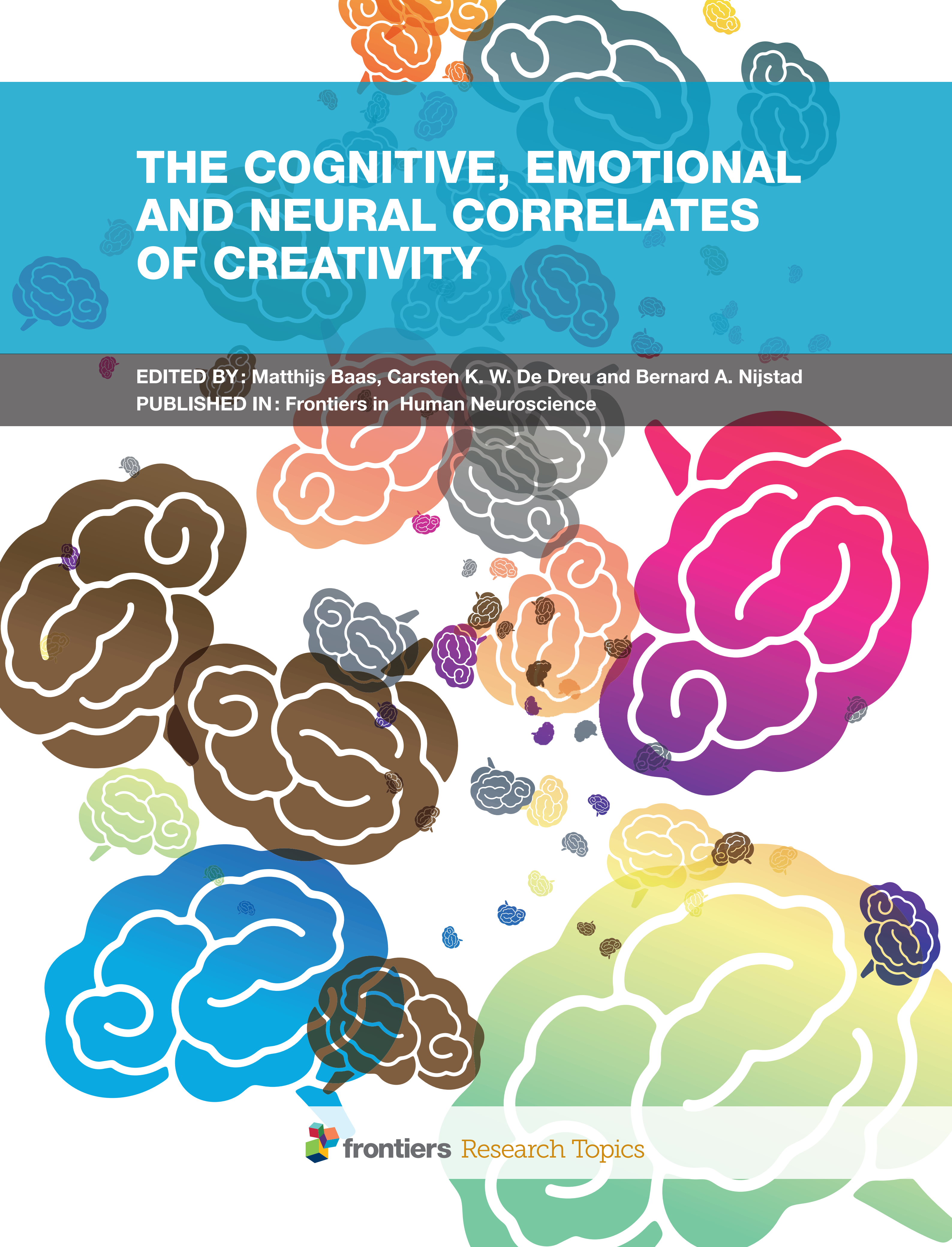

THE COGNITIVE, EMOTIONAL AND NEURAL CORRELATES OF CREATIVITY

EDITED BY: Matthijs Baas, Carsten K. W. De Dreu and Bernard A. Nijstad
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THE COGNITIVE, EMOTIONAL AND NEURAL CORRELATES OF CREATIVITY

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Across species, humans have an unsurpassed capacity for creative thought and innovation. Human creativity is at the roots of extraordinary achievements in the arts and sciences, and enables individuals and their groups to adapt flexibly to changing circumstances, to manage complex social relations, and to survive and prosper through social, technological, and medical innovations. The ability to generate novel and potentially useful ideas and problem solutions (viz., creativity) is a key driver of human evolution, and among the most valued and sought after competencies in contemporary societies that struggle with complex problems and compete for technological and economic supremacy. Because creativity provides fitness functionality in both ancestral and contemporary societies, it stands to reason that (i) the human brain evolved to sustain and promote creative thinking and we should be able to identify (ii) the brain circuitries, genetic drivers, and neurohormonal modulators of the human capacity for creative problem solving and original ideation; and (iii) the core cognitive and emotional processes underlying creative thought.

In this Research Topic, we bring together a collection of papers to provide an encyclopedic, open access snapshot of the current state of the art on the neural, cognitive, and emotional correlates of creativity.

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EDITORIAL
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Editorial: "The cognitive, emotional and neural correlates of creativity"

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Keywords: creativity, divergent thinking, incubation, motivation, emotion, EEG, neuroscience

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Creativity is at the roots of extraordinary achievements in the arts and sciences, and enables individuals and their groups to adapt flexibly to changing circumstances, to manage complex social relations, and to survive and prosper through social, technological, and medical innovations. The ability to generate novel and potentially useful ideas and problem solutions (viz., creativity) is a key driver of human evolution, and among the most valued and sought after competencies in contemporary societies. Because creativity provides fitness functionality in both ancestral and contemporary societies, it stands to reason that (i) the human brain evolved to sustain and promote creative thinking and we should therefore be able to identify, (ii) the brain circuitries and neurohormonal modulators of the human capacity for creativity, and (iii) the core cognitive, motivational, and emotional processes underlying creative thought.

In support of these propositions, in the past decade, creativity researchers have made great headway in identifying the neural, cognitive, motivational, and emotional correlates of creativity (e.g., Baas et al., 2008; Dietrich and Kanso, 2010; Nijstad et al., 2010; De Dreu et al., 2014). This Research Topic offers a collection of empirical work, and review and opinion papers about these and other stimulating endeavors.

Cognitive Correlates of Creativity

Research has shown that creative outcomes are a function of multiple cognitive processes, including divergent and flexible thinking, the use of flat and broad (as opposed to steep and narrow) associative hierarchies, convergent and persistent thinking, and incubation-driven processes (Sio and Ormerod, 2009; Nijstad et al., 2010; Baas et al., 2011).

In this Research Topic, Kenett and colleagues re-examined the classic proposition of Mednick (1962) that creative individuals are characterized by flat associational hierarchies. Using novel computational network paradigms, they revealed that the semantic memory network of low creative people seems to be more rigid, compared to the network of highly creative persons. Ritter and Dijksterhuis reviewed evidence for the intriguing possibility that creative discoveries oftentimes result from a period during which one refrains from task-related conscious thought (i.e., incubation). These authors explored possible causes of incubation effects and argue that during incubation periods unconscious processes contribute to creativity. Colzato and colleagues examined whether convergent and divergent thinking are differentially affected by acute moderate and intense physical exercise in athletes and non-athletes. Finally, Stevenson and colleagues researched whether creativity could be improved by practicing divergent thinking. Participants indeed improved in creative ideation and cognitive flexibility, with adolescents often benefitting more from training than adults.

Emotional and Motivational Correlates of Creativity

Past work shows that creativity and divergent thinking are triggered by appetitive cues, such as love, performing approach behavior, and mating cues (Friedman and Förster, 2010) and positive emotions, such as happiness and joy (Baas et al., 2008). Other work revealed that aversive cues and negative emotions may reduce divergent and flexible thinking (Baas et al., 2008; Byron and Khazanchi, 2011), but may nevertheless lead to enhanced creativity under the right circumstances (De Dreu et al., 2008; Baas et al., 2011; Roskes et al., 2012). In this Research Topic, Icekson and colleagues highlight the role of optimism as a potential remedy for the creativity undermining effects of avoidance motivation, due to its beneficial impact on cognitive (e.g., threat appraisals), affective (e.g., anxiety), and volitional processes (e.g., low intrinsic motivation). Oleynick, Thrash and colleagues took the formidable challenge to define and measure inspiration, a motivational state that compels individuals to bring ideas into fruition. They challenge the well-known observation by Edison that creativity is 1% inspiration and 99% perspiration and argue that both play important—but different—roles in creativity.

Neural Correlates of Creativity

Exciting research has identified the (interplay among) brain regions associated with creative ideation and insight (Kounios and Beeman, 2009; Jung et al., 2010), the neurohormonal modulators, such as dopamine and oxytocin (Chermahini and Hommel, 2010; De Dreu et al., 2014), the genetic components (Reuter et al., 2006; Simonton, 2008), and important methodological problems associated with the neuroscientific study of creativity (Dietrich and Kanso, 2010).

In this Research Topic, Mok addressed the inconsistent results regarding the neural signatures of creativity, suggesting that creative cognition likely emerges from an *optimal* balance between PFC mediated controlled processing and spontaneous processing that is mediated by the default-mode network. Abraham makes a case for studying the neural correlates of distinct cognitive processes underlying creativity, to uncover the information processing brain mechanisms by which creativity occurs. Schwab and colleagues took a different approach and focused on time-related changes of EEG alpha activity patterns during creative ideation. Among other things, they discovered that the production of more original ideas was accompanied by increasing hemispheric asymmetry (more alpha in the right than left hemisphere) with increasing duration of the idea generation period. Vartanian and colleagues nicely integrated findings from sleep research with research on PFC-mediated divergent thinking. Exploring the impact of a single night of sleep deprivation on idea generation (i.e., fluency) and PFC function during divergent thinking, these authors discovered that cognitive effectiveness and fluency were impaired following sleep deprivation.

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Investigating the structure of semantic networks in low and high creative persons

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According to Mednick's (1962) theory of individual differences in creativity, creative individuals appear to have a richer and more flexible associative network than less creative individuals. Thus, creative individuals are characterized by "flat" (broader associations) instead of "steep" (few, common associations) associational hierarchies. To study these differences, we implement a novel computational approach to the study of semantic networks, through the analysis of free associations. The core notion of our method is that concepts in the network are related to each other by their association correlations—overlap of similar associative responses ("association clouds"). We began by collecting a large sample of participants who underwent several creativity measurements and used a decision tree approach to divide the sample into low and high creative groups. Next, each group underwent a free association generation paradigm which allowed us to construct and analyze the semantic networks of both groups. Comparison of the semantic memory networks of persons with low creative ability and persons with high creative ability revealed differences between the two networks. The semantic memory network of persons with low creative ability seems to be more rigid, compared to the network of persons with high creative ability, in the sense that it is more spread out and breaks apart into more sub-parts. We discuss how our findings are in accord and extend Mednick's (1962) theory and the feasibility of using network science paradigms to investigate high level cognition.

Keywords: creativity, associative thinking, network science, individual differences, semantic networks

INTRODUCTION

Creativity is one of the few qualities that define human nature (Lindell, 2010). While in the past, the mental processes enabling creativity were considered mystical and un-researchable, nowadays an ample body of research has been established, permitting the examination of the creative ability like any other cognitive process (Dietrich, 2004; Dietrich and Kanso, 2010; Sawyer, 2011; Abraham, 2013). Dietrich (2004) argues that creativity is not a special feature of the cognitive system, but rather requires a variety of classic cognitive abilities such as working memory, sustained attention, and cognitive flexibility. Thus, this perspective allows breaking down the concept of creativity into specific cognitive abilities which can be measured separately with conventional empirical measures. One of the areas that have been extensively studied within the multifaceted concept of creativity is linguistic semantic creativity. Semantic creativity refers to flexibility, fluency and originality which results in high-order language products such as irony, humor, and metaphors (Faust, 2012; Mirous and Beeman, 2012). Such high-order language products share the need of the language system to process and maintain multiple alternative meanings of a concept, including meanings which are distantly or unusually connected (Cushen and Wiley, 2011). As such, semantic creativity is realized by the association of seemingly unrelated or distantly related concepts that nevertheless create a meaningful linguistic expression. Hence, the semantic network of semantically creative persons may be different than that of less creative people, allowing for more flexible and novel conceptual combinations during semantic processing. The goal of the present research is to quantitatively examine individual differences in the semantic networks of individuals with low semantic creative (LSC) and high semantic creative (HSC) abilities.

One of the hallmarks of creativity is that memory is searched more widely and in a less-defined manner than during everyday thinking (Bink and Marsh, 2000; Lindell, 2010). Thus, when describing creativity, Amabile et al. (2005) and Simonton (1999) note that the larger the number of potentially relevant elements that are retrieved during processing, the higher the likelihood that unusual associations or solutions will be generated, and the larger is the pool of novel ideas from which to choose. Recent reviews on creative thinking support this claim by emphasizing the retrieval of remote associations during creative problem solving (Helie and Sun, 2010). This view was strengthened by Friedman and Förster (2002) who presented empirical evidence that creative behavior can be mediated by a memory search-based mechanism. Finally, Griffiths et al. (2007) provide theoretical and empirical evidence to the similarity between memory search and the Google search engine algorithm. Such search processes are executed while people engage in semantic creativity tasks, and is the basis of Mednick's (1962) theory of creativity and his Remote Association Test (RAT).

Mednick (1962), focusing on individual differences in semantic creativity, envisioned the creative process as the combination of remote associations into new and useful combinations. To examine his theory, Mednick developed the RAT. In this test, subjects are presented with a triplet of seemingly unrelated words (e.g., *Cottage, Swiss, Cake*) and are required to find a single fourth word that is related to each of these words (e.g., Cheese; Bowden and Jung-Beeman, 2003). This task is accepted as examining semantic creativity and has been empirically widely used for its investigation (Gold et al., 2011; Storm et al., 2011; Mirous and Beeman, 2012). Investigating the significance of combination of remote associations, Benedek et al., recently demonstrated the importance of the RAT in predicting divergent thinking (the hallmark factor of creative ability) and intelligence (Benedek et al., 2012b). Thus, creative ability is highly related to associative thinking, a notion that has recently been corroborated in a critical review of neurocognitive research on creativity (Sawyer, 2011).

Despite the wide use of the RAT to investigate creativity, some argue against the RAT as a measure of creativity (Taft and Rossiter, 1966; Lee and Therriault, 2013). These objections are mainly due to the fact that the RAT is considered a convergent, and not a divergent, measure of creativity. Divergent thinking refers to an ideational process which involves generating a broad range of solutions or ideas to a given stimuli and is considered the hallmark of creative ability (Runco and Acar, 2012; Lee and Therriault, 2013). Convergent thinking, on the other hand, is considered a deductive process that involves systematically applying rules to arrive at a single, correct solution (Brophy, 2001; Lee and Therriault, 2013). As the RAT measures the success of a participant to find the single correct solution, it is considered a convergent test of creativity. However, Taft and Rossiter (1966) examined whether the RAT measures divergent or convergent modes of thought, by having participants complete the RAT with other convergent (such as school achievement and verbal IQ) and divergent (such as ideational and word fluency) measures. While the authors show how the RAT highly correlated with the convergent measures (measured by IQ and achievement scores), they also found significant correlations between the RAT and the divergent measures (measured by flexibility, originality, and fluency scores). Thus, it can be concluded from the work of Taft and Rossiter (1966) that the RAT demands both convergent and divergent thinking.

Recent studies examine performance in the RAT from a cognitive search perspective (Gupta et al., 2012; Smith et al., 2013). Smith et al. (2013) view the RAT as a multiple constraint problem, 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 constrains of the problem to rate the acceptability of the solution (Smith et al., 2013). Smith et al. (2013) found that participants solve RAT problems 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 agreements with the spreading activation model (Collins and Loftus, 1975). By examining the guesses provided by participants in attempting to solve RAT problems, the authors focus on the search process required in the RAT and not the end solution. This perspective may resolve the convergent-divergent debate of the RAT. As Smith et al. (2013) show, the RAT first requires a divergent thinking process to generate candidate solutions and then executive functions are required to examine the acceptability of the solution (see also Klein and Badia, 2014). Thus, the differences between low and high creative persons can be related to the structure of their semantic memory, executive functions, or both. Here we will focus on any possible differences related to the structure of semantic memory.

Mednick's (1962) theory of individual differences in associative hierarchies proposes that creative individuals have a richer and more flexible associative network than less creative individuals. According to his theory (Mednick, 1962), creative individuals are characterized by "flat" (more and broader associations to a given stimulus) instead of "steep" associational hierarchies few, common associations to a given stimulus (but see Benedek and Neubauer, 2013 for an opposing view). Thus, creative individuals may have more associative links in their network and can connect associative relations faster than less creative individuals, thereby facilitating more efficient search processes (Rossman and Fink, 2010). Gruszka and Necka (2002) examined the priming of close and remote associations by low creative and high creative persons. They show how high creative participants may be characterized by having a more complex lexicon network structure and how high creative participants may activate a wider range of associations across their lexicon network (Gruszka and Necka, 2002). Rossman and Fink (2010) found that creative subjects give lower estimates of the semantic distance between unrelated word pairs as compared to less creative subjects, implying that the former group may have a wider, interconnected semantic network which could lead to more efficient search process compared to less creative persons. To date, no direct examination of the difference in semantic network organization between low and high creative persons exists. Such examination of semantic memory networks has been recently become possible through the use of network science tools.

