result in desynchronization of alpha when comparing alpha power during task processing with a pre-task reference period. Moreover, opening the eyes typically results in alpha suppression, whereas alpha power increases during closed eyes conditions. The latter is usually attributed to a decrease of active information processing given that the information stream from the visual system is interrupted. Early findings of creativity and frontal alpha synchronization therefore assumed that increases in alpha could reflect some kind of "hypofrontality" in which functions attributed to systematic-analytic problem solving might be temporarily suppressed (e.g., Dietrich, 2003; Fink and Neubauer, 2006). However, as an increasing number of EEG studies reported task-related increases of alpha power in response to a broad range of different cognitive task demands, it has become increasingly less probable that alpha synchronization merely reflects reduced mental activity or cortical idling (Buzsáki and Draguhn, 2004; Klimesch et al., 2007; Ward, 2003). Fink et al. (2009a) reported a further test of whether alpha synchronization in creative ideation is indicative of an increase or a decrease of cortical activation (i.e., cortical idling) by combining the methods of EEG and fMRI. They found that creative cognition tasks were associated with frontal alpha synchronization in the EEG study, while the same tasks showed an increase of the BOLD response in frontal brain regions in the fMRI study. This finding strongly suggests that alpha synchronization during creative ideation reflects an active cognitive process rather than cortical idling.

3.2. Alpha synchronization as a sign of internal processing demands

Meanwhile there is a large body of evidence which indicates that synchronization of alpha activity does not solely reflect cortical deactivation or cortical idling (e.g., Cooper et al., 2003; Jensen et al., 2002; Klimesch et al., 1999, 2007; Ray and Cole, 1985; Sauseng et al., 2005). Rather it seems that alpha synchronization is particularly sensitive to sensory inhibition or internal processing demands. For instance, Jensen et al. (2002) interpreted their finding of an increase of alpha activity over occipital-parietal sites with increasing memory load as being indicative of some kind of suppression of the input from the visual system, which would disturb working memory processing in frontal brain areas (cf. Ray and Cole, 1985). Klimesch et al. (1999) observed event-related synchronization of alpha activity during the retention interval of a memory task which they referred to as "paradoxical alpha synchronization in a memory task" (p. 493; see also Krause et al., 1995, 1996), as this result is contrary to the usual finding that alpha desynchronizes when individuals are engaged in the performance of cognitively demanding tasks. In a similar vein, Sauseng et al. (2005) observed alpha synchronization in prefrontal areas during working memory processing which they interpreted in a manner that "… frontal areas must not become involved in (distracting) new activities as long as an ongoing working memory task is carried out" (p. 154). In another highly relevant study in this field, Cooper et al. (2003) compared EEG alpha activity related to tasks requiring sensory processing of visual, haptic and acoustic stimuli with a condition requiring the mental imagination of these stimuli. They found that internally-directed attention in the mental imagination tasks yielded stronger alpha power than externally-directed attention in the sensory-intake tasks, and that alpha power also increased with increasing task demands. In all of the cited studies, alpha synchronization has been interpreted as a functional correlate of inhibition or top-down control (see e.g.,Sauseng et al., 2005; Klimesch et al., 2007). According to that view, alpha increases may reflect an inhibition of cognitive processes that are not directly relevant for task performance (e.g., retrieval of interfering information during a retention interval of a working memory task), and are observed "… over sites that probably are under, or exert top-down control." (Klimesch et al., 2007, p. 63).

3.3. The role of frontal alpha synchronization in creative ideation

Benedek et al. (2011) recently examined to what extent alpha synchronization is related to general internal processing demands or to other specific creativity-related processes. They devised a convergent thinking task (i.e., finding 4-letter anagram solutions) and a divergent thinking task (i.e., creating original sentences with four given initial letters) which had to be performed either involving low or high internal processing demands. The experimental condition involving high internal processing demands was realized by masking the stimulus letters after a brief encoding period of half a second, ensuring that the task had to be processed internally. In the condition involving low internal processing demands, the stimulus remained visible and thus allowed for steady bottom-up processing. In this study, frontal alpha synchronization was found only in the high internal processing condition – but for both the convergent and the divergent thinking task. It was concluded that frontal alpha synchronization reflects a state of high internal processing demands which may be prevalent in divergent but also in convergent tasks. Importantly, divergent thinking was accompanied by alpha synchronization at right posterior parietal sites, while convergent thinking was not, which may point at an activation pattern that is specific for creative thought.

Prefrontal alpha synchronization during creative ideation could thus generally reflect a state of high internal processing demands or a state of enhanced internally oriented attention (Knyazev, 2007). This is in line with other studies showing that alpha power is reduced when participants have to respond to external stimuli as compared to internal mental processing, and that alpha power is enhanced during mental imagery and imagination tasks (Ray and Cole, 1985; Cooper et al., 2003, 2006). This view is also supported by Von Stein and Sarnthein (2000), who suggest that alpha activity reflects the absence of stimulus-driven, external bottom up stimulation and, thus "is maximal in situations where cortical processes … are driven by free floating associations, mental imagery, planning, etc." (p. 311). Such a state of internal attention is prevalent in creative ideation tasks. Let us consider the common divergent thinking task of generating alternate uses e.g. for a brick. Once the stimulus word is encoded, this task does usually not involve any further bottom-up sensory processing. It rather involves memory processes for the retrieval of known uses, for the scanning of object properties which might cue new uses and for accessing remote associations which can be recombined to useful new ideas (Benedek et al., 2012b; Gilhooly et al., 2007). This is especially true for creative ideation tasks in the verbal domain using conceptual stimuli but it might be less true for figural ideation tasks which require stronger sensory processing of the visuo-spatial stimulus properties (cf. Jaušovec and Jaušovec, 2000).

Moreover, prefrontal alpha was also conceived to indicate top-down control which serves to actively inhibit task-irrelevant activity such as irrelevant sensory processing or the retrieval of interfering information (Klimesch et al., 2007; Sauseng et al., 2005). This may be particular relevant for creative ideation which is known to involve effective executive processes such as the inhibition of dominant associations and of prepotent response tendencies (Beaty and Silvia, 2012; Benedek et al., 2012a; Gilhooly et al., 2007). However, it should be noted that internal processing and top-down control are not specific to the process of creative ideation but are also relevant in many other cognitive tasks (Benedek et

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al., 2011). It can rather be assumed that efficient internal processing and top-down control are essential – but certainly not the only – characteristics of creative ideation.

3.4. The role of parietal alpha synchronization in creative ideation

Alpha synchronization during creative ideation is also often seen over posterior parietal and occipital sites (e.g., Fink et al., 2009a,b; Jaušovec, 1997; Mölle et al., 1999). This finding does not seem to be restricted to creative ideation tasks but has been observed in other creativity-related tasks as well (e.g., imagining dancing: Fink et al., 2009b; insightful problem solving: Jung-Beeman et al., 2004; music imagery: Schaefer et al., 2011). Kounios et al. (2006) observed evidence that neural activity prior to problem presentation predicts whether problems are subsequently solved with insight (accompanied by subjective experience of "AHA!", as a reflection of a sudden conscious availability of a solution) or in an analytical manner. The authors found less alpha over a broad region of the posterior cortex prior to non-insightful, analytical problem solving which they interpreted in a manner that preparing for analytical problem solving was more likely realized in directing attention outwardly (i.e., in a more bottom-up fashion), while the preparation for solving upcoming tasks with insight was in contrast associated with focusing attention more inwardly (see also Kounios et al., 2008; Kounios and Beeman, 2009). Increased alpha over occipital-parietal sites has therefore commonly been interpreted as suppression of distracting information flow from the visual system (e.g., Jensen et al., 2002). At this, frontal brain regions may exert top-down control over posterior regions which might be mediated by functional coupling between these brain regions (Klimesch et al., 2007; Sauseng et al., 2005).