Semantic memory is the system of human memory that is responsible for the storage of semantic categories and of natural and artificial concepts (Budson and Price, 2005; Patterson et al., 2007). However, the way in which semantic memory is organized into categories and subcategories remains an open question (Rogers, 2008). Recently, this issue is more and more directly addressed via the application of computational network tools. Network science is based on mathematical graph theory, providing quantitative methods to investigate complex systems as networks. A network is comprised from nodes, which represent the basic unit of the system (e.g., mental lexicon) and links, or edges, that signify the relations between them (e.g., semantic similarity). This field has greatly advanced in the past few decades due to technological and quantitative theoretical advances, which allowed a rapid development of tools and theory to investigate both structural properties and dynamics of a network (reviewed in Baronchelli et al., 2013). 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). This model has successfully described a wide range of sociological, technological, biological and economical networks (Boccaletti et al., 2006; Cohen and Havlin, 2010; Kenett et al., 2010; Newman, 2010) and is also widely used in studying structural and functional brain networks (Sporns, 2011; Bullmore and Sporns, 2012; Stam and van Straaten, 2012; van Straaten and Stam, 2013).

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 (a neighbor is a node *j* that is connected through an edge to node *i*) of a node will themselves be neighbors. The ASPL refers to the average shortest amount of steps (nodes being traversed) needed to be taken between any two pair of nodes. A SWN is characterized by having a large CC and a short ASPL. Further structural properties of such network are the network diameter (D), which represents the largest path length in the network (and thus related to the spread of the network). Furthermore, network science examines the community structure of complex networks (Fortunato, 2010). Community structure research examines how a complex system, comprised of many nodes and edges, break apart (or partition) into smaller sub-networks. This area of research has been promoted, to a great extent, by Newman (2006), who introduced the notion of Modularity (Q). The modularity measure is a statistical measure that quantifies how much a network is partitioned into sub-communities. The larger the modularity measure is, the more the network is comprised from sub communities (Newman, 2006). The notion of modularity is extensively investigated at the neural (Meunier et al., 2010; Bullmore and Sporns, 2012; Hilgetag and Hütt, 2014), and more recently, cognitive (Arenas et al., 2012; Kenett et al., under review) levels of brain organization. Finally, a recent measure has been presented (S), which aims to quantitatively measure the "small-world-ness" feature of a specific network (Humphries and Gurney, 2008). This measure is a ratio of the CC and ASPL and allows investigating how much a network is "small-worlded," to the extent that any S-value greater than one is a SWN. In order to examine the small-world nature of an empirical network, its statistical properties are compared to those of a random, null network with the same amount of nodes and edges (Boccaletti et al., 2006).

At the cognitive level (the level of information processing in the brain), application of network science tools is also developing, mainly to investigate complex systems of language and memory structure (Vitevitch, 2008; Borge-Holthoefer and Arenas, 2010; Chan and Vitevitch, 2010; Vitevitch et al., 2012, 2014; Baronchelli et al., 2013). In the linguistic domain, lexicons of different languages seem to display SWN characteristics, considered to be a fundamental principle in lexical organization (Steyvers and Tenenbaum, 2005; De-Deyne and Storms, 2008a,b; Borge-Holthoefer and Arenas, 2010; Kenett et al., 2011). Investigating the complexity of semantic knowledge with network science allows to uniquely examine fundamental questions such as the nature of semantic organization (what are the structural principles that characterize semantic knowledge?), process and performance (to what extent can human performance in semantic processing tasks be explained in terms of general processing in semantic memory network?) and typical and non-typical semantic lexicon development (Steyvers and Tenenbaum, 2005; Beckage et al., 2011; Kenett et al., 2013). In fact, network research in language is slowly shifting from an interest in investigating the structure of mental lexicons to investigating cognitive processes operating on these lexicon networks (Borge-Holthoefer and Arenas, 2010; Arenas et al., 2012). We have recently introduced a novel approach to the study of semantic networks (Kenett et al., 2011) that makes use of correlation and network methodologies to define semantic similarity between concepts in the semantic network. The core idea of our method is the definition of connections between concepts in the semantic network by the similarity of association responses generated to these concepts, or alternatively, as the overlap of "association clouds." This notion is in accord with classic cognitive theory on the organization of semantic memory (Collins and Loftus, 1975), and thus differs from standard methods of extracting semantic similarity based on standard statistical properties (Kenett et al., 2011). Thus, such a method is suitable to study the differences between low and high creative persons, as proposed by Mednick (1962), which are theoretically found in their structure of associative hierarchies.

A small but slowly growing amount of research investigating creativity with network science tools is starting to appear. Schilling (2005) has presented a theory that suggests that insight problem solving is a result of a successful search throughout semantic memory network, enabled by either finding "shortcuts" or by the creation of new links between previously unconnected nodes in the network. Yet, this theory has not been empirically examined. Kenett et al. (2011) proposed that the structure of the mental lexicon constrains cognitive search processes such as those required in the RAT. Recently, a neural network model has been proposed aiming to model the dynamics of spontaneous thought (the spontaneous emergence of ideas), by directly examining associative processes such as those in the RAT (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. Recently, Doumit et al. used 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 vs. "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, as the authors admit themselves, this work is quite preliminary and requires further investigation. Furthermore, both corpora analyzed in this research are comprised from skilled and creative individuals (either poets or prose writers).

In the present research, we apply a network science methodology to directly and quantitatively examine Mednick's (1962) theory of individual differences in low and high creative persons. We collected a large sample of participants who underwent several creativity measures and were divided into a LSC and HSC groups. The approach developed by Kenett et al. (2011) was used to represent and compare the semantic networks of both groups. First, LSC and HSC groups generated free associations to 96 target words. Next, the semantic networks of both groups were calculated based on the overlap of association responses ("associative clouds") between the target words. Finally, we quantitatively analyzed and compared the two networks to examine any possible difference between them. We hypothesized, in accordance with Mednick's (1962) theory, that the LSC network would be more modular than the HSC network (higher Q measure for the LSC network). Furthermore, in accordance with Rossman and Fink (2010) findings, we hypothesized that the LSC network would be less condensed than the HSC network (higher ASPL and D measures for the LSC network). Finally, in accordance with Schilling's (2005) theory, we expected the LSC network to be less connected than the HSC network (lower CC and S measures for the LSC network).

METHODS

PARTICIPANTS

One hundred and forty-four persons were recruited for the study. Five subjects were removed from the final sample (three subjects due to incompliance with the tasks and the data of two subjects were lost due to technical issues), resulting in a final sample of 139 subjects (47 men, 92 women), with mean age of 23 years ($SD = 2.4$). All subjects were Hebrew native speakers, had normal or corrected to normal eyesight and were right handed, as measured by the Edinburgh Handedness Inventory (EHI; Oldfield, 1971; mean score = 92, $SD = 9$). Subjects either took part in the study as partial fulfillment of academic credit or were paid for their participation. This experiment was approved by the Bar-Ilan University institutional review board.

MATERIALS

Creativity measurement

Remote Association Test. The RAT (Mednick, 1962) was developed to investigate individual differences in creative ability (as described above). In our research we used the Hebrew version of the RAT (Nevo and Levin, 1978) which contains 25 triplets with varying degree of difficulty and lasts 15 min. The RAT score is the sum of correct answers given by the participant.

Tel-Aviv University Creativity Test (TACT; Milgram and Milgram, 1976). This test is a modified Hebrew version of the Wallach and Kogan (1965) battery of creativity tests (see Kaufman et al., 2012 for a current review of creativity measurements). This battery of tests includes several different measures of divergent thinking, which is considered the hallmark predictor of creative ability (Runco and Acar, 2012), frequently used in creativity research (Baird et al., 2012). The TACT measures verbal and visual creativity by producing two scores—fluency (number of responses provided), and quality (originality and applicability of response). The test is comprised of four sub-tests—two verbal (alternative uses and pattern matching) and two visual (similarities and line meanings). Each sub-test lasts 6 min and includes four open questions. The results of both verbal and visual subtests of the TACT were combined into TACT verbal and TACT visual scores. Fluency score was calculated by counting the number of different answers, and quality score was determined by three independent judges judging the originality and applicability of responses to stimuli for unique answers only, namely, answers which appeared in only 5% or less of the sample (Milgram and Milgram, 1976).

Comprehension of Metaphors (CoM; Faust, 2012). In this task, subjects are presented with word-pairs in Hebrew, which can either have a literal, conventional metaphoric, novel metaphoric meaning or are meaningless, and are asked to decide whether the two words comprise a semantically meaningful expression or not (Faust, 2012). This paradigm has been used in converging behavioral and neurocognitive techniques to investigate neural and hemispheric processing of novel metaphors compared to conventional metaphors, literal expressions and unrelated, meaningless word-pairs (reviewed in Faust, 2012). Recently, a significant positive correlation between scores on this on-line semantic judgment task for processing novel metaphors and the RAT has been shown (Gold et al., 2011). As such, this semantic judgment task provides a further measure of semantic creative ability (see also Silvia and Beaty, 2012).

Raven Progressive Matrices Test-Short Version (RSPM-SV; Van der Elst et al., 2013). In order to rule out any artifacts due to intelligence (Silvia and Beaty, 2012; Lee and Therriault, 2013), all participants underwent the Raven progressive matrices test (Raven and Raven, 2008). We used the shorten version of the RSPM, which has recently been shown by Van der Elst et al. (2013) to be a short valid method to assess intelligence, while taking into consideration age and gender effects on RSPM performance. This shortened version includes only series B, C and D of the original RSPM (Van der Elst et al., 2013).

Classifying participants into LSC and HSC groups

The TACT battery of creativity measures was used to classify the participants into LSC and HSC groups. One possible way to do so is to divide the sample into quarters, or thirds and compare the lowest quarter (or third) against the top quarter (or third) (Altman and Bland, 1994). However, recent objections have been raised at this method, especially when measuring continuous variables such as creative ability (Preacher et al., 2005). Preacher et al. (2005) discuss several challenges of what they term the "extreme groups analysis," related to statistical power, effect size, and group selection (see Preacher et al., 2005). Such concerns call for a more objective method to classify the participants into LSC and HSC groups. In this research, we used the decision tree approach, which is a statistical method at analyzing multivariate data (Lafond et al., 2009; Galimberti and Soffritti, 2011; Brandmaier et al., 2013). This approach has been mainly used in medicine and biology and is now being applied in psychological research, among other applications to classify subjects into low and high groups (Kopiez et al., 2006; Lafond et al., 2009; Strobl et al., 2009). Kopiez et al. (2006) used this approach to classify participants into low and high musical "sight-reading" ability (i.e., unrehearsed performance of music) groups, based on multiple independent variables. Thus, the decision tree approach is an efficient approach when analyzing a construct which has no comprehensive model to classify into low and high ability groups, such as creativity (Runco and Jaeger, 2012). Decision trees are implemented by a family of statistical algorithms that identify ways to split a multidimensional dataset into branch like segments (deVille, 2006). A decision tree attempts to predict, based on independent variables (for example, different measures of the TACT) specific classes of a dependent variable (for example, all participants who received a certain score on the RAT). The dependent variable can be split into smaller and smaller classes (branches), till specific stopping rules are achieved (Galimberti and Soffritti, 2011; Brandmaier et al., 2013). Thus, this method strives to find clusters that represent a sufficient range of the dependent variable and are separable with an accepted error (Kopiez et al., 2006). This method derives decisions, or classification rules, which form the different branches of the tree. Such rules are based on a method that extracts the relationship between the classes of the dependent variable and certain aspects of the independent variables (i.e., range of values in one specific variable and another range of another variable). The values in the independent variables are used to estimate the likely value in a specific class of the dependent variable. Once the relationship is extracted, one or more decision rules can be derived that describe the relationships between the independent variables and classes of the dependent variable.

In our research, we used the divergent thinking measures (TACT scores) as the independent variables and the participants' RAT scores as the dependent variable. This was chosen since divergent thinking is widely accepted as a measure of creativity (Runco and Acar, 2012) and the RAT measures another aspect of creativity, namely convergent thinking, in addition to divergent thinking, as discussed above. Thus, we reasoned that classifying the participants by the ability of their divergent thinking scores to estimate their RAT scores will result in a valid and reliable classification. In this sense, the decision tree classifier aims to predict RAT scores via various TACT measures classification rules. In this sense, this approach attempts to classify the participants based on their TACT performance into each of the possible RAT scores (1–25) and thus objectively sort participants into a low creative and a high creative sample. Finally, we will verify the validity of this classification method by examining the difference in performance of the two groups on the CoM task, which has been shown to measure creative ability (Gold et al., 2011; Silvia and Beaty, 2012).

Free association task

The free association task is based on the method used in Rubinstein et al. (2005), where subjects are presented with a target word and have one minute to generate as many associative responses they could for that target word. This method differs from classical association tasks, where subjects are only required to generate either one or three associative response to a target word (Nelson et al., 2004; De-Deyne and Storms, 2008a). This method is superior to previous methods in collecting association norms, as it exposes a greater part of the mental lexicon, helping to statistically strengthen significant associations to target words within the network (Kenett et al., 2011; De-Deyne et al., 2013).

The target words used in the free associations task were taken from Kenett et al. (under review). These words were drawn from a list of 36 categorical norms gathered by Henik and Kaplan (2005; e.g., fruits, trees, countries). The top 4 high frequency words from each category were selected. These high frequency words were then tested for their degree of concreteness by independent judges. Only words which were judged to be concrete were selected. The final target word pool thus consisted of 96 words from 24 categories (Kenett et al., under review).

Association correlation networks

The association correlation matrix is computed from the association data. The correlations between the target word associations profiles (the associative responses given to the target words by all subjects), are calculated by Pearson's correlation. This correlation is based on the contribution of two parameters—the extent of similar associative responses given to a pair of target words and the amount of participants generating these similar associative responses to these target words. Thus, the more similar associations generated and the larger amount of participants generating these association responses to a pair of target words, the higher the association correlation between this pair of words is. The target word-target word correlations (or for simplicity association correlations) for all pairs of words define a symmetric correlation matrix whose (i, j) element is the correlation between target words i and j.

For example, if a pair of target words are *dad* and *mom* we examine the overlap of associative responses for these two target words. A possible overlap of associative responses given both to the target word *dad* and the target word *mom* can be *family* (given by a amount of participants to *dad* and b amount of participants to *mom*), *home* (given by c amount of participants to *dad* and d amount of participants to *mom*), *love* (given by e amount of participants to *dad* and f amount of participants to *mom*) and so on. Then, each of the associative responses given to both target words and the amount of participants generating these associative responses for both target words is taken into account, in relation to all of the associative responses generated to each of the two target words and their standard deviation, to generate an association correlation between the two target words. Note that the association correlation was determined on the basis of the overlap of targets' responses. If a target words was generated as a response it was not included in the computation of the association correlation between these two target words.

The association correlation matrix can be studied in terms of an adjacency matrix of a weighted, undirected network. In this view, each target word is a node in the network, and an edge (link) between two nodes (words) is the association correlation between them, with the correlation value being the weight of that link. Since most of the edges have small values (weak correlations), the relevant information about the network can be obscured. To overcome this obstacle, we make use of the Planar Maximally Filtered Graph (PMFG; Tumminello et al., 2005) to construct from the complete network a sub-graph that captures the most relevant information embedded in the original network. This method is based on hierarchical clustering and the resulting sub-graph includes all the nodes in the network whose edges represent the most relevant association correlations. To construct the PMFG the $N(N-1)$ values of the correlation matrix are ordered in decreasing rank. The method starts from the pair of nodes *i* and *j*, with the highest correlation and draws a link $j \rightarrow i$ between them. This reiterates according to rank order where in each iteration, a link is added if and only if is the resulting graph is still planar, i.e., can be drawn on the surface of a sphere without link crossing (Tumminello et al., 2005). Since we are interested in the structure of the semantic networks, we binarized each association correlation network (by converting all edges to uniform weight $= 1$) and analyzed these networks as unweighted undirected networks.

Finally, it is important to note that this method can only examine group sample networks and is not sensitive to individual differences of specific participants (see Morais et al., 2013 for a novel approach measuring individual semantic networks). When applying this method to compare between two networks (for example, LSC vs. HSC semantic networks), this method focuses on how the responses generated to all target words in one group differ from that of the second group. Thus, if the same target words are presented to both groups in a free association task, this computational method analyzes the general difference of the network structure arising from each complete sample.

Network analysis

To empirically analyze and compare the structural network properties of the LSC and HSC semantic networks, the nodes in both networks must be controlled in order to eliminate any possible spurious results (van Wijk et al., 2010). This was achieved by constraining both networks to 96 target words. We did not control for the number of edges in the two networks. Network parameters calculated, with the MatLab Brain Connectivity Toolbox (Rubinov and Sporns, 2010) were: CC, ASPL, the average mean amount of edges per node [<k>, van Wijk et al., 2010 and the network's diameter (D)]. Furthermore, in order to examine the network's CC and ASPL, a random network was created with the same number of nodes and edges. For this random network, we calculated its clustering coefficient (CCrand) and its average shortest path length (ASPLrand). To examine the modularity of each network, we made use of Newman's modularity measure (Newman, 2006) to investigate how each network divides into sub-clusters of words, by calculating its modularity index (Q). Finally, the S measure (Humphries and Gurney, 2008) was computed to quantitatively evaluate the small-world nature of each network.

We also investigated the importance of each node in the network. In network theory, the importance of a node in a given network is quantified using different measures, such as the betweeness measure and eigenvalue centrality (Boccaletti et al., 2006). Here we used the word centrality measure (Kenett et al., 2011). The impact of a specific node is quantified as the difference between the ASPL of the network after removing word *i* with the ASPL of the full network. A positive impact score signifies that after the deletion of word *i*, the ASPL became longer than the ASPL of the full network, indicating that this word has a positive effect on the spread of activation within the network. We refer to these words as "facilitating nodes" (FN). In contrast, a negative impact score signifies that after the deletion of word *i*, the ASPL became shorter than the ASPL of the full network, indicating that this word has a negative effect on the spread of activation within the network. We refer to these words as "inhibiting nodes" (IN). this method allows us to investigate the effect each node has on the spread of activation in the network (see Vitevitch and Goldstein, 2014 for a similar approach).