The complex process of creative ideation can certainly not satisfactorily be explained by the mere absence of bottom-up stimulation. As mentioned before, it must beyond that also involve other cognitive processes such as memory retrieval and association processes (Benedek et al., 2012b). That is, creative ideation (and creativity in a broader sense, respectively) certainly requires the retrieval of stored knowledge and the (re-)combination of stored memory elements into a new creative solution. Dietrich (2004) already supposed that tasks that draw more strongly on memory appear to be more likely to involve posterior brain regions. The observed parietal alpha synchronization could thus also reflect efficient memory processing in a manner that cognitive resources are devoted to effective memory search and retrieval. We will dwell upon this issue thereinafter.

One question in this particular context that still needs to be addressed is why parietal alpha synchronization during creative ideation is sometimes somewhat more pronounced in right than in left posterior parietal sites (cf. Benedek et al., 2011; Fink et al., 2009a,b; see also Martindale, 1999). Note that alpha synchronization recorded over the right parietal cortex appears to be more unique to creative processes, unlike frontal synchronization that seems to be generally associated with internal processing demands (Benedek et al., 2011). In search for possible explanations early concepts referred to the parallel or holistic processing mode of right hemispheric cortices, in contrast to the more sequential, logic-analytical processing mode of the left hemisphere (see e.g., Martindale, 1999); likewise it has been suggested that the right hemisphere operates in a more free-associative, primary process manner, typically observed in states such as dreaming or reverie (Martindale, 1999). More specifically, the left

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hemisphere has been proposed to be primarily engaged in relatively fine semantic coding (e.g., focusing activation on a single interpretation or meaning of a verbal stimulus), whereas the right hemisphere is supposed to be engaged in more coarse semantic coding by weakly and diffusely activating alternative or more distant associations (cf. Bowden and Jung-Beeman, 2003; Bowden et al., 2005; Jung-Beeman, 2005).

The interpretation of right parietal alpha synchronization during creative ideation appears to be particularly challenging when we take a look at recent fMRI findings in this field. Fink et al. (2009a, 2010, 2012) observed evidence that the generation of original ideas (AU task) in contrast to the production of typical characteristics of objects was amongst others associated with comparatively low activation (or even with deactivations) in regions of the right parietal cortex (such as the angular gyrus, AG). Similar findings were revealed by Howard-Jones et al. (2005) who led their participants generate creative and uncreative stories during fMRI assessment. They observed that creative (vs. uncreative) story generation was associated with stronger bilateral frontal activation but lower brain activity in the right inferior parietal lobe. Kowatari et al. (2009) reported inverse correlations between creativity and brain activity in bilateral parietal brain regions while designing new pens. In another creativity domain, Berkowitz and Ansari (2010) found that musicians but not non-musicians deactivated the right temporo-parietal junction (including the angular gyrus) during musical improvisation, which was discussed in terms of inhibition of stimulus-driven attention aiding creative thought (see also Berkowitz and Ansari, 2008).

In reviewing classical lesion and imaging data, Petersen and Posner (2012) recently came up to the conclusion that attentional processes such as tonic alertness or orienting to external stimuli are strongly lateralized to the right hemisphere (see also Sturm and Willmes, 2001). Corbetta and Shulman (2002) and Corbetta et al. (2008) specifically propose a strongly right-lateralized ventral cortical network including the temporoparietal junction and the ventral frontal cortex which is involved during the detection of behaviorally relevant sensory events. Suppressed or attenuated activity in this region has been observed to occur if attention is goal-directed and focused, in order to prevent reorienting attention to task-irrelevant stimuli which would interfere with task performance. In fact, deactivations of right temporoparietal brain regions have been shown to correlate with successful task performance (for review see, Corbetta et al., 2008). Interestingly, in the creativity domain it was found that tasks that strongly draw on the originality facet of creativity were associated with suppressed activity in temporal and parietal brain regions as well (e.g., Berkowitz and Ansari, 2010; Fink et al., 2012; Howard-Jones et al., 2005).