Statistical hypothesis testing methods to compare between networks is currently lacking (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 only few statistical methods to compare between networks (see Moreno and Neville, 2013). To statistically analyze our findings, we used three complementing approaches. First, we simulated random networks to determine that the network measures calculated for both networks did not result from a null-hypothesis of a random network. To this end, we generated a large sample of Erdos-Renyi random networks with a fixed edge probability (Boccaletti et al., 2006) and compared the network measures to the values resulting from the simulated random distributions for each measure. Second, we examined whether differences between the LSC and HSC network measures were statistically significant by applying the bootstrap method (Efron, 1979) to simulate partial random LSC and HSC networks and compared these networks. This procedure had a twofold rationale: (1) if the two networks truly differ from each other, then any sub-network consisting of the same nodes in both networks should also be different, and (2) the bootstrap method enables the generation of many simulated partial LSC and HSC networks, allowing for statistical examination of the difference between the two networks. In order to conduct the bootstrapping procedure, half of the target words (nodes) were randomly chosen. Then partial LSC and HSC networks were constructed separately using these random nodes, and for each partial LSC and HSC network, CC, L, S, and Q measures were computed. This procedure was simulated with 1000 realizations. Finally, we analyzed the difference in the amount of unique association generation per target word between the two groups. If the LSC semantic network contains more "steep" association hierarchies, as suggested by Mednick (1962), we would expect that their ability to generate associative responses to target words would be significantly lower than that of the HSC group. Thus, for every target word, we examined the mean amount of unique associations generated by each of the two groups (LSC and HSC), and statistically examined any group difference.

PROCEDURE

For the creativity measurements, each participant performed the four tasks in a Latin square random order. The CoM task was conducted using the E-prime software (Schneider et al., 2002) and stimuli were presented centrally to the participant on a standard CRT computer screen. Subjects were instructed to recognize whether the two words created a meaningful expression. The RAT was administered as a paper and pencil task. The instructions of the task were presented to the participant and two examples (not used in the task itself) were given. Participants had 15 min to complete the RAT. The TACT was administered as a paper and pencil task. The participants completed each of the TACT sub-tests separately, after they were presented with the instructions for the specific sub-test. Participants had 6 min for each sub-test of the TACT. The RSPM-SV was administered as a paper and pencil task. Instructions of the task were presented to the participant.

The free association generation task was conducted via an in-house Google Application (see De-Deyne and Storms, 2008b for a similar approach). In this application, each target word was presented separately with a clock counting down from a minute and a response box below the target word, where associative responses were entered via the keyboard. Once one minute elapsed, the next target word appeared. All associative responses entered by participants via this application were stored on the Google App Engine Server and were constantly monitored. The 96 target words were divided into four groups of 24 target words per group. Each group of target words was entered separately to our Google application, thus creating four separate sub-applications, each containing a group of 24 target words. Participants were free to complete the association generation task at their own time and computers, They were sent the four applications via a single email and were instructed that each part takes 24 min and that once begun they must complete the whole part without stopping. Furthermore, they were instructed that they could complete the four parts in any order they chose. Only participants that completed all four lists were entered into data analysis. The opening screen of each of the four applications gave the following instructions: "This is an association task. In front of you will appear a single word separately. Please write down as many related responses to this word you can think of. You will have 60 s for each word. For example, for the word *dad* you might write the following responses: mom, son, family, etc.".

RESULTS

LOW AND HIGH SEMANTIC CREATIVITY ANALYSIS

Creativity measures correlation analysis

To examine the relations between the creativity measures, we conducted a correlation analysis between RAT scores, all TACT fluency and quality measures, RSPM-SV scores and all of the CoM measures (response times and accuracy for all four conditions). The full correlation analysis is reported in Supplementary Information Table 1. This analysis did not find any significant correlations between RSPM-SV scores and any of the other creativity measures. The correlation analysis revealed a significant positive correlation between RAT and TACT fluency and quality scores [$r_{(137)} = 0.22$, $p < 0.008$ and $r_{(137)} = 0.21$, $p < 0.012$ for fluency and quality, respectively (two tailed)]. This finding positively relates convergent (RAT) and divergent (TACT) measures of creativity (i.e., Ward, 1975; Runco and Acar, 2012). The correlation analysis also revealed a negative significant correlation between RAT and CoM response times of novel metaphors [$r_{(137)} = -0.26$, $p < 0.002$ (two tailed)] and a positive significant correlation between TACT quality and CoM accuracy of novel metaphors [$r_{(137)} = 0.18$, $p < 0.032$ (two tailed)]. These two significant correlations replicate findings relating creative ability and novel metaphor processing (Gold et al., 2011).

Decision tree analysis

We applied the decision tree approach on the participant's creativity measures data, using the JMP software (www.jmp.com). In our decision tree, participants TACT measures were used as the independent variables and the RAT scores as the dependent variable. Classification rules were derived which compiled various ranges of the different TACT measures in order to predict the classification of specific participants to the different classes of the RAT (25 classes portraying all possible values of the RAT). These classification rules were then sorted from classifying participants with lowest RAT scores to participants with highest RAT scores. Participants positioned in the lower tertile of these classification rules were considered as LSC and participants positioned in the highest tertile as HSC (**Table 1**). Participants achieving low RAT scores seemed to be classified by having a general low TACT fluency score (<73). They were more specifically classified by various relations between quality and fluency scores in specific sub-tests of the TACT (both verbal and visual). Participants achieving high RAT scores seem to be classified by either having a general high TACT fluency score (≥73) or by having a general low TACT fluency score (<73) combined with low TACT verbal quality scores and high fluency in specific TACT sub-tests (either verbal or visual). Thus, fluency is not a sufficient factor in classifying participants who achieve high RAT scores. **Table 1** summarizes the classification rules for both LSC and HSC participants.

To validate this classification to LSC and HSC groups, we examined the difference in performance of the two groups on the CoM task, which has been shown to reliably measure creative ability (Gold et al., 2011; Silvia and Beaty, 2012). An independent samples *t*-test analysis on the difference in CoM scores between LSC and HSC groups revealed that the HSC group had significantly higher accuracy rates and lower average response times in comprehending novel metaphors as compared to the LSC group [$t_{(64)} = -1.75$, $p < 0.03$, $\eta^2 = 0.07$ and $t_{(64)} = 2.23$, $p < 0.08$, $\eta^2 = 0.05$ for response times and accuracy rates respectively (two-tailed)]. Since significant relations have been found between creativity and novel metaphor processing (Gold et al., 2011; Silvia and Beaty, 2012), this analysis validates the decision tree classification to LSC and HSC groups.

LSC and HSC group

70 participants (35 LSC and 35 HSC) completed all parts of the free association task. In order to match both groups on the RSPM-SV, from each group two participants with extremely low (less than two standard deviations in the LSC group) or high (more than two standard deviations in the HSC group) RSPM-SV scores were removed. All participants were native Hebrew speakers, with normal or corrected to normal eyesight. Participants received 80 NIS for their participation in the experiment. While the two groups did not significantly

Table 1 | Classification rules created by the decision tree to classify RAT scores based on TACT measures to LSC (upper panel) and HSC (lower panel) groups.

Leaf label	Mean	Count
LSC		
TACT_F<73&TACT_Verb_Q<15&TACT_1_F<17&TACT_2_F>=10&TACT_4_F<15&TACT_2_F>=13	6.89	9
TACT_F<73&TACT_Verb_Q<15&TACT_1_F>=17&TACT_3_Q<5	8.86	7
TACT_F<73&TACT_Verb_Q>=15&TACT_4_Q<9	5.75	8
TACT_F<73&TACT_Verb_Q>=15&TACT_4_Q>=9&TACT_1_Q>=7	7.11	9
TACT_F<73&TACT_Verb_Q>=15&TACT_4_Q>=9&TACT_1_Q<7	9.50	6
TACT_F<73&TACT_Verb_Q<15&TACT_1_F<17&TACT_2_F<10	6.00	6
Average	**7.35**	
HSC		
TACT_F>=73&TACT_3_F>=22&TACT_Q>=66	12.09	11
TACT_F>=73&TACT_3_F<22&TACT_F>=76	13.50	12
TACT_F<73&TACT_Verb_Q<15&TACT_1_F>=17&TACT_3_Q>=5	12.13	16
TACT_F<73&TACT_Verb_Q<15&TACT_1_F<17&TACT_2_F>=10&TACT_4_F>=15	10.86	7
Average	**12.14**	

Mean, mean average RAT score of a specific classification rule; count, amount of participants answering to a specific classification rule; Average; average RAT score of the entire groups (LSC, HSC). TACT_1_F, fluency scores of the 1st TACT sub test; TACT_1_Q, quality scores of the 1st TACT sub test; TACT_2_F, fluency scores of the 2nd TACT sub test; TACT_2_Q, quality scores of the 2nd TACT sub test; TACT_3_F, fluency scores of the 3rd TACT sub test; TACT_4_F, fluency scores of the 4th TACT sub test; TACT_4_Q, quality scores of the 4th TACT sub test; TACT_Verb_Q, combined quality scores of the two TACT verbal sub tests (1 and 3); TACT_F, combined fluency scores of all four TACT sub tests; TACT_Q, combined quality scores of all four TACT sub tests.

differ in any of the demographic details (age, education years, EHI, RSPM-SV), they significantly differed in all creative measures, in the sense that the HSC group had significantly higher scores on all creativity measures (RAT, TACT, CoM-NM) (**Table 2**).

LSC AND HSC NETWORK ANALYSIS

Preprocessing

In order to analyze the data for each group, we first standardized the data into a matrix, in which every column is a different target word and every row is a different association response to a target word. This resulted in a 32,370 (association responses) × 96 (target words) for the LSC group and a 42,367 (association responses) × 96 (target words) for the HSC group.

Since many similar association responses were received for different target words and due to various typing errors within the data, we proceeded to a preprocessing phase in order to construct a matrix where each row was a unique singular association response. This stage entailed two actions—standardizing association responses (i.e., neighbour → neighbor) and converting plural into singular (i.e., fruits → fruit). Next, all standardized association responses were organized into a single matrix and identical association responses were merged using the Minitab software (www.minitab.com). In this matrix, row i is a unique association response given by the entire sample, column j is a target word and cell(i, j) denotes the amount of response of associative response i to target word j. This resulted in a 5557 (unique association responses) × 96 (target words) for the LSC group and a 7617 (unique association responses) × 96 (target words) for the HSC group.

Network analysis

The association correlations networks were constructed from the association correlation matrices, using the PMFG filtering process (as described in section Association correlation networks). We then calculated different SWN properties of the semantic networks of both groups, to quantitatively examine network differences between them. The values of the different SWN parameters calculated for the LSC and HSC networks are summarized in **Table 3**. To visualize the network we plotted the graphs using the Cytoscape software (Shannon et al., 2003), and in order to present the Hebrew target words as the labels of the nodes, we translated them into English (**Figure 1**). In these 2D visualizations of the networks, nodes (words) are marked as red circles and links between them are marked as blue lines. Since these networks are unweighted and undirected, the links merely convey symmetrical relations between two nodes. Both the quantitative analysis of the calculated SWN measures and the qualitative examination of the network visualization reveal differences between LSC and HSC networks. First, the LSC network is more spread out than the HSC network. This is both apparent in the LSC network having a larger ASPL and a larger D than the HSC network. Furthermore, the LSC is less small-worlded than the HSC network, as evident in the S measure. Finally, the LSC network is more modular than the HSC network, as evident in the Q measure. Taken together, these findings indicate that the LSC network is more spread out, less connected and more modular than the HSC network (**Table 3**).

Table 2 | Low Semantic Creative (LSC) and High Semantic Creative (HSC) group details (standard deviations in brackets).

	LSC	HSC
N	33 (13/20)	33 (6/27)
Age	24 (2.4)	23 (2.2)
Education	14 (1.5)	14 (1.4)
EHI	92.5 (9)	90.7 (9.5)
RSPM-SV	111 (8.5)	114 (8.9)
RAT***	7 (2.7)	13.2 (3)
TACT F***	65.9 (15.7)	88 (24)
TACT Q***	34 (12.5)	50.4 (21)
CoM NM-RT**	1245 (886)	874 (358)
CoM NM-ACC*	0.49 (0.23)	0.6 (0.24)

N, number of participants comprising each group (male/female in brackets); Age, mean group age in years; Education, mean education years; EHI, mean Edinburgh Handedness Inventory score; RSPM-SV, mean Raven Standard Progressive Matrices Short Version score; RAT, mean Remote Association Test score; TACT F, mean Tel Aviv Creativity Test fluency score; Tel Aviv Creativity Test Q, mean TACT quality score; CoM NM-RT, mean Comprehension of Metaphors Novel Metaphors Response Time; CoM NM-ACC, mean Comprehension of Metaphors Novel Metaphors Accuracy rates. **$p < 0.1$ for a two-tailed t-test on the difference between groups;* ***$p < 0.05$ for a two-tailed t-test on the difference between groups;* ****$p < 0.001$ for a two-tailed t-test on the difference between groups.*

Table 3 | SWN measures calculated for the LSC semantic network and the HSC semantic network.

Parameter	LSC	HSC
CC	0.67	0.66
ASPL	4.6	3.93
<k>	5.88	5.88
D	12	8
CCrand	0.07	0.06
ASPLrand	2.7	2.7
Q	0.62	0.58
S	6.86	7.76

CC, clustering coefficient; ASPL, average shortest path length; <k>, average amount of edges a node in the network has; D, diameter; CCrand, Clustering coefficient of random graph; ASPLrand, average shortest path length of random graph; Q, modularity measure; S, small-world-ness measure.

Next, we conducted the impact analysis to examine any differences between the impact of a specific node between the two networks (LSC and HSC). The impact score for each node for each network was independently calculated as presented above. A Mann–Whitney test analysis on the difference in impact score revealed a significant difference between the two networks [$U_{(192)} = 3523$, $z = -2.818$, $p < 0.005$]. When comparing the amount of negative (impact < 0) and positive (impact ≥ 0) nodes for the two networks an opposing pattern of negative-positive nodes in the two networks is revealed. While in the LSC network there are more negative impact nodes than positive impact nodes, the HSC has more positive impact nodes than negative impact nodes. Furthermore, while the negative-positive impact nodes in the LSC network is more balanced (56–44%), the HSC network has a high percentage of positive impact nodes (65%). This high rate of positive impact nodes might indicate more efficient spread of activation in the network, thus providing another feature characterizing the difference between LSC and HSC networks.

To statistically validate our results, we applied the network validation methods. The simulated random network analysis revealed that for both LSC and HSC networks, all four network measures (CC, ASPL, S, and Q) were statistically significant (all p's $<$ 0.001). Next, we applied the partial bootstrapped analysis. This resulted in a sample distribution of 1000 samples for all measures (CC, ASPL, S, and Q). An independent samples t-test was conducted on each network measure to test the difference between the bootstrapped partial networks. These analyses (summarized in **Table 4**) revealed significant differences between the bootstrapped sample distributions of all measures, indicating that the CC of the partial LSC network was significantly smaller than that of the partial HSC network and the ASPL, S and Q measures of the partial LSC network were significantly larger than that of the partial HSC network (all p's < 0.001). Thus, while these differences were numerically small, they were significantly different and replicated the main finding that the HSC is more small-worlded, more condensed and less modular than the LSC network. These small numerical values probably arise from the partial networks being small.

Finally, the difference in association responses generated between the two groups (LSC, HSC) were analyzed by examining the mean amount of unique association responses generated for all target words (**Figure 2**). As can be seen in **Figure 2**, the HSC group generated more unique responses than the LSC group for all target words. Despite this difference the amount of unique responses for a specific target word was highly correlated between the two groups [$r_{(190)} = 0.75$, $p < 0.001$]. A One-Way analysis of variance conducted on the effect of group on mean association responses per target word revealed a significant main effect [$F_{(1,\ 191)} = 310.937$, $p < 0.001$, $\eta^2 = 0.614$]. A simple effect analysis [corrected for multiple comparisons using the Benjamin-Hochberg correction (Thissen et al., 2002)] was conducted on the average association responses for a given target word between the LSC and HSC groups. This analysis revealed that for 60% of the taget words, there is a significant difference between groups (all p's < 0.01), in the sense that the HSC generated significantly more unique association responses to a target word than the LSC group.

To eliminate any possible associative fluency contamination on network structure, we conducted a network analysis based only on the 10 first associative responses given by a participant to a target word (Benedek and Neubauer, 2013). First, for each group a subset of the raw association responses dataset was comprised, containing the first 10 association responses given to each target word by a specific participant. Next, we extracted the LSC 10 responses and HSC 10 responses semantic networks and examined any possible difference between them. This analysis revealed that the LSC-10 semantic network is less connected, more spread out and less small-worlded than the HSC-10 semantic network (Supplementary Table 2). Thus, the structure of the two networks

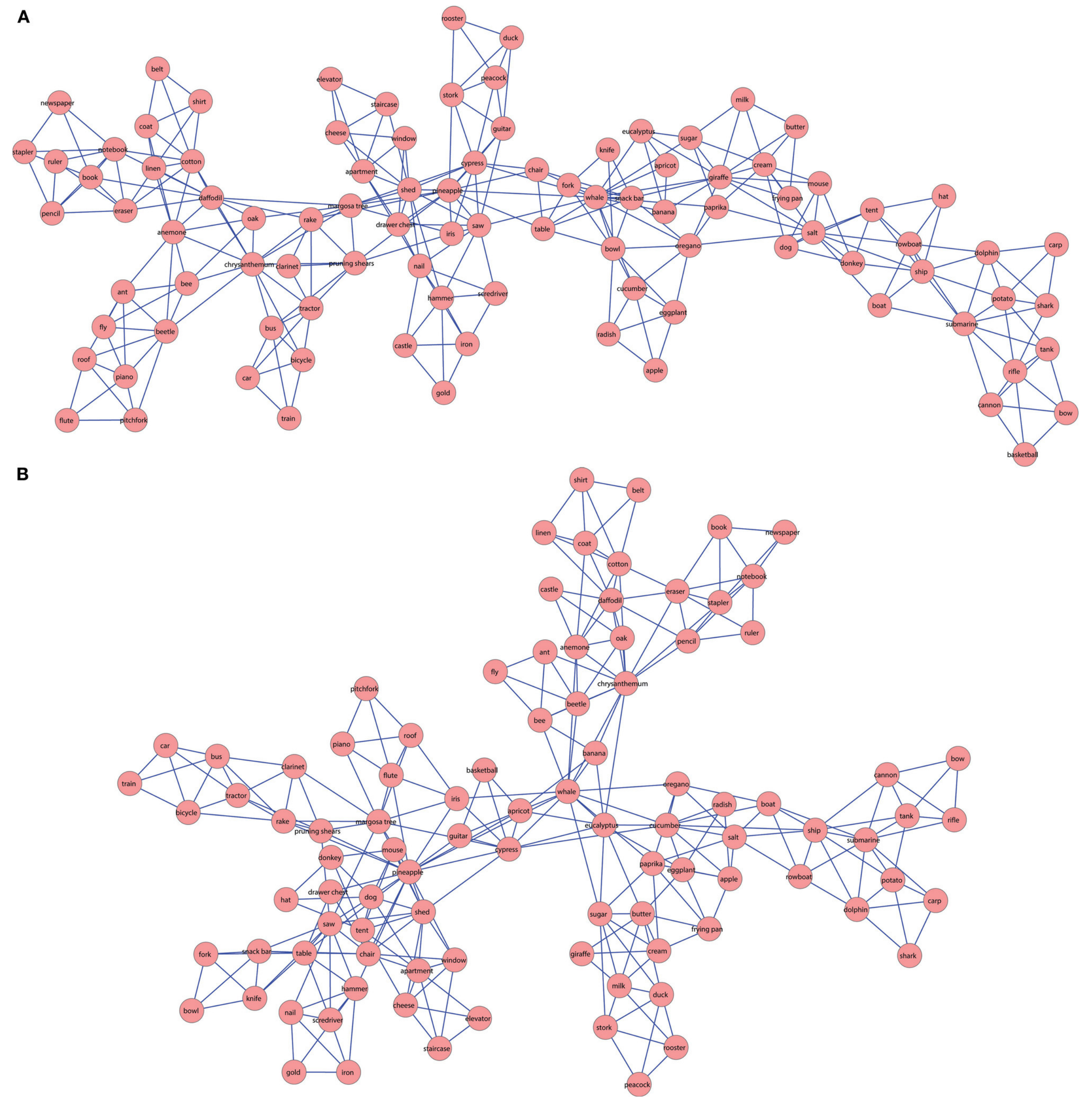

FIGURE 1 | A 2D visualization of the LSC (A) and HSC (B) semantic networks. Nodes are the 96 Hebrew target words translated into English. The links between nodes represents an unweighted, undirected connection between nodes.

based on the first 10 responses was similar to the original structure based on all responses. The only network measure which differed was the network modularity, which was lower for the LSC-10 network compared to the HSC-10 network.

DISCUSSION

In the work presented here, we quantitatively examine the difference in semantic memory network organization between individuals with LSC and HSC ability. A large sample of participants underwent a battery of creativity measures and was classified into LSC and HSC groups based on an objective statistical decision tree approach. Both groups completed a free association paradigm and generated free associations to 96 target words. The similarities between target words based on their free association responses were calculated and used to construct the association correlation matrix separately for each group. These association correlation matrices were used to model the associative networks of both groups, thus representing the organization of the target words in their mental lexicon. This was done to directly investigate, for the first time, Mednick's (1962) theory on individual differences in creativity, by means of network science methodology.

Mednick envisioned the creative process as the combination of remote associations into a novel and appropriate product (Mednick, 1962). He proposed that low creative persons have "steep" compared to "flat" associative hierarchies characterizing more creative persons. Thus, high creative persons may have a more flexible semantic memory organization. Examining the differences between the LSC and HSC networks revealed that the semantic memory network of persons with LSC ability is more spread out (indicated by a higher ASPL), more modular (indicated by a higher modularity measure) and less connected (indicated by a lower small-world-ness measure), than the semantic network of persons with HSC ability. We statistically validated our results by several complementary methods: first, we simulated a large sample of random networks to ascertain that the LSC and HSC network measures calculated did not result from a null-hypothesis random network. Next, we used the bootstrap method (Efron, 1979) to create a large sample of partial LSC and HSC networks and statistically examined the difference between the distribution of networks measures calculated for this large partial networks sample. This analysis found significant differences between the partial-LSC and partial-HSC sample in all network measures examined (CC, ASPL, S, and Q). Finally, we examined the amount of unique association responses generated to each target word by both groups. This analysis revealed a significant difference between groups, in the sense that the HSC group generated significantly more associative responses per target word than the LSC group.

Table 4 | SWN measures calculated for the partial LSC and HSC semantic networks (standard deviations in brackets).

Parameter	PLSC	PHSC
CC***	0.68 (0.01)	0.69 (0.01)
ASPL***	3.19 (0.3)	3.16 (0.3)
S***	4.53 (1.05)	4.66 (1.04)
Q***	0.55 (0.05)	0.54 (0.05)

*CC, clustering coefficient; ASPL, average shortest path length; S, small-world-ness measure; Q, modularity measure; ***p < 0.001 for a two-tailed t-test on the difference between groups. PLSC, mean partial bootstrapped LSC networks; PHSC, mean partial bootstrapped HSC networks.*

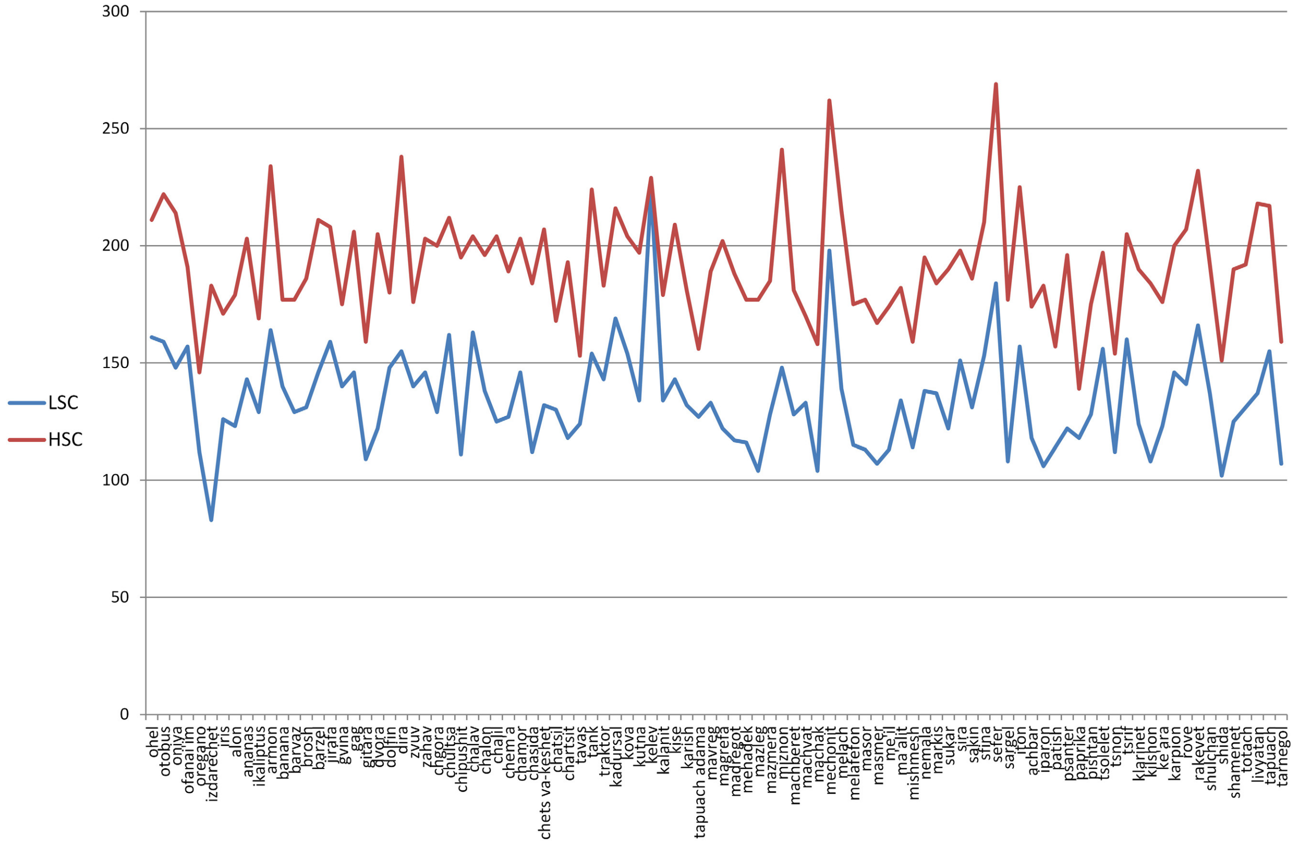

FIGURE 2 | Average unique association responses generated for target words for the LSC and HSC groups. X-axis, 96 target words used in the research; Y-axis, amount of mean association responses for a target word. LSC, low semantic creativity group; HSC, high semantic creativity group.

To eliminate any possible associative fluency contamination on the semantic networks, we analyzed the semantic networks of LSC and HSC with only the first 10 associative responses generated by each participant in the group for each of the target words (Benedek and Neubauer, 2013). This analysis verified our general network analysis findings, in the sense that the LSC-10 network is less connected, more spread out and less small-worlded than the HSC-10 network. The only network measure which seems to be affected by associative fluency was the modularity measure, in the sense that the LSC-10 network was less modular than the HSC-10 network. This is in contrast to the results of our analysis of the general networks, which showed that the LSC network was more modular than the HSC network. This higher association fluency for HSC might contribute to the modular structure of the network, leading to more connections between nodes in the network, thus lowering the overall modularity of the network. This is in line with Schilling's theory (2005), that relates creativity to the creation of new links in the network. Future research is required to directly examine the effect of associative fluency on semantic network structure.

The word impact measure (Kenett et al., 2011) was used to examine the effect of each node in both networks. This analysis allows to further examine any general differences between the two networks, but also to examine specifically how each node affects the spread of activation in the network. This is possible as this analysis examines the effect of a node on the ASPL, which is related to spread of activation in the network (Collins and Loftus, 1975; Den-Heyer and Briand, 1986). The null hypothesis for this analysis is a similar effect upon removal of a specific node in both networks. A Mann-Whitney test revealed a significant difference between the impact scores of the two groups. This difference further indicates how the networks differ in their structural properties. Furthermore, a possible dissociation between the percent of positive and negative impact scores between groups was found. In this sense, while the LSC network had a more balanced ratio between negative impact nodes and positive impact nodes (56–44%), the HSC network had a lower ratio of negative impact nodes than positive impact nodes (35–65%). This difference presents another feature which differentiates between the LSC and HSC networks. Possibly, the higher ratio of positive impact nodes in the HSC network facilitates more efficient spread of activation within the network, as removal of these nodes raises the ASPL resulting in the network being further apart.

How can Mednick's theory be related to network measures? first, we argue that Mednick's notion of creativity as a process of connecting remote associations can be measured by a network's small-world-ness nature—the more a network is small worlded, it has a higher CC (connectivity) and a lower ASPL (distance). Thus, a more small-worlded state enables better connectivity within the network, thus better allowing the connection of remote associations and bringing about a creative product (Mednick, 1962; Schilling, 2005). However, a network which is extremely small-worlded may lead to more inappropriate associative relations, thus raising the possibility of semantic chaos (e.g., loose association in schizophrenic states (see Faust and Kenett, under review for a theoretical account of semantic network states). Furthermore, Mednick's theory of "steep" and "flat" associative hierarchies is related to community structure in networks as measured by the network modularity (Newman, 2006; Fortunato, 2010). The modularity measure quantifies the extent to which a network breaks apart into sub-communities, in the sense that the larger it is, the more the network is comprised of sub-communities. Thus, a high modularity score can quantitatively define "steep" associative hierarchies while a low modularity score can quantitatively define "flat" associative hierarchies. To this end, the semantic network of creative individuals needs to be highly connected and contain as small numbers of large association clusters (or "attractor basins;" Rodd et al., 2004; Lerner et al., 2012) as possible (see Cushen and Wiley, 2011, for a recent support of this notion). An extension of Mednick's theory on the difference between the semantic memory structure of low and high creative persons is the spread of the network. Rossman and Fink (2010) have suggestedthat the semantic memory network of more creative persons is more condensed than low creative persons. Our analysis of the structural measures of the LSC and HSC networks empirically verifies this notion (Rossman and Fink, 2010).

How can the features of the semantic network of HSC better facilitate the creative process, including better performance in the RAT? Based on Schilling's (2005) theory that insight is a result of restructuring of the mental lexicon and Griffiths et al. (2007) findings that memory retrieval is similar to the Google search algorithm, we propose that the structure of semantic memory constrains cognitive search processes such as those required in the RAT (Kenett et al., 2011). Once presented with the primed words, the subject activates a search through the semantic network to find the adjoining target word. If the target word is weakly connected or far away from one or more of the primed words, the search process may not have enough activation strength or "get stuck" within a strongly connected module of words surrounding one or more of the primed words. Thus, the search cannot be completed. The successful completion of this search process through the semantic network requires activation of distant associations and creation of new connections within the semantic network (Schilling, 2005), which is more connected, less modular and more condensed.

Recently, Benedek and Neubauer (2013) examined the associative hierarchies of low and high creative participants. This was done by estimating associative hierarchies based on associative strength (relative response frequency). These association strengths were used to map the gradient of associative generation in low and high creative persons which represents their associative hierarchies (see Benedek and Neubauer, 2013 for a full description). The authors did not find any significant difference between the associative hierarchies of low and high creative persons. However, the authors found that the high creative persons differred from the low creative persons in associative fluency and uncommonnes of associations, which are related to each other (Beaty and Silvia, 2012). Thus, the authors concluded that what differentiates between low and high creative persons is not the structure of their associative hierarchies, but rather executive functions required to access semantic content. This approach is in line with increasing literature which shows a tight link between executive functions and creative ability (Nusbaum and Silvia, 2011; Beaty and Silvia, 2012; Benedek et al., 2012a; Silvia et al., 2013). This line of research moves away from a bottom–up (structural) to a top–down (executive functions) difference between low and high creative persons. Nevertheless, the top–down perspective of creativity still recognizes the importance of bottom–up, structural processing in the creative process (Beaty and Silvia, 2012). As Smith et al. (2013) show, the RAT requires a two stage process—a divergent, spreading activation process to generate possible solutions and a convergent, executive process to determine the acceptability of a possible solution. Thus, a full model of the creative process must account for both bottom–up and top–down processing which comprise the creative process. In this regard, network science can provide unique quantitative tools to examine search processes being commenced throughout a semantic memory network. Currently, few attempts have been made at investigating, through a network science perspective, cognitive search processes throughout semantic memory (Goñi et al., 2010; Capitán et al., 2012; Smith et al., 2013). More work is needed to incorporate such work in the study of individual differences in creativity. Thus, the creative process might be envisioned as an efficient search process being commenced upon a semantic memory network. This process is both constrained by the structure of the network and by the efficiency of the search process itself.

A few limitations of this research are related to the small amount of target words comprising the network (96), This is due to the time demanding nature of the paradigm (one minute per word), as larger semantic networks better allow quantitative examinations (Kenett et al., 2011; De-Deyne et al., 2013). Thus, future research is required to investigate larger semantic networks of LSC and HSC groups, to replicate and verify the results presented here. Another limitation due to the method of extracting the semantic networks is that it currently can only represent the network of the entire sample and cannot account for individual semantic networks. Future research is required to expand our network approach to the analysis of individual semantic networks (see Morais et al., 2013 for such a recent novel approach). As individual semantic networks appear to be stable and consistent (Morais et al., 2013), we predict that extracting the semantic networks of individual LSC and HSC persons will replicate the group findings we show in this work. Thus, we do not expect the results found in this research to be due to low consistency between individual semantic networks of participants comprising both groups. Finally, although the LSC network had a higher modularity score than that of the HSC, this difference was small (0.62 compared to 0.58), possibly related to the small amount of words comprising the networks. While this difference was statistically validated via our bootstrapping methodology, further research is required with larger semantic networks of LSC and HSC groups to further examine the modular difference between these two networks. Future work, which we are currently conducting, will empirically examine how the differences we found between the semantic memory structure of low and high creative persons is expressed in behavioral performance and neural activation. Furthermore, more advanced network analysis is in order to further elucidate what differentiates between low and high creative persons from a network perspective. A few examples of such advanced network analyses are dependency network analysis (Kenett et al., 2012), network cascading failures (Buldyrev et al., 2010), and modeling search dynamics in semantic networks.