Thus, the right-lateralized pattern of deactivations in parietal brain regions which has been observed in recent fMRI studies on creativity coincides with right-lateralized increases in parietal alpha band power in the EEG.[2] Right parietal alpha synchronization during creative ideation may thus–similar to prefrontal alpha synchronization–reflect a more focused state of internal attention that is less likely disturbed by interfering, task-irrelevant stimuli. But

[2]Note that a direct comparison between EEG and fMRI studies in terms of "activation" or "deactivation" is somewhat complicated by the fact that EEG alpha power increases during creative ideation relate to a pre-stimulus reference (resting) period, while fMRI studies usually report contrasts between two active tasks or conditions (e.g., creative vs. control task).

creative ideation would certainly not succeed if merely distracting information would be temporarily screened out from consciousness awareness. Given the prominent role of the parietal cortex in different memory-related demands (Cabeza et al., 2008; Wagner et al., 2005), parietal alpha synchronization during creative ideation may be also indicative of a state in which attention is directed to efficient memory search and retrieval. Wagner et al. (2005) proposed that posterior parietal brain regions could be a part of a neural network which is involved in shifting attention to (or maintaining attention on, respectively) internal mnemonic representations. Similarly, in the Attention-to-Memory (AtoM) hypothesis by Cabeza et al. (2008) dorsal parietal brain regions (largely corresponding to Brodmann area 7) are thought to be associated with the allocation of attentional resources to memory retrieval according to the goals of the rememberer, which they referred to as “top-down attention” (Cabeza et al., 2008). “Bottom-up attention”, in contrast, is driven by incoming sensory information such as the capturing of attentional resources by relevant memory cues and is supported by a more ventrally located attentional network of the parietal cortex (including the supramarginal and angular gyri; note that in in the AtoM model attention is triggered by incoming information that can both come from the senses or from memory, p. 618).

4. Conclusions and potential future research directions

The reported studies on the relationship between EEG alpha power and creative ideation have yielded a reliable and robust picture of some brain mechanisms underlying creativity, which may be among the most consistent findings in this field. The frequently observed alpha power increases during creative ideation could reflect more internally oriented attention that is characterized by the absence of external bottom-up stimulation, the inhibition of task-irrelevant cognitive processes and, thus, a form of top-down activity. They could also indicate the involvement of specific memory processes such as the efficient (re-)combination of unrelated semantic information. Taken as a whole, however, neuroscientific research on creativity is still at an early stage of its development and there are a number of important issues that are in great need to be addressed in future research in order to make the field advancing more effectively.

Some critical issues deal with specific methodological details in the employed experimental designs and measurements procedures. In this review we focused on the cognitive process of creative ideation. But even for this construct we observed a considerable variability of methodological approaches. Creative ideation tasks differed in many basic task properties including that (a) instructions either focused on fluency or creativity of ideas, (b) the task duration, which was ranging from some seconds to some minutes, (c) the reference duration, again ranging from a few seconds to some minutes, (d) responses should either be verbalized immediately or withheld until the end of the task, (e) tasks were performed with eyes open but in some studies also with eyes closed, (f) the tasks differed in other features such as modality (i.e., verbal vs. figural tasks) or complexity. Most of these task properties can be argued to directly affect the expected results. Moreover, studies also differed in many aspects of quantifying brain activation including the use of either raw power measures, or event-related power changes. In addition, some of the studies analyzed alpha power in different alpha sub-bands (lower and upper alpha band), while others focused on the broad

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alpha frequency range. Of course, the variation of methods could be seen as major source of scientific discovery and should be used to test the robustness of findings. However, this is only true when most general factors are held constant and only some specific factors are varied intentionally according to an experimental design. Unless studies are not consistent in basic aspects of the design, their results cannot be compared and integrated reasonably.