In summary, we conducted a network science research which quantitatively validates and extends Mednick's (1962) theory on individual differences in creativity. We define Mednick's notion of "flat" and "steep" associative hierarchies in network terms of modularity and show that the semantic network of low creative persons is more modular than that of high creative persons. We also relate his notion of creativity as a process of connecting remote associations to network measures of connectivity, in network terms of small-world-ness state. Finally, we extend his theory and propose the spread of the network as another feature which differentiates between low and high creative persons. Thus, network science allows quantification and examination of classical cognitive theories, such as Mednick's theory of creativity (Mednick, 1962), which were difficult to examine until recently. Analyses of the structure of semantic memory are revelant to several cognitive domains, such as memory, language and high-level cognition and thus network research such as the one presented here is crucial to advancing these fields. Further than investigating and verifying Mednick's theory, we ground semantic creativity with semantic memory structure and cognitive search processes. While we investigate only a specific aspect of creative ability, this work contributes to the expanding neurocognitive empirical investigation of creativity.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://www.frontiersin.org/journal/10.3389/fnhum.2014.00407/abstract

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Creativity—the unconscious foundations of the incubation period

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Creativity is one of the most important assets we have to navigate through the fast changing world of the 21st century. Anecdotal accounts of creative individuals suggest that oftentimes, creative discoveries result from a process whereby initial conscious thought is followed by a period during which one refrains from task-related conscious thought. For example, one may spend an embarrassing amount of time thinking about a problem when the solution suddenly pops into consciousness while taking a shower. Not only creative individuals but also traditional theories of creativity have put a lot of emphasis on this incubation stage in creative thinking. The aim of the present article is twofold. First, an overview of the domain of incubation and creativity is provided by reviewing and discussing studies on incubation, mind-wandering, and sleep. Second, the causes of incubation effects are discussed. Previously, little attention has been paid to the causes of incubation effects and most findings do not really speak to whether the effects should be explained by unconscious processes or merely by consequences of a period of distraction. In the latter case, there is no need to assume active unconscious processes. The findings discussed in the current article support the idea that it is not merely the absence of conscious thought that drives incubation effects, but that during an incubation period unconscious processes contribute to creative thinking. Finally, practical implications and directions for future research will be discussed.

Keywords: creativity, problem solving, incubation, mind wandering, sleep, unconscious processes

Important achievements in the arts and sciences depend on creativity (Feist and Gorman, 1998; Kaufman, 2002), and creativity is associated with the development of new social institutions (Bass, 1990; Mumford, 2002) and economic growth (Amabile, 1997; Simonton, 1999). It is generally accepted that a creative idea or a creative solution to a problem has to be *novel* (i.e., original) and *useful* (Amabile, 1983; Runco and Pritzker, 1999). Creativity is not limited to the realms of greatness, but can also be found in daily life, for example, when one has to accomplish a task in a new way (Cropley, 1990) or when one has to adapt to changes (Runco, 2004). Today's world of continuous change thrives on creative individuals. Creativity has been related to cognitive abilities, expertise, and practice (Patrick, 1986; Amabile, 1996; Runco, 2004; Ericsson, 2006; Sawyer, 2012), and one may expect that creativity mainly thrives on extensive conscious thought. However, creative individuals, in describing their work habits or the process of creative problem solving, have suggested that oftentimes, creative ideas result from a period of incubation—a process whereby initial conscious thought is followed by a period during which one refrains from task-related conscious thought (for anecdotal accounts, see Ghiselin, 1952). The most frequently cited anecdote is probably the one from the mathematician Poincaré:

> "[. . .] I left Caen, where I was living, to go on a geologic excursion under the auspices of the School of Mines. The incidents of the travel made me forget my mathematical work. Having reached Coutances, we entered an omnibus to go some place or other. At the moment when I put my foot on the step, the idea came to me, without anything in my former thoughts seeming to have paved the way for it, that the transformations I had used to define the Fuchsian functions were identical with those of non-Euclidian geometry. I did not verify the idea; I should not have had the time, as, upon taking my seat in the omnibus, I went on with a conversation already commenced, but I felt a perfect certainty. On my return to Caen, for conscience' sake, I verified the result at my leisure." (Poincaré quoted in Hadamard, 1945, p. 13).

In addition, several famous anecdotes suggest that sleep facilitates creativity, ranging from musical compositions to scientific insights (Mazzarello, 2000). In speaking of the attainment of solutions, "Beatle" Paul McCartney announced that he came up with the melody for "Yesterday" in a dream, and the Nobel Prize winner Loewi woke up with the idea for how to experimentally prove his theory of chemical neurotransmission. The idea that a period of incubation might facilitate creativity has not only been suggested by creative minds, but has also been stressed in creativity models. Wallas (1926) proposed that the creative process entails four stages: Preparation (acquisition of knowledge to some task), Incubation (process that occurs when conscious attention is diverted away from the task), Illumination (creative idea flashes into sight), and Verification (creative idea is subjected to evaluation). Certainly a creative idea may be found *before* a decrease in conscious effort, that is, before the Incubation stage.

Sometimes, however, a period of incubation seems to precede creative breakthroughs as illustrated above for several scientific discoveries and artistic compositions. Sparked by the anecdotal accounts on incubation and creativity, various attempts have been made to investigate incubation effects. As demonstrated by a Google Scholar search (Sio and Ormerod, 2009), with the search restricted to the years 1997–2007 and the subject areas to social sciences, arts, and humanities, the term *incubation* along with either *creativity, insight*, or *problem*, yielded more than 5000 articles. Empirical research has shown that a period of incubation indeed helps creativity (Dodds et al., 2003; Sio and Ormerod, 2009).

However, it is not yet clear why incubation is helpful. The moderators discovered thus far do not really speak to whether the effects should be explained by unconscious processes or merely by other consequences of a period of distraction (e.g., relaxation, forgetting of fixating elements, mental set-shifting) without the need to assume active unconscious processes (see also Orlet, 2008). The aim of the current article is to provide an overview of the domain of incubation and creativity, and to review and discuss findings that speak to whether during an incubation period unconscious processes contribute to creative thinking, or whether it is merely the absence of conscious thought that drives creativity. Finally, practical implications and directions for future research will be discussed.

INCUBATION

Many anecdotal accounts and traditional theories of creativity have put emphasis on incubation. The basic phenomenon is a familiar one: we are working on a problem, we can't solve the task, we leave it aside for some period of time—the incubation period—and when we return attention to the task we have some new insight that helps us to solve the problem. In general, there are two frequently used methods to conduct incubation experiments. In the "interpolated activity" method, participants work on a task or problem for a period of time, are then given an incubation period, and finally return to the task. Participants' performance is compared with that of a control group of people who worked on the same problem continuously. In the "multiple trial or multiple item" method, multiple tasks or problems are presented and, afterwards, items that have not been solved are re-administered. For example, participants work for one minute apiece on several problems. Then, the unsolved problems are re-administered for one minute apiece. It is presumed that the time between the first and second encounter with the tasks or problems allows incubation to occur. Some researchers using this approach also insert an incubation period between the first and second encounter with the problems. For example, after the first encounter with the problems participants perform a distractor task and after this incubation interval return to work for a certain time on problems that they did not solve. Participants' performance is compared with that of a control group, and if a within-participant design is used, the increase in number of problems is used.

Whereas some studies reported strong incubation effects (e.g., Kaplan, 1989; Smith and Blankenship, 1989; Smith and Dodds, 1999; Dodds et al., 2003), others have failed to find any effects at all (e.g., Olton and Johnson, 1976). To resolve the uncertainties surrounding incubation effects, Dodds et al. (2003) conducted a review of experimental literature on incubation in problem solving and creativity, and revealed that 29 out of 39 experiments have found a significant effect of incubation. The authors suggested that incubation length and preparatory activities can increase incubation effects. Moreover, the authors demonstrated that presenting a clue during the incubation period can either have strong positive (if the clue is useful) or negative effects (if the clue is misleading). For example, "ocean" or "floor" could be a misleading clue when trying to find a fourth word that functions as an associative link between the three items "ship, outer, crawl", whereas "space" could be a useful clue. Sio and Ormerod (2009) conducted a statistical meta-analytic review of empirical studies of incubation. In their meta-analysis 117 independent studies were included, and the contributions of moderators such as problem type, presence of cues, and lengths of preparation and incubation periods were investigated. Overall, a positive incubation effect was found. In a recent study, Gilhooly et al. (2013) investigated interactions between the type of creativity task (verbal or spatial) and the type of incubation activity (verbal or spatial) on creative performance. Experimental groups, after 5 min of conscious work on a verbal creativity task (Alternative Uses Task) or a spatial creativity task (Mental Synthesis), had a 5-min incubation period that involved either spatial (Mental Rotation) or verbal (Anagrams) tasks. Following incubation, participants resumed their main task for a further 5 min. Control groups undertook Alternative Uses or Mental Synthesis for 10 min without any incubation periods. Significant incubation effects were found overall and there were interactions in that spatial incubation benefited verbal fluency and verbal-rated creativity, and verbal incubation benefited spatial-task fluency and spatial-rated creativity but not vice versa. These findings suggest that an interpolated incubation activity of a dissimilar nature to the target task leads to stronger effects of incubation as compared to an interpolated activity similar to the target task.

Not only the task that is performed during an incubation period, but also the time interval of an incubation period can vary. It can vary from a few moments or a night of sleep through days or weeks away from the problem. An example of a relatively short incubation period is *mind-wandering*—a state of mind that occurs spontaneously, and largely autonomously, whenever an awake individual is not engaged in a cognitively demanding task. Research on mind-wandering has a long history, and was recently popularized by Smallwood et al. (2003) who used thought sampling and questionnaires to investigate mind-wandering. In past and recent literature, alternative names to the term mind-wandering (Smallwood and Schooler, 2006; Mason et al., 2007) have been used, such as "day dreaming" (Giambra, 1979), "spontaneous thought" (Christoff et al., 2011), "task-unrelated thought" (Giambra and Grodsky, 1989; Smallwood et al., 2003), and "stimulus independent thought" (Teasdale et al., 1995). In a recent study, Baird et al. (2012) examined whether creative performance was facilitated differentially by engaging in mind-wandering (i.e., a 0-back task, an undemanding task without memory load that has been shown to elicit mind-wandering, Smallwood et al., 2009), a demanding task (i.e., a 1-back working memory task), a rest period, or no break between creativity problems. To measure creative performance, the Unusual Uses Task (a task that requires participants to generate as many unusual uses as possible for a common object) was used. All participants performed two Unusual Uses Task problems (2 min per problem) to measure baseline creative performance. Subsequently, participants were assigned to one of the four between-subjects conditions. After the incubation interval (or following the baseline measure, in the case of the no-break condition), participants worked on the Unusual Uses Task again. Four problems (2 min per problem) were presented in a random order: two problems that were identical to the problems presented at baseline and two new problems. Engaging in an undemanding task during an incubation period led to significant increases in creative solutions to the target problems as compared to the demanding task, rest, and no break conditions. This improvement was observed only for repeated-exposure problems, which demonstrates that it resulted from an incubation process rather than a general increase in creative problem solving. The unrelated thoughts that occur during mind wandering uniquely seem to facilitate incubation. According to Baird et al., one possible explanation may be that mind wandering enhances creativity by increasing unconscious associative processing, as predicted by the spreading-activation account of incubation (e.g., Yaniv and Meyer, 1987; Dijksterhuis and Meurs, 2006).

In recent years, functional Magnetic Resonance Imaging (fMRI) research has been used to focus on understanding how the brain generates the spontaneous and relatively unconstrained thoughts that are experienced when the mind wanders. One candidate neural mechanism for mind-wandering is a network of regions in the frontal and parietal cortex known as the default mode network (Mason et al., 2007; Christoff et al., 2009). The default mode network, also called the default network, default state network, or task-negative network, is defined as a set of interconnected brain regions including the medial prefrontal cortex (MPFC), posterior cingulate cortex (PCC), and lateral and medial temporal lobes (Spreng et al., 2010). It is a brain system that is especially active when an individual is not focused on the outside world (Buckner et al., 2008) and when cognitive control is low (Andreasen, 1995). Moreover, it has been related to complex, evaluative and unconscious forms of information processing (Vincent et al., 2007; Yang et al., 2010), and it contrasts with the cognitive control network (Fox et al., 2005)—a set of brain regions including the anterior cingulate cortex (ACC), dorsolateral prefrontal cortex (DLPFC), inferior frontal junction (IFJ), anterior insular cortex (AIC), dorsal pre-motor cortex (dPMC), and posterior parietal cortex (PPC; Cole and Schneider, 2007). Indeed, when one network is activated, the other is deactivated (Fox et al., 2005). In addition to these findings, structural MRI research has provided a first indication that the default mode network may be involved in creativity. Jung et al. (2010) have linked cortical thickness measures to psychometric measures of creativity and found a negative correlation between creative performance and activity in the lingual gyrus and a positive correlation between creative performance and grey matter volume in the right PCC, a brain area that is part of the default mode network.

In a recent structural MRI study, Kühn et al. (2013) provided further support for the involvement of the default mode network in creativity. Participants performed a well-established creativity task by which a participant's cognitive flexibility and the average uniqueness and average creativity of a participant's ideas were assessed. For all psychometric measures of creativity a positive correlation was observed between inter-individual differences in creative performance and inter-individual differences in volume of the default mode network. Based on these findings, it can be assumed that greater volume in the default mode network (i.e., in the counterpart of the cognitive control network) provides more neural resources for generating creative ideas. These findings suggest that less controlled processes such as mind-wandering are important in creativity. One relatively controversial finding is that periods of mind-wandering are associated with increased activation in both the default and executive system, a result that implies that mind-wandering may often be goal oriented (Smallwood and Schooler, 2006; Smallwood et al., 2009). Apart from studies about the default mode network, there are several important other studies on neuroimaging and creativity. For example, the research from Reverberi et al. (2005) demonstrates that the lateral frontal cortex impairs problem solving, and the research by Kounios and Jung-Beeman (2009) on the cognitive neuroscience of insight suggests that insight is the culmination of a series of brain states and processes operating at different time scales. Recently, Dietrich and Kanso (2010) reviewed 72 neuroimaging studies on creativity and insight and concluded that the neuroscientific literature on creativity, thus far, is self-contradicting and that creative thinking does not appear to critically depend on any single mental process or brain region. The default mode network can, therefore, be considered one, but not the single neural underpinning of creativity.

Whereas mind-wandering can be considered a relatively short incubation period, sleep can be considered an incubation period that covers a longer period of time. Sleep is divided into two broad types, rapid eye movement (REM) sleep and non-rapid eye movement (NREM) sleep. Each type has a distinct set of associated physiological and neurological features. REM sleep is a stage of sleep characterized by the rapid and random movement of the eyes, and typically occupies 20–25% of total sleep. During REM, the activity of the brain's neurons is quite similar to that during waking hours and subjects' vividly recalled dreams mostly occur during REM sleep. Unlike REM sleep, during NREM sleep there is usually little or no eye movement and dreaming is rare. The differences in the REM and NREM activity reported is believed to arise from differences in the memory stages that happen during the two methods of sleep (Manni, 2005). For example, Stickgold et al. (1999) have shown that cognition during REM sleep is qualitatively different from that of waking and NREM sleep, and may reflect a shift in associative memory systems. They suggest that this shift in cognitive processing is responsible, in large part, for the bizarre nature of dreams and may serve to enhance the strength of associations between weakly associated memories, an important skill underlying creative thinking. The mental activity that takes place during NREM sleep is believed to be thought-like, whereas REM sleep includes hallucinatory and bizarre content (Manni, 2005). Thus far, sleep research has mainly been focused on memory performance. A prominent finding is that sleep, and certain stages of sleep in particular, are important in memory processing, resulting in delayed learning without the need for further practice or task engagement (Stickgold et al., 2001). These findings of sleep-dependent learning are now strongly supported by cellular and molecular evidence of sleep-dependent plasticity across a broad range of phylogeny (Bennington and Frank, 2003). Yet memory consolidation is only one of many cognitive virtues possessed by the human brain, another is creativity.

The link between creativity and sleep, especially dreaming, has long been a topic of intense speculation (Stickgold and Walker, 2004). In recent years, the facilitatory effect of sleep on creativity has also received empirical support. Research from Barrett (1993) has shown that college students incubated answers to real-life homework and other objective problems on which they were working, finding that in one week's time, half of the students had dreamed about their topic and 25% had a dream that provided an answer. Barrett (2001) also interviewed modern artists and scientists (including Nobel Prizes winners) about their use of their dreams and concluded that while anything—math, musical composition, business dilemmas—may get solved during dreaming, the two areas dreams are especially likely to help are anything where vivid visualization contributes to the solution and any problem where the solution lies in thinking outside the box—i.e., where the person is stuck because the conventional wisdom on how to approach the problem is wrong. Moreover, in an experimental study Wagner et al. (2004) have shown that sleep inspires creative insight. Subjects completed a number reduction task, and each numerical sequence could be completed in a slow, stepwise way, but the trials could also be completed according to a hidden, more abstract rule that would speed up participants' responses. The initial training was followed by 8 h of nighttime sleep, nighttime wakefulness, or daytime wakefulness. Of the people who slept before they resumed, almost 60% discovered the rule, as opposed to 23% of the people in the two groups that did not sleep. Thus, participants who got several hours of sleep were more than two times as likely during retesting to gain insight into a hidden rule built into the task.