Besides the consistent use of well-established methods, future research in this field should also specifically focus on *the time-course of creative ideation*. Alpha oscillations during creative ideation have been studied in relatively long time intervals, and power estimates were obtained for comparatively long periods of time. This is unsatisfying, particularly for the following two reasons. First, it is commonly known that the generation of creative ideas occurs in different stages or phases and might thus considerably vary as a function of time (Finke et al., 1992). And second, the high temporal resolution of EEG techniques would be especially suited to study the time-course of creative ideation. There are some exciting studies which focused on the time-course of brain activity during insightful problem solving or the subjective experience of “AHA!” (e.g., Jung-Beeman et al., 2004; Kounios et al., 2006; Sandkühler and Bhattacharya, 2008; Sheth et al., 2009). For instance, in employing EEG time-frequency analyses, Jung-Beeman et al. (2004) observed evidence that the right-hemispheric alpha effect over parietal-occipital sites they observed in insight- vs. non-insightful solutions (i.e., more alpha in insightful solutions) was only apparent from approx. 1.4 until 0.4 s before response (see p. 506). In a similar vein, Sandkühler and Bhattacharya (2008) as well as Sheth et al. (2009) utilized sophisticated EEG analysis techniques for the quantification of spatio-temporal signatures of brain oscillations which yielded valuable insights into the manifold cognitive processes involved in the process of insight which goes beyond the mere classification of insight vs. non-insight solutions.

Studies also need to demonstrate some *specificity of the observed effects*. As shown in this article, the concepts of inhibitory top-down control, internally-directed attention, absence of bottom-up stimulation or attention to memory processes could all be seen as plausible explanations of some processes involved in creativity. We have shown that prefrontal alpha synchronization is relevant for all tasks involving internal processing demands, while alpha synchronization at (right) posterior parietal sites seems to be more specific to creative ideation (cf. Benedek et al., 2011). What we need in this context are methodologically sound experimental designs (e.g., manipulating attentional and/or memory demands during creative ideation) in order to disentangle the manifold processes involved in creativity, thereby allowing for more specific interpretations of the observed effects.

Also, the *potential impact of individual differences variables* such as sex or intelligence on creativity-related brain activation patterns needs to be clarified in future research. Up to the present there are only some preliminary findings in this regard. The studies of Jaušovec (2000) and Fink and Neubauer (2006) for instance were able to demonstrate a relationship between intelligence and creativity on the neurophysiological level. The group of Razumnikova observed sex differences with respect to brain activity during creativity-related tasks (Razumnikova, 2004, 2007b; Razumnikova et al., 2009; see also Fink and Neubauer, 2006). Beyond that there are also some studies which point to the importance of other individual differences variables such as extraversion (Fink and Neubauer, 2008).

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Taken together, these studies do not just yet empty into a coherent and consistent picture about the role of individual differences variables in this context. We hope that future research will pay attention to this crucial point.

There are beyond that also some general challenges in this field that should be briefly mentioned (see also Arden et al., 2010; Dietrich and Kanso, 2010):

Conceptual clarity

Perhaps the most important problem in the neuroscientific study of creativity is a general lack of conceptual clarity. While researchers usually aim to investigate the neural correlates of creativity, they can actually address only a specific aspect of the construct. As briefly outlined in the introduction, creativity can be viewed from many conceptual levels including transient creative states, creative potential, or creative achievement and so on. Moreover, creativity may refer to different definitions such as divergent thinking, imagination, cognitive flexibility, or insight, and it may be related to different domains such as story generation, poetry, drawing, or musical improvisation. Surely, we cannot expect consistent brain correlates related to all of these processes (cf. Dietrich and Kanso, 2010). But the diversity of possible conceptualizations of creativity led to the employment of a broad diversity of different tasks and methods and we believe that this is the major reason why this field has produced highly variegated results, which finally led to rather disappointing conclusions on our understanding of potential neural mechanisms underlying creativity (Arden et al., 2010; Dietrich and Kanso, 2010). Consequently, future studies need to be very specific in their definitions of the construct under investigation. This does not only involve the differentiation of creativity from other classic mental ability constructs such as intelligence. There is also the general challenge to decompose the complex construct of creativity into *definable neurocognitive processes* (see e.g.,Dietrich and Kanso, 2010), and at the same time maintaining *valid psychometric properties* in the tasks and paradigms that are used (Arden et al., 2010). In using psychometrically sound tasks that involve well-defined creativity-related demands, findings need to be replicated across different studies and laboratories, which would in the long run also facilitate the promotion of neurocognitive theories of specific aspects related to creativity.

Adequate neurocognitive theories and methods

The neural basis of creativity can definitely not be quantified in terms of “activation” or “deactivation” of some specific brain regions. Neither can creativity or creative ideation be localized in a specific brain area. Creative cognitive processes can rather be seen as the result of the functional interplay between brain areas of a complex neural network involved in various cognitive processes such as semantic information processing, memory, or attention. In order to learn more about the functional connectivity network underling creativity, we need to focus not only on single brain parameters but rather on the combined use of well-established and functionally well-defined neuroscientific measurement approaches. Such combined approaches should be applied on similar tasks involving well-defined, isolated neurocognitive processes. In this way, findings across different studies and laboratories would be better comparable. For instance, EEG techniques that measure the functional cooperation (or functional coupling, respectively) between different cortical areas

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might provide an extremely valuable tool in the study of creativity (Bhattacharya and Petsche, 2005; Jaušovec, 2000; Jaušovec and Jaušovec, 2000; Mölle et al., 1999; Petsche, 1996; Razumnikova, 2000, 2004, 2007a). Also, studies using fMRI would be extremely helpful in this context particularly with respect to their high spatial resolution. Such combined approaches appear to be especially exciting in view of the rapidly increasing availability of new and more fine-grained neuroscientific methods aiming at delineating structural characteristics of the brain associated with creativity (such as cortical thickness, gray matter, fractional anisotropy etc.; see e.g., Takeuchi et al., 2010). For instance, Jung et al. (2010b) recently reported exciting empirical evidence whereupon structural brain characteristics are significantly associated with performance in different well-established divergent thinking tasks. The same group reported a magnetic resonance spectroscopy study in which they investigated the relationship between brain chemistry (concentrations of the neurometabolite N-acetyl-aspartate) and divergent thinking (Jung et al., 2009), and another study in which they investigated the relationship between creativity and white matter integrity (as assessed by fractional anisotropy; Jung et al., 2010a). These studies seem to converge into a coherent picture as they "… point to a decidedly left lateralized, fronto-subcortical, and disinhibitory network of brain regions underlying creative cognition and achievement …" (Arden et al., 2010, p. 152). It would be particularly exciting to see some studies in future which use both structural and functional methods in the same sample of participants, in order to learn how structural characteristics relate to functional brain activity patterns during creative thought.

Generalizability to "real-life" creativity

And finally, the vast majority of studies in this field used (or were required to use, respectively) comparatively simple type of tasks, and the question as to how the observed findings might be generalizable to "real-life" creative achievements still remains unresolved. So once we are confident in the understanding of relevant basic brain mechanisms relevant for creativity, we may move a step further by investigating brain activity in more complex, "real-life" creativity tasks (cf. Hasson and Honey, 2012). There are some promising approaches following this direction, e.g. the studies of Berkowitz and Ansari (2010), Bhattacharya and Petsche (2005), Ellamil et al. (2012), or Kowatari et al. (2009), who extended neuroscientific research to the domain of artistic creativity including the study of brain activity during musical improvisation, visual art or designing book covers or new pens, respectively. Similarly, brain correlates underlying creativity have mostly been studied in samples of university students or in samples of the normal population. Studies employing more "creativity-related" samples such as artists, musicians, dancers etc. are comparatively rare in literature. Some noteworthy exceptions are the studies by Petsche (1996), Bhattacharya and Petsche (2005), Chávez-Eakle et al. (2007) or Fink et al. (2009b) who investigated creativity-related brain activity in samples of scientists, musicians, artists or dancers.