In addition, sleep has been shown to enhance important aspects of creativity, including cognitive flexibility and the ability to find remote associations. In a study on cognitive flexibility across the sleep-wake cycle, Walker et al. (2002) found that when woken from REM sleep, participants had a 32% advantage in the number of anagrams solved compared with NREM awakenings, which were equal to that of wake time performance. These findings suggest that REM sleep may offer a different mode of problem solving compared with wake and NREM. The authors hypothesized that REM sleep is highly conducive to fluid reasoning and flexible thought due to the lack of aminergic dominance in REM sleep. In a study on the ability to find remote associations, Sio et al. (2012) participants were presented with a set of Remote Associates Test (RAT) items. Each RAT item contains a triplet of words presented horizontally along with a blank space. For each item, the participant has to find a fourth word that functions as an associative link between these three words (e.g., cookies, sixteen, heart: . . . .; the answer to this item is sweet: cookies are sweet, sweet sixteen, sweetheart). Reaching a solution requires creative thought as the first, most probable associate to each of the items is often not correct, so the participant must think of more remote associations (i.e., distantly related information) to connect the three words. In the current study the RAT items varied in difficulty as a function of the strength of the stimuli–answer associations. After a period of sleep, wake, or no delay, participants reattempted earlier unsolved problems. The sleep group solved a greater number of difficult RAT items than did the other groups, but no difference was found for easier RAT items. These findings suggest that sleep facilitates creative thinking for harder problems. While evidence for the role of sleep in creative problem-solving has been looked at by prior research, underlying mechanisms such as different stages of sleep had not been explored. Cai et al. (2009) used the RAT, and tested participants in the morning, and again in the afternoon, after either a nap with REM sleep, one without REM or a quiet rest period. Participants grouped by REM sleep, non-REM sleep and quiet rest were indistinguishable on measures of memory. Most importantly, although the quiet rest and NREM sleep groups received the same prior exposure to the task, they displayed no improvement on the RAT test, whereas the REM sleep group improved by almost 40% over their earlier performances. The authors hypothesized that the formation of associative networks from previously unassociated information in the brain, leading to creative problem-solving, is facilitated by changes to neurotransmitter systems during REM sleep. Thus, REM sleep is assumed to enhance the integration of unassociated information for creative problem solving.

To recap, various attempts have been made to investigate incubation effects in creativity and creative problem solving. The conclusion of the literature is that overall, a positive incubation effect can be observed. Especially the work by Dodds et al. (2003) and Sio and Ormerod (2009), who conducted reviews of empirical studies of incubation, justify the conclusion that incubation can enhance creative performance. This is also supported by research on mind-wandering and sleep, which can be seen as short and relatively long periods of incubation. However, the process(es) underlying incubation effects remain unclear. In the next section, we aim to shed light on the question whether during an incubation period unconscious processes contribute to creative thinking, or whether it is merely the absence of conscious thought that drives incubation effects.

MECHANISMS UNDERLYING INCUBATION EFFECTS

Whereas the effects of incubation are generally accepted (Sio and Ormerod, 2009), its causes are controversial. The main debate between different theories is about whether during an incubation period unconscious processes contribute to creative thinking (*unconscious work theory*), or whether it is merely the absence of conscious thought that drives creativity (*conscious work theory*). Historically, incubation effects refer to the idea that setting a problem aside for a while helps creative thought and problem solving as *unconscious processes* are working on the problem while the individual is not consciously thinking about the problem (see Wallas, 1926, as well as, e.g., Hadamard, 1945;

Kris, 1952; Rugg, 1963; Kubie, 1985). That is, the unconscious actively thinks and contributes to solving a problem (see also Koestler, 1964; Claxton, 1997). In contrast, conscious work theories have ascribed incubation effects on creative performance to *relaxation* (being well-rested, one can do better the next time one engages in the problem; Helmholtz, 1896; Woodworth and Schlosberg, 1954) and to the effects of *facilitating cues* from the environment (environmental cues trigger retrieval of previously un-retrieved relevant information; e.g., Yaniv and Meyer, 1987; Langley and Jones, 1988). Moreover, sometimes old and inappropriate ideas can cause *mental fixation*, impeding the generation of new and appropriate ideas (Smith, 2003). Therefore, in addition to relaxation and facilitating cues, it has been suggested that incubation effects can lead to *forgetting of fixating elements* (Smith and Blankenship, 1989; Segal, 2004) and to *mental set-shifting* (wrong cues become less accessible, leading to a fresh, new and unbiased start; Schooler and Melcher, 1995).

Recently, Gupta et al. (2012) investigated whether high-frequency candidate answers should be avoided in order to find creative solutions in for instance a RAT. They tested individual differences in creativity as measured with a complex problem-solving task, and developed a computational model of the RAT. Findings showed that individuals performed poorly on the RAT when they were biased to consider high-frequency candidate answers. Storm and Angelo (2010) investigated whether inhibition may facilitate creative problem solving by providing a mechanism by which to bypass fixation. They measured participants' retrieval-induced forgetting and, thereafter, participants had to solve RAT problems. Half of the participants were exposed to misleading associates prior to problem solving (fixation condition) and half were not (baseline condition). Correlating the retrieval-induced forgetting measure with performance on the RAT revealed that the propensity to inhibit irrelevant information comes at a price, as potentially relevant information may be inhibited. However, inhibition can also provide a means by which to overcome fixation and, thereby, facilitate creativity. There is no denying that a period of distraction allows for forgetting of fixation and/or mental set-shifting, relaxation, and exposure to environmental cues, and that these effects can contribute to creative thoughts or problem solving. However, it can be questioned whether these effects are the only benefit of an incubation period, or whether during an incubation period unconscious processes contribute to creative thinking.[1]

Research from Bowers et al. (1990) suggests that the unconscious is able to "close in" on the correct answer some time before the answer is accessible to consciousness. They asked participants to find a target word while they were given successive hints, such as an associated word. Individuals felt clueless for some time and then suddenly came up with the correct answer. However, analysing the prior guesses revealed that individuals were slowly getting closer to the right solution before the solution reached consciousness. Participants' successive guesses, thus, converged towards the correct answer. Moreover, a study conducted by Betsch et al. (2001) demonstrated that people can unconsciously integrate large amounts of information. Participants watched TV ads shown on a computer screen and simultaneously the numerical increases and decreases of hypothetical shares were shown at the bottom of the screen. Participants could not correctly answer specific questions about the shares, but they had developed a liking or disliking towards each of the shares. These findings suggest that participants processed and integrated the information while they were attending to the TV ads. Recently, Ric and Muller (2012) have shown that people can unconsciously initiate and follow arithmetic rules, such as addition. In several studies participants were instructed to detect whether a symbol was a digit, and this symbol was preceded by two digits and a subliminal instruction (i.e., the "add" instruction or a control instruction). Participants were faster at identifying a symbol as a number when the symbol was equal to the sum of the two digits and they received the instruction to add the digits. In line with these findings, Sklar et al. (2012) demonstrated that presenting participants with additions or subtractions subliminally leads to higher accessibility of correct answers (i.e., answers could be verbalized faster) than incorrect answers. A recent review on unconscious higher-order cognition conducted by Van Gaal et al. (2012) revealed strong evidence for unconscious response-inhibition, conflict resolution, as well as for error detection. Importantly, they also concluded that people can unconsciously integrate multiple pieces of information across space and time.To resume, evidence from various research areas demonstrates that processes that we consider thought processes can ensue unconsciously. This makes it reasonable to assume that thought processes in the service of creativity and problem solving can, in principle at least, also take place unconsciously.

The idea that during an incubation period unconscious processes are active was one of the building blocks of Unconscious Thought Theory (Dijksterhuis and Nordgren, 2006). Unconscious thought, that is, "deliberation in the absence of conscious attention directed at the problem," (Dijksterhuis et al., 2006, p.1005) has mainly been studied in the context of decision-making (Strick et al., 2011; see also Dijksterhuis and Nordgren, 2006; Bargh, 2011; Nieuwenstein and van Rijn, 2012). In the literature on unconscious thought in decision-making, participants are typically first presented with information pertaining to a decision. Thereafter, they are distracted for a while, before they make a decision. For example, Bos et al. (2008) compared participants decision performance after three conditions, a conscious thought condition and two incubation conditions, that is, an unconscious thought condition and a mere distraction condition. Whereas participants in the unconscious thought condition were told that they would engage in an unrelated task before returning to the actual task, participants in the mere distraction condition were told that they had finished the task and would move on to unrelated tasks. In the mere distraction condition participants were, thus, distracted just as in the unconscious thought condition, but did not have a problem-solving goal. A period of distraction only improved decision-making in the unconscious thought condition, that is, when participants expected to make a decision following the distraction period. Comparing an unconscious thought condition with a mere

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[1] Note that the section below greatly overlaps with Dijksterhuis (submitted for publication).

distraction condition provides evidence for true, active thought taking place unconsciously. Given the evidence for unconscious thought processes that we have from multiple research areas (e.g., decision making, lie detection), the question raises whether there is also evidence for unconscious thought effects in the domain of creativity.

Dijksterhuis and Meurs (2006) investigated the relation between different thought processes and the generation of creative ideas. In several experiments participants were asked to generate a list of items (new names for products, names of places beginning with a certain letter, things one can do with a brick), and three conditions were compared. In the immediate condition (i.e., the baseline condition) participants started right after receiving the instruction. In the conscious thought condition, participants were given three minutes to consciously think about the items before they were given time to list them. In the unconscious thought condition, people were first given the instruction, and were then distracted for three minutes before they were given the opportunity to list the items. Conscious thought led to more accessible items and to items in line with a cue, whereas unconscious thought led to more inaccessible items and to items diverging from the cue. Moreover, unconscious thought led to more creative and unusual items than conscious thought. In all experiments, unconscious thinkers also differed significantly from participants who were not given time to think at all. These findings suggest that whereas conscious thought may be focused and convergent, unconscious thought may be more associative and divergent. Ritter et al. (2012b) investigated the role of unconscious thought for both idea generation and idea selection. Participants generated creative ideas immediately, after conscious thought, or after a period of unconscious thought. After having listed their ideas, participants selected their most creative idea. Performance in idea generation was similar between conscious and unconscious thought; however, individuals who had unconsciously thought about ideas were better in selecting their most creative idea. These findings are in support of the idea that unconscious processes actively contribute to creativity, as it is unlikely that these findings are the consequence of set-shifting or relaxation. During task instruction no examples were provided and no hints or cues were given, meaning that no fixating elements or specific mental sets were induced that could have become less accessible, changed, or forgotten altogether during a period of distraction. Recovering from fatigue is also unlikely to account for the current findings, as incubation effects also occurred in the study when a cognitively demanding task (n-back task) was used as distracter task (Dijksterhuis and Meurs, 2006).

Zhong et al. (2008) investigated the effect of unconscious thought on the ability to find remote associations, as measured by the RAT. Participants were presented difficult RAT triads (selected from Bowden and Jung-Beeman, 2003). Afterwards, participants in the conscious thought condition were told that they had 5 min to think about these triads, and during this time, they were shown the screen containing all triads, but were not allowed to write down notes or answers. Participants in the unconscious-thought condition were told that they would engage in an unrelated task before returning to the word task. Participants in the distraction condition were told that they had finished the task and would move on to unrelated tasks. To prevent conscious thought about the RAT items in the unconscious thought and mere distraction conditions participants completed a 2-back task for 5 min (see Dijksterhuis (2004)). After 5 min of conscious thought or distraction, all participants engaged in a lexical decision task (Bargh et al., 1995). Strings of letters appeared on the center of the screen, and participants indicated whether or not each string constituted an English word by pressing one of two buttons. The letter strings included the RAT answers plus control words. After completing the lexical decision task, participants in all three conditions were again shown the RAT items and were asked to report their answers. In the current research two separate outcomes of the RAT test were assessed: implicit accessibility of correct RAT answers (i.e., mental accessibility of RAT answers, as measured by a lexical decision task) versus expression of those correct answers (Wegner and Smart, 1997). A period of incubation, compared with the same duration of conscious thought, did not increase the reporting of correct answers. The results on accessibility, however, revealed a striking difference: Unconscious thought, compared with conscious thought and mere distraction, increased the mental accessibility of RAT answers. These results are consistent with unconscious thought theory, which systematically differentiates conscious and unconscious thought processes, and suggest that unconscious processing is more adept at associating and integrating information than conscious processing is (Dijksterhuis and Nordgren, 2006). Importantly, in the unconscious-thought condition the level of activation of RAT answers was higher than in the mere-distraction condition, which suggests that the increased accessibility after unconscious thought was not due to relaxation, forgetting or the release of incorrect associations (i.e., “mental set-shifting”). These findings indicate that unconscious processes may actively facilitate the discovery of remote associations, an important mental skill underlying creative thinking, and may contribute to divergent thinking.

Yang et al. (2012) investigated under what conditions unconscious thought can outperform conscious thought on creativity tasks. Their results demonstrated that unconscious thought did not provide creative advantage over conscious thought when deliberation duration was either short or long (1 or 5 min, respectively). However, when deliberation duration was of a moderate length (3 min), the creative output of unconscious thought exceeded that of conscious thought. These findings suggest that the duration of unconscious thought has an inverted-U shaped relationship with creativity. However, as different tasks require different amounts of mental effort, the appropriate duration of a moderate length can be assumed to be task dependent. In line with these findings, a meta-analysis on unconscious thought effects on decision-making (Strick et al., 2011) has shown that unconscious thought effects are larger with moderate unconscious thought intervals. Moreover, unconscious thought effects in decision-making have been shown to be larger when a task is used that does not require much processing capacity, that is, a relatively undemanding task. Similarly, Sio and Ormerod’s (2009) statistical meta-analytic review of incubation effects revealed that the benefits of an incubation period are greater when participants are occupied by an undemanding task than when they engage in either a demanding task or no task at all (Sio and Ormerod, 2009). Moreover, Ellwood et al. (2009) demonstrated that the type of break during the incubation period effects later solutions. As the functional fixedness theory as well as the general fatigue theory predict that a break, independent of its content, should be equally effective in producing an incubation effect, these findings suggest that systematic effects beyond relief from functional fixedness or general fatigue are at play.

Gallate et al. (2012) and Ritter et al. (2012b) investigated whether one can manipulate unconscious thought processes. In the study from Gallate et al., participants were either aware or unaware that they would soon be returning to a divergent thinking task. During the break period, all participants were distracted from the task (they did an arithmetic task), ensuring that any ongoing problem solving was not conscious, but unconscious. Immediately after finishing the arithmetic task, participants returned to the divergent thinking task. Participants in the aware condition had significantly higher post-break creativity scores than those in the unaware condition. Ritter et al. (2012a) investigate whether one can actively enhance the beneficial effect of sleep on creativity by covertly reactivating the creativity task during sleep. Individuals' creative performance was compared after three different conditions: sleep-with-conditioned-odor; sleep-with-control- odor; or sleep-with-no-odor. In the evening prior to sleep, all participants were presented with a problem that required a creative solution. In the two odor conditions, a hidden scent-diffuser spread an odor while the problem was presented. In the sleep-with-conditioned-odor condition, task reactivation during sleep was induced by means of the odor that was also presented while participants were informed about the problem. In the sleep-with-control-odor condition, participants were exposed to a different odor during sleep than the one diffused during problem presentation. In the no odor condition, no odor was presented. After a night of sleep with the conditioned odor, participants were found to be more creative and better able to select their most creative idea than participants who had been exposed to a control odor or no odor while sleeping. Task reactivation during sleep seems to actively trigger creativity-related processes during sleep. These findings give a first indication that one can manipulate unconscious thought processes and, thereby, facilitate creative performance.

The idea that unconscious processes work on a problem in the absence of conscious guidance has been described by many great artists and thinkers, and the above mentioned findings provide first scientific evidence for the idea that a period of incubation benefits from unconscious processes. This may be related to the fact that unconscious thought organizes information. Representations become better organized and more polarized, and memory becomes more gist-based. Moreover, unconscious thought theory postulates that unconscious thought leads to a process of weighting whereby the importance of information is assessed. However, this idea awaits further study, as it was supported in some experiments (Bos et al., 2011; Usher et al., 2011), but not in others (Ashby et al., 2011; Pachur and Forrer, 2013). These findings may suggest that unconscious thought is a process whereby disorganized information becomes more and more organized until some kind of equilibrium is reached, and the conclusions can be transferred to consciousness. Recently, the first neuroscientific evidence into unconscious thought was provided. As in earlier studies on unconscious thought and decision-making, Creswell et al. (2013) showed that unconscious thinkers made better decisions than conscious thinkers and than immediate decision makers. Moreover, their fMRI data demonstrated that participants who thought unconsciously while doing a distraction task showed more activity in the right DLPFC and left intermediate visual cortex than participants who merely performed the same distraction task. These areas were already involved in the initial encoding of the information in the first place, and the authors proposed a "neural reactivation account" for unconscious thought, indeed demonstrating unconscious processing to continue after encoding. Importantly, neural reactivation in the right DLPFC and left intermediate visual cortex was predictive of decision quality of unconscious thinkers. Further neuroscientific research on creativity and incubation should investigate brain activity during incubation to shed further light on the underlying cognitive mechanisms of incubation effects.

To conclude, several studies suggest that it is not merely the absence of conscious thought that drives creativity, but that during an incubation period unconscious processes can contribute to creative thinking. Often, it takes time to come up with creative ideas and solutions. It is reasonable to assume that most thought processes underlying creative thought are neither fully conscious nor fully unconscious. Instead, prolonged creative thought processes may have both conscious and unconscious elements, and conscious and unconscious thought may alternate. You think about a problem consciously, you get stuck and perform another task, you think some more, you sleep on it for a while, you then think a bit more after you've encountered relevant new information, et cetera.

PRACTICAL APPLICATIONS AND FUTURE RESEARCH

Previous studies have shown that creativity training can enhance everyday creative performance (e.g., Scott et al., 2004), and many tactics have been identified to facilitate creative thinking skills, such as set-shifting, questioning assumptions, and using analogies (i.e., finding correspondence of inner relationship or function between different concepts). The application of unconscious processes, however, has not been systematically introduced to educational, innovation and business contexts. By demonstrating that unconscious processes can be important for creativity, the current findings may encourage practitioners to use unconscious processes in order to enhance creative thinking. Applying unconscious processes could, for example, entail that people set a goal to find creative solutions for a problem before they are distracted from the problem by doing something different. What people do in the meantime should be chosen carefully. Sio and Ormerod's (2009) meta-analytic review revealed that the benefits of an incubation period are greater when participants are occupied by an undemanding task than when they engage in a demanding task or no task at all. Moreover, Gilhooly et al. (2013) found that spatial incubation benefited verbal-rated creativity, and verbal incubation benefited spatial-rated creativity but not vice versa. Therefore, when stuck on a creative task, during an incubation period one should do something undemanding that is very different from the main task, before returning to it.

Although unconscious processes can be a powerful source to facilitate creativity, only engage in daydreaming or sleeping to produce groundbreaking discoveries or great artistic creations will not do the trick. A plethora of raw materials has to be available to be connected and one has to be able to focus on some options out of an array of options. In this sense, conscious processing is needed to establish a knowledge base, to know what problems to tackle, and to verify and implement new ideas. Future research may investigate what combination of conscious and unconscious processes is most fruitful for creativity. One could think about the order of the two processes (e.g., a period of task-related conscious thought that is followed by a period during which one refrains from task-related conscious thought, or repeatedly switch between the two modes of thought), and the optimal duration of each of the two processes. People are likely to benefit more from an incubation period when they get stuck and, therefore, one can assume that a relatively long period of conscious thought should be preferred above a short period of conscious thought. Also for unconscious processes the duration of the incubation period seems to be of importance. In a recent study from Yang et al. (2012), 3 min (as compared to 1 min and 5 min) seemed to be the optimal duration of unconscious thought. However, it is likely that 3 min of incubation is not the most appropriate duration for all creativity tasks. It can be assumed that the optimal duration is contingent on the task (Weisberg, 1999). Besides exploring the optimal duration of unconscious processes as a function of task characteristics and the optimal combination of conscious and unconscious processes, future research could also focus on the similarities and disparities between the different unconscious processes (i.e., incubation, unconscious thought, mind-wandering and sleep) and could investigate which process is most beneficial for creativity and for the distinct mental processes underlying creative thought (Baer, 1998). Finally, future research may study potential moderators, for example, whether experts and people with ample prior knowledge exhibit a different pattern of creative performance as a result of unconscious and conscious processes.

The present article aimed to provide an overview of the domain of incubation and creativity, and to shed more light on the causes of incubation effects. Research on incubation, mind wandering, and sleep was presented and discussed, and it was investigated whether people can think unconsciously and whether unconscious processes can contribute to creativity. The current findings provide first empirical support for the idea that during an incubation period unconscious processes contribute to creative thinking, and that it is not merely the absence of conscious thought that drives incubation effects. We hope that the current article inspires researchers to further tackle the unconscious foundations of creativity. This will not only increase our theoretical knowledge on the role of unconscious processes in creativity, but will also offer valuable insights for practical implication. Understanding and facilitating creativity is important, as the ability to think creatively plays an important role in many areas of our life, such as education, arts, sciences, and the economic sector.

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The impact of physical exercise on convergent and divergent thinking

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Anecdotal literature suggests that creative people sometimes use bodily movement to help overcome mental blocks and lack of inspiration. Several studies have shown that physical exercise may sometimes enhance creative thinking, but the evidence is still inconclusive. In this study we investigated whether creativity in convergent- and divergent-thinking tasks is affected by acute moderate and intense physical exercise in athletes ($n = 48$) and non-athletes ($n = 48$). Exercise interfered with divergent thinking in both groups. The impact on convergent thinking, the task that presumably required more cognitive control, depended on the training level: while in non-athletes performance was significantly impaired by exercise, athletes showed a benefit that approached significance. The findings suggest that acute exercise may affect both, divergent and convergent thinking. In particular, it seems to affect control-hungry tasks through exercise-induced "ego-depletion," which however is less pronounced in individuals with higher levels of physical fitness, presumably because of the automatization of movement control, fitness-related neuroenergetic benefits, or both.

Keywords: physical exercise, creativity, convergent thinking, divergent thinking, fitness

INTRODUCTION

Anecdotal literature suggests that creative people sometimes use bodily movement to help overcome mental blocks and to get deeper into a problem. Indeed, the philosopher Henry David Thoreau stated: "the moment my legs begin to move my thoughts begin to flow – as if I had given vent to the stream at the lower end and consequently new fountains flowed into it at the upper" (Thoreau, 1851). Several studies have indeed shown that physical exercise in healthy adults may sometimes enhance creative thinking – even though the size of this effect can vary substantially (Gondola and Tuckman, 1985; Gondola, 1986, 1987; Steinberg et al., 1997; Blanchette et al., 2005). Gondola and Tuckman (1985) investigated the effects of long-term physical exercise on creativity performance, showing small but significant improvements in Alternate Uses (spontaneous flexibility) and Remote Consequences (originality) tasks, but not for an Obvious Consequences (different ideas) task. Gondola (1986) used the same creativity tasks to compare the effect of long-term and acute physical exercise and found improvements for both conditions and all three creativity measures. Gondola (1987) tested another form of acute aerobic activity (dance) and reported comparable enhancing effects. Steinberg et al. (1997) found only small improvements in a group of fit participants, and only in one of the three measures of the Torrance test of creative thinking. Blanchette et al. (2005) used the same test and found enhancing effects of exercise over a 2 h period. It is possible that in some or all of these previous studies physical exercise provided the opportunity for mind-wandering or incubation in trained (and, thus, less challenged) people. Indeed, Baird et al. (2012) have reported that engaging in simple external tasks that allow the mind to wander may facilitate creative problem solving.

The methodological diversity across the available studies with regard to sample characteristics and creativity assessment (mainly targeting aspects of divergent thinking) is considerable, which renders it questionable whether they were actually assessing the same constructs and processes. Moreover, there is still no mechanistic model explaining how creative processes operate and how physical exercise might affect these operations. To address this issue, we tried to avoid addressing creativity as a whole but focused on particular components of creative performance – components that are more transparent at the process level and thus easier to investigate. More concretely, we investigated the impact (during and after) of acute moderate and intense physical exercise on creativity tasks tapping into convergent and divergent thinking. Guilford (1950, 1967) has considered these two as the main ingredients of most creative activities, even though other processes are also likely to contribute (Wallas, 1926).

Divergent thinking is taken to represent a style of thinking that allows many new ideas being generated, in a context where more than one solution is correct. The probably best example is a brainstorming session, which has the aim of generating as many ideas on a particular issue as possible. Guilford's (1967) alternate uses task (AUT) to assess the productivity of divergent thinking follows the same scenario: participants are presented with a particular object, such as a pen, and they are to generate as many possible uses of this object as possible. Convergent thinking, in turn, is considered a process of generating one possible solution to a particular problem. It emphasizes speed and relies on high accuracy and logic. Mednick's (1962) remote associates task (RAT) that aims to assess convergent thinking fits with this profile: participants are presented with three unrelated words, such as "time," "hair," and "stretch," and are to identify the common associate ("long"). Interestingly for our purposes, performance on the AUT and the RAT were found to be uncorrelated (Akbari Chermahini and Hommel, 2010) and differently affected by the same experimental manipulations (Hommel et al., submitted), which supports Guilford's (1967) suggestion that convergent and divergent thinking represent different, separable components of human creativity. Such a scenario would fit with considerations of De Dreu et al. (2008), who proposed the Dual Pathway to Creativity model suggesting that creative performance arises from the interaction between cognitive flexibility and cognitive persistence – two dissociable cognitive control functions (Goschke, 2000; De Dreu et al., 2012). Consistent with this, divergent thinking was less pronounced in avoidance-motivated than in approach-motivated individuals, suggesting that the former need to compensate for their inflexible processing style by effortful and controlled processing (Roskes et al., 2012).

Along the same lines, Colzato et al. (2012) have argued that convergent thinking requires strong top-down control because it represents the tightly constrained search of very few or just one item. In contrast, divergent thinking should rely on weak top-down control, given that it implies a broad, loosely defined search space so to activate many items that satisfy the often relatively soft criteria (Hommel, 2012). Hence, convergent and divergent thinking are likely to differ in their reliance on executive control for the processing of information. If so, acute exercise should affect these two processes differently. According to the ego-depletion hypothesis (Baumeister et al., 1998), the cognitive resources required for cognitive-control operations are tightly limited and thus deplete quickly during and after control-demanding tasks. Following a similar, though more motivational rationale, Inzlicht and Schmeichel (2012) have developed a process model to explain self-control failure. According to that model, "exerting self-control at Time 1 reduces success at self-control at Time 2 by initiating shifts in motivation and attention that conspire to reduce self-control and increase immediate gratification" (p. 460). According to this reasoning, poorer self-control at Time 2 is attributed to reduced motivation to exert control and to reduced attention to cues that signal a need for control, as well as more impulsive behavior and more attention to reward cues. Given that exercising must use up some amount of control resources, more control-demanding tasks (like convergent thinking) should suffer more from exercise than less control-demanding tasks (like divergent thinking).

However, how resource-hungry exercise should not only depend on the kind of exercise (e.g., the complexity of the coordination required) but also on the skill level of the exercising individual. The same exercise that exhausts the resources of the less sportive student may have little impact on the highly practiced athlete. In athletes, many movement routines are overlearned and automatized, which can lead to dramatic reductions of conscious monitoring and control demands (Beilock and Carr, 2001; Schneider and Chein, 2003). Moreover, long-term fitness training leads to an increase of oxygenation and glucose in the frontal brain regions, which has been found to produce rather selective benefits for executive-control processes (Colcombe and Kramer, 2003). This means that athletes may not exhibit the same effects as non-athletes. While the latter should show exercise-induced costs in more control-demanding tasks (like convergent thinking), the former might either not show such costs or perhaps even show exercise-induced benefits.

To investigate these possibilities, we tested the impact of acute physical exercise on convergent and divergent thinking in athletes and non-athletes. We also took into account possible moderating factors, such as the intensity of the exercise (which was moderate or high, in different sessions) and the temporal overlap between exercise and creativity task (with the latter being performed during or after the exercise).

METHODS

PARTICIPANTS

Ninety-six healthy, native Dutch speakers (48 females and 48 males), of which 48 were athletes (mean age = 20.6 years; mean body mass index, BMI = 22.3) and 48 non-athletes (mean age = 20.7 years; mean BMI = 22.2), participated for an energy bar and a sports drink or one study credit. Participants were considered athletes if they exercised at least three times a week during the recent 2 years and non-athletes if they did not exercise on a regular basis (less than 1 time per week). All participants had normal systolic and diastolic blood pressure at rest (mean systolic blood pressure, SBP = 122 and diastolic blood pressure, DPB = 74), and reported no current or history of medication or drug use. Informed consent was obtained from all participants after the nature of the study was explained to them. The protocol was approved by the local ethical committee (Leiden University, Institute for Psychological Research).

REMOTE ASSOCIATION TASK (CONVERGENT THINKING)

In this task, participants are presented with three unrelated words (such as "time," "hair," and "stretch") and asked to find a common associate ("long"). Our Dutch version comprised of 30 previously validated items (Akbari Chermahini et al., 2012). In each of the three sessions, participants completed 10 different items.

ALTERNATE USES TASK (DIVERGENT THINKING)

In this task, participants were asked to list as many possible uses for six common household items ("pen," "towel," "bottle"). In the three sessions, participants completed 1 of these items. The results can be scored in several ways with *flexibility*, the number of different categories used, being the theoretically most transparent and the empirically most consistent and reliable score (Akbari Chermahini and Hommel, 2010). In the case of the item "pen," "writing an essay," and "writing a letter" would fall into the same category, but "drumming on the table" would fall into a different category.

In this study we considered four scores:

Flexibility: The number of different categories used.

Originality: Each response is compared to the total amount of responses from all of the subjects. Responses that were given by only 5% of the group count as unusual (1 point) and responses given by only 1% of them count as unique (2 points).

Fluency: The total of all responses.

Elaboration: The amount of detail (e.g., "a door stop" counts 0, whereas "a door stop to prevent a door slamming shut in a strong wind" counts

2 (1 point for explanation of door slamming and another for further detail about the wind).

EXERCISE CONDITIONS

During the rest condition, participants sat on a cycle ergometer (Kettler Cycle) without cycling. During the moderate cycling condition, participants cycled at a normal pace (level 8) without exhausting themselves. During the intense cycling condition, the resistance level on the bicycle was adjusted to high (level 16), and the participants cycled at a maximum level of effort.

PHYSIOLOGICAL AND MOOD MEASUREMENTS

Heart rate (HR) and systolic and diastolic blood pressure (SBP and DPB) were measured from the non-dominant arm with an OSZ 3 Automatic Digital Electronic Wrist Blood Pressure Monitor (Speidel and Keller). BMI was measured by Omron BF511 medical device. Mood was rated on a 9 × 9 Pleasure × Arousal grid (Russell et al., 1989) with values ranging from –4 to 4.

PROCEDURE AND DESIGN

A between-group (athletes vs. non-athletes) randomized cross-over design with counterbalancing of the order of the exercise conditions (rest vs. moderate vs. intense) was used (Latin-square design). All participants were tested individually. Half of the participants in each group ($n = 24$) executed the creativity tasks during cycling, the other half ($n = 24$) thereafter. Upon arrival, participants were asked to rate their mood and HR, SBP, DPB, and BMI were collected (baseline measurement). Next, the participant was introduced to the assigned exercise condition. When the rest condition was preceded by the moderate or intense exercise condition, the participant started the next exercise condition only after a couple of minutes (never more than 5) when HR returned to the baseline measurement level.

After each condition, HR, SBP, DPB, and mood were measured again. The creativity tasks (AUT and RAT) were performed either during or after the physical exercise, depending on the condition subjects had been randomly assigned to, see **Figure 1**. Participants had 3 min to execute the RAT (10 items per test condition) and 3 min for the AUT (1 item per test condition). Participants were confronted with a printed version of the creativity tasks on a clipboard positioned on the cycle ergometer in front of them so that they could fill in their responses comfortably while cycling. After the experimental session was ended, participants were rewarded for their participation in the study.

STATISTICAL ANALYSIS

Independent t-tests were performed to test differences between the two groups. Mood, HR, BPS, and BPD, and five creativity measures (from the two tasks) were extracted for each participant: flexibility, originality, fluency, and elaboration scores from the AUT, the number of correct items from the RAT. All four AUT measures were scored by two independent raters [Cronbach's alpha = 1.00 (fluency); 0.85 (flexibility); 0.71 (originality); 0.74 (elaboration)]. All measures were analyzed separately by means of repeated-measures ANOVAs with Session (rest vs. normal vs. intense) as within-subjects factor and group (athletes vs. non-athletes) and moment in which participants carried out the creativity tasks (during vs. after exercise) as between-group factor. A significance level of $p < 0.05$ was adopted for all tests.

RESULTS

PARTICIPANTS

No significant group differences were obtained for age, $t(94) = 0.05$, $p = 0.95$, and BMI, $t(94) = 0.34$, $p = 0.73$, but there was a significant difference for sport units per week, $t(94) = 21.68$, $p = 0.00001$: athletes exercised more often per week (3.4) than non-athletes did (0.5).

PHYSIOLOGICAL AND MOOD MEASUREMENTS

We found a main effect of session on HR, $F(2,184) = 768.01$, $p < 0.00001$, MSE = 109.063, $\eta 2p = 0.89$, SBP, $F(2,184) = 165.76$, $p < 0.00001$, MSE = 163.793, $\eta 2p = 0.64$, and DBP, $F(2,184) = 29.18$, $p < 0.001$, MSE = 104.509, $\eta 2p = 0.24$. Participants showed increased HR, SBP, and DBP in the moderate (95, 130, 76) and intense (133, 150, 85) exercise condition as compared to the rest condition (75, 116, 74). No other significant interaction involving group was found, $p > 0.14$.

Replicating earlier findings (Steptoe and Bolton, 1988), arousal, $F(2,184) = 768.01$, $p < 0.00001$, MSE = 109.063, $\eta 2p = 0.89$, but not mood, $F(2,184) = 43.71$, $p < 0.0001$, MSE = 1.077, $\eta 2p = 0.32$, was elevated after intense exercise (1.9, 1.1) as compared to normal exercise (1.1, 1.3) and rest (0.6, 1.2), respectively. As in the case of physiological measurements, no other significant interaction involving group was found, $F < 1$.

CREATIVITY TASKS

In general, performance in the AUT and RAT was good and comparable to performance in other studies without exercise manipulations (e.g., Akbari Chermahini and Hommel, 2010); see **Table 1**.

Convergent thinking: As expected, we found a significant interaction between group and session on RAT scores, $F(2,184) = 5.16$, $p < 0.01$, MSE = 2.838, $\eta 2p = 0.05$. *Post-hoc* multiple comparisons tests revealed that, even if not quite significant, athletes tended to perform better in convergent thinking in the moderate (4.1) and intense (4.2) exercise conditions than in the rest condition (3.5), $p = 0.072$, 0.095. This effect was reversed in non-athletes, where intense exercise (3.6) impaired convergent thinking compared to moderate exercise (4.4), $p = 0.002$ and rest (4.6), $p = 0.029$. The interaction was not modified by testing moment, as the insignificant three-way interaction indicated, $F(2,184) = 1.01$, $p = 0.364$, MSE = 2.838, $\eta 2p = 0.01$.

Divergent thinking: From the four scores of the AUT, only flexibility yielded a significant main effect of session, $F(2,184) = 3.69$, $p < 0.05$, MSE = 3.169, $\eta 2p = 0.03$; *post-hoc* tests revealed that participants showed greater flexibility in the rest condition (7.4) than with intense (6.7) exercise, $p = 0.011$, while the difference between rest and moderate exercise (7.0) only approached significance, $p = 0.150$. Numerically similar, but statistically insignificant trends were obtained for originality, $F(2,184) = 0.42$, $p = 0.66$, MSE = 0.320, $\eta 2p = 0.05$, fluency, $F(2,184) = 2.47$, $p = 0.09$, MSE = 5.420, $\eta 2p = 0.03$, and elaboration, $F(2,184) = 2.19$,

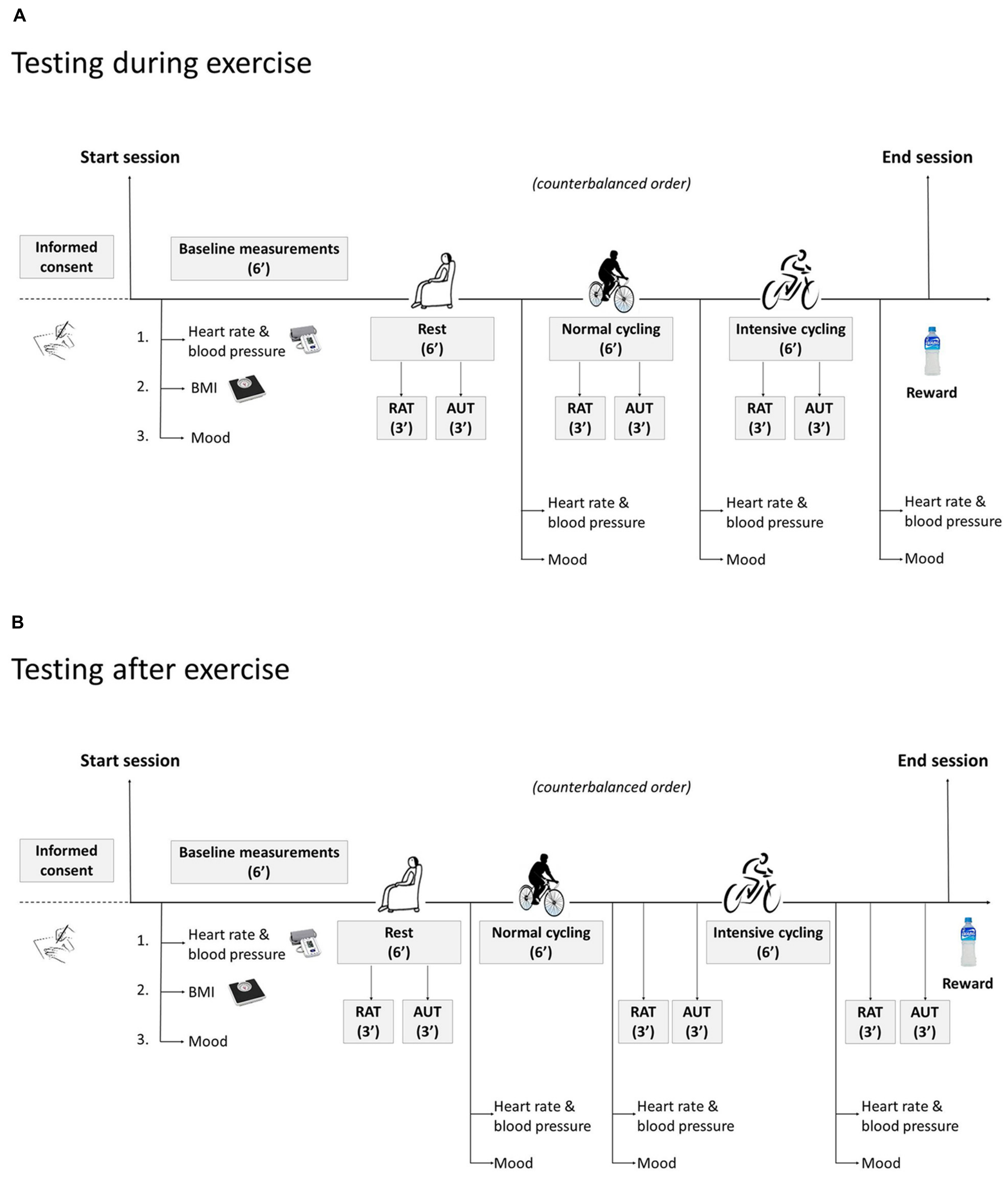

FIGURE 1 | Sequence of events for the participants who performed the creativity tasks during exercise (A) or after exercise (B).

$p = 0.11$, MSE $= 0.247$, $\eta 2p = 0.02$. In contrast to the RAT findings, the flexibility effect was not modulated by group, $F < 1$, and the same was true for originality, $F(2{,}184) = 1.20$, $p = 0.302$, MSE $= 0.320$, $\eta 2p = 0.01$, fluency, $F < 1$, and elaboration, $F(2{,}184) = 1.07$, $p = 0.346$, MSE $= 2.838$, $\eta 2p = 0.01$. There was also no indication of any three-way interaction, p's > 0.21.

DISCUSSION

In this study we investigated whether creativity in convergent- and divergent-thinking tasks is affected by acute physical exercise. The results provide some preliminary evidence for a link between exercise and creativity, but they also suggest that the nature and the consequences of this

Table 1 | Means for the number of correct items from the remote associates task (RAT), for flexibility, originality, fluency, and elaboration scores from the alternate uses task (AUT), and perceived mood ratings as a function of group (athletes vs. non-athletes), session (rest vs. normal vs. intense) and moment in which participants carried out the creativity tasks (during vs. after exercise).

Group	Moment	Session	RAT	AUT-flexibility	AUT-originality	AUT-fluency	AUT-elaboration	HR	BPS	BPD	Mood	Arousal
Athletes	During	Rest	3.6	7.3	0.50	11.0	0.83	77.0	113.5	74.4	1.5	0.7
		Normal	3.9	6.7	0.79	11.0	0.67	94.4	127.9	74.8	1.9	1.3
		Intense	4.0	6.2	0.75	10.5	0.62	126.1	148.6	83.1	1.8	2.0
	After	Rest	3.5	6.9	0.83	11.1	0.96	71.9	116.9	71.5	1.2	0.2
		Normal	4.3	6.7	0.79	10.8	0.87	91.0	134.8	74.6	1.1	1.1
		Intense	4.3	6.8	0.70	10.8	0.96	134.8	151.5	83.1	0.8	1.7
Non-athletes	During	Rest	4.7	7.2	0.46	10.4	0.92	75.5	117.5	77.2	1.2	0.6
		Normal	4.8	6.4	0.50	9.2	0.79	93.2	130.6	76.4	0.9	1.1
		Intense	3.4	6.7	0.37	8.6	0.62	131.6	150.8	88.1	0.9	2.0
	After	Rest	4.5	7.9	0.54	10.6	1.04	76.0	117.2	74.3	0.9	0.8
		Normal	4.0	7.9	0.46	11.0	1.00	102.8	127.3	79.2	1.5	0.8
		Intense	3.9	7.1	0.42	10.2	0.96	140.7	148.0	85.5	0.9	1.8

link depend on the particular task and the fitness of the individual.

First, non-athletes did not benefit from acute exercise; in fact, exercise caused their performance to drop in both creativity tasks. The fact that this drop was not modified by the moment of testing suggests that it was not due to dual-tasking or related online demands. Rather, in this group acute exercise seems to lead to ego-depletion, hence, exhaust limited cognitive-control resources (Baumeister et al., 1998) that are then no longer available for the control of processes involved in convergent and divergent thinking. Future research needs to clarify whether there is something specific about physical exercise that depletes cognitive resources over and above the complexity of the exercise. In particular, it would be important to determine whether depletion reflects the physical aspect of exercise or the cognitive demand.

Second, athletes tended to benefit from acute exercise in the convergent-thinking task. While this benefit was not quite reliable, we may speculate that athletes are shielded from the exercise-induced cognitive costs that non-athletes exhibited. This shielding effect is likely to reflect one or both of two possibilities. For one, athletes may have developed more automatic action-control routines, which frees capacity-limited processes from engaging and action monitoring and control (Beilock and Carr, 2001; Schneider and Chein, 2003). If so, the exercise might have been less control-hungry and capacity demanding in our athletes than in the non-athletes, so that more control capacity was left for the convergent-thinking task. Further testing this possibility would require a conceptual framework that allows determining the resource overlap between exercise and cognitive task pre-experimentally, and which allows predictions regarding the kind of resource that can be saved through automatization. For another, the shielding effect seems to fit with the idea that physical exercise, and the resulting increase of oxygenation and glucose in frontal brain regions, prevents or at least works against exercise-related ego-depletion. It is also partially in line with Colcombe and Kramer's (2003) consideration that aerobic fitness training might lead to the enhancement of cognitive-control processes and tasks relying on them. Even though our data do not show reliable enhancement, it is true that our criterion for categorizing participants as athletes was relatively modest. Hence, it is not unreasonable to suspect that even more active individuals do show reliable benefits in tasks relying on convergent thinking. However, athletes performed worse on the RAT than non-athletes in the rest condition. It is not to exclude that the enhancement of cognitive-control processes by aerobic fitness is so short-lived that positive effects are restricted to performance during or directly after exercising. From the current results, one may even speculate that for people who are used to exercise, the absence of exercise (rest) impairs (creative) performance more than its presence improves it. More generally, performance may be best whenever one carries out one's preferred (non-)activity.

Third, we sought to characterize the relationship between creativity and physical exercise by investigating the impact of two potential moderators: the intensity of the exercise and the temporal overlap between exercise and cognitive task. Whereas the latter factor did not seem to have any measurable impact, which rules out an account of our findings in terms of technical or motor problems (e.g., motor interference when responding to the items), the former does: intense exercise seems to enhance performance in athletes (at least numerically) and to impair performance in non-athletes the most. This opens the possibility to use more parametric manipulations of exercise and the possibly resulting ego-depletion to investigate both positive and negative exercise effects. In any case, future research needs to replicate and extend the present observations.

Even though we found more evidence for negative than for positive effects, our observations suggest that more exercise may enhance convergent thinking, at least in individuals with a higher degree of physical fitness. We should point out that there was no main effect of fitness, in the sense that athletes outperformed non-athletes in convergent thinking as such. However, given that we did not manipulate fitness experimentally, this may very well be an artifact of self-selection. Testing this possibility would require more extended studies in which physical fitness is under direct experimental control. It would also require more consideration of the role of individual differences, especially with respect to pre-existing neuro-developmental factors. Such differences may affect the degree to which individuals can benefit from fitness training: individuals with a certain genetic predispositions may take advantage from a given type of training whereas individuals with another predisposition may not. It would also be important to include other physiological measures such as volumes of oxygen to further investigate the neural mechanism by which exercise may affect creativity.

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Training creative cognition: adolescence as a flexible period for improving creativity

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Creativity commonly refers to the ability to generate ideas, solutions, or insights that are novel yet feasible. The ability to generate creative ideas appears to develop and change from childhood to adulthood. Prior research, although inconsistent, generally indicates that adults perform better than adolescents on the alternative uses task (AUT), a commonly used index of creative ideation. The focus of this study was whether performance could be improved by practicing alternative uses generation. We examined the effectiveness of creative ideation training in adolescents (13–16 years, $N = 71$) and adults (23–30 years, $N = 61$). Participants followed one of three types of training, each comprising eight 20-min practice sessions within 2 week time: (1) alternative uses generation (experimental condition: creative ideation); (2) object characteristic generation (control condition: general ideation); (3) rule-switching (control condition: rule-switching). Progression in fluency, flexibility, originality of creative ideation was compared between age-groups and training conditions. Participants improved in creative ideation and cognitive flexibility, but not in general ideation. Participants in all three training conditions became better in fluency and originality on the AUT. With regard to originality, adolescents benefitted more from training than adults, although this was not specific for the creative ideation training condition. These results are interpreted in relation to (a) the different underlying processes targeted in the three conditions and (b) developmental differences in brain plasticity with increased sensitivity to training in adolescents. In sum, the results show that improvement can be made in creative ideation and supports the hypothesis that adolescence is a developmental stage of increased flexibility optimized for learning and explorative behavior.

Keywords: divergent thinking, creative ideation, cognitive training, alternative uses task, adolescence

INTRODUCTION

Creativity is considered one of humans most complex as well as important behaviors. Its effects are evident and widespread, recognized in domains ranging from daily life problem solving to science and the arts. Creativity commonly refers to the ability to generate ideas, solutions, or insights that are novel yet feasible (e.g., Mumford, 2003). Within the *creative cognition* framework (e.g., Ward et al., 1999), creative capacity is considered inherent to normative human cognitive functioning, rather than an innate talent available to only a select few. The ability to create and use new mental categories to organize our experiences, and the ability to mentally manipulate objects are some examples of creativity that support the creative cognition approach (Ward et al., 1999). The creative cognition framework and more recent dual-processing models of creativity emphasize the dependence of creative thinking on fundamental cognitive processes such as working memory and executive control (Nijstad et al., 2010; Sowden et al., 2014). As such, individual differences in creativity can be understood in terms of variations in the efficiency of such cognitive processes (e.g., Ward et al., 1999). Furthermore, the development and malleability of the underlying mental operations used in creative problem solving processes (e.g., Klingberg, 2010; Jolles et al., 2011; Karbach and Schubert, 2013) imply that creativity develops with training and age. Indeed, numerous studies have demonstrated the effectiveness of interventions geared toward improving creativity—training in divergent thinking particularly influences performance gains in terms of originality, and to a lesser extent fluency and flexibility (e.g., Scott et al., 2004). Moreover, studies show that practice with creative ideation is highly effective in both adults (Glover, 1980; Bott et al., 2014; Kienitz et al., 2014), and children (Torrance, 1972; Cliatt et al., 1980).

In this study we examine the possibility that creative ideation develops from adolescence to adulthood, and can be trained with relatively simple interventions. Adolescence is a phase of development characterized by flexible adaption to a rapidly changing social landscape marked by changes from dependency to autonomy and individuality (Crone and Dahl, 2012). It forms a crucial phase for the development of cognitive abilities assumed to be related to creative cognition such as working memory and cognitive control (e.g., Diamond et al., 2002; Bunge and Wright, 2007; Huizinga and van der Molen, 2007; Crone and Dahl, 2012). Yet, relatively little is known about whether and how malleable divergent thinking is in adolescence. Training in other higher cognitive skills such as working memory (Klingberg, 2010; Jolles et al., 2012), executive control (Karbach and Kray, 2009; Zinke et al., 2012), relational reasoning (Dumontheil et al., 2010), and algebraic equation solving (Qin et al., 2004) emphasize the plasticity of the adolescent brain. In this study we test this hypothesis with regard to the development of creative ideation skills.

Creative ideation can be tracked with the Alternative Uses Task (AUT, Guilford, 1967; Kim, 2008), in which participants generate alternative uses for a common object (e.g., a brick; with alternative, original uses such as "making music" or "Geisha pillow"). These ideas are typically coded for three core components of creative ideation: originality or uniqueness (less frequent is considered more original), flexibility (more semantic categories implies more flexible), and creative fluency (more ideas translates to greater fluency). Especially originality improves with age (e.g., Runco and Bahleda, 1986; Urban, 1991; Lau and Cheung, 2010; Kleibeuker et al., 2013a)—although performance slumps at different stages in adolescence may occur (Lau and Cheung, 2010). Studies comparing adolescents and adults on the AUT often reveal advantages for adults. For example, Kleibeuker et al. (2013c) found that adults' AUT solutions were more unique than those of 12–13 and 15–16 year olds.

Results with regard to fluency and flexibility are more mixed. In some studies no differences were found between adolescents and adults (Wu et al., 2005; Kleibeuker et al., 2013c). In contrast, Kleibeuker et al. (2013b) found that late adolescents of 15–17 years had lower fluency and flexibility scores, but not originality scores, than adults on the AUT. Furthermore, Jaquish and Ripple (1981) found that adolescents obtained higher fluency and flexibility scores, but not originality scores, compared to children. On the whole, in the verbal divergent thinking domain applied in this study, adolescents generally provide less original solutions and, especially in late adolescence, show less fluency and flexibility than adults.

The present study aimed to extend investigations into the development of creative ideation by examining the progression of adults and adolescents within a simple training paradigm. The main question was whether creative ideation in adolescents is limited by maturational constraints or that exposure to divergent thinking training leads to progression in creative ideation thereby narrowing the gap in performance between adolescents and adults. To this end, participants were asked to practice generating alternative uses for everyday objects over a 2 week period. To examine the effects of training two active control groups were employed (Jolles and Crone, 2012), both trained in cognitive processes that were associated with but not directly related to creative ideation. One control group generated ordinary characteristics of everyday objects (adapted from Fink et al., 2009). This task has successfully served as a general ideation control task (Fink et al., 2009, 2010; Kleibeuker et al., 2013b). The second active control group practiced in rule-switching. Here, participants were asked to quickly and accurately apply and switch between two rule sets (Huizinga et al., 2010).

Given findings from previous research, routine practice in alternative uses generation for everyday objects was expected to improve creative performance over the course of a short, but intensive training period for both adolescents and adults. Participants who practiced generating alternative uses (creativity training condition) were expected to improve more on measures of creative fluency, flexibility and originality compared to the active control group. Adults were expected to initially provide more creative solutions to the AUT than adolescents on originality, and perhaps fluency and flexibility (Kleibeuker et al., 2013a,b); however, adolescents were expected to improve more over the course of training based on the hypothesis that adolescence is a period of enhanced sensitivity to training of high-level cognitive skills compared to adults (Steinberg, 2005; Jolles and Crone, 2012).

MATERIALS AND METHODS

PARTICIPANTS

The sample comprised 71 adolescents ($M_{age} = 14.9$, $SD