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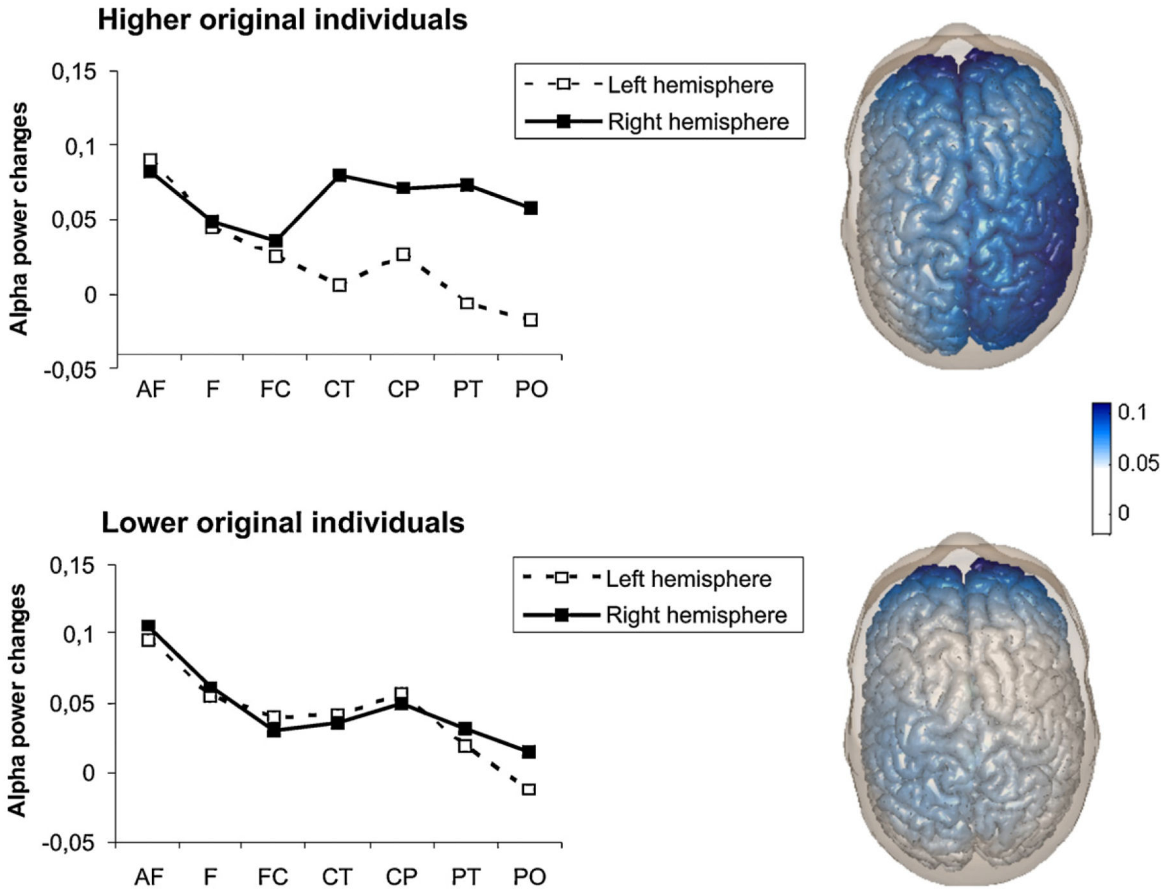

Fig. 1.

Task-related changes in EEG alpha power (upper alpha band, 10–12 Hz) during the generation of creative/original uses in the Alternative Uses (AU) task. Blue regions indicate increases in alpha power relative to rest. AF: anteriofrontal; F: frontal; FC: frontocentral; CT: centrotemporal; CP: centroparietal; PT: parietotemporal; PO: parietooccipital. Participants' task was to generate alternative uses of conventional everyday objects such as "umbrella", "pencil" or "vase of flowers", etc. Based on the originality of ideas, the total sample was divided into a group of lower (n = 25) and into a group of higher originality (n = 22). Both groups showed comparatively strong increases in alpha power (relative to a pre-stimulus reference interval) over anteriofrontal sites. Higher original individuals exhibited a hemispheric asymmetry with respect to alpha activity, with stronger increases in alpha in the right than in the left hemisphere, while in lower original individuals no hemispheric differences emerged. Figure redrawn from Fink et al. (2009a), Human Brain Mapping, 30, 734–748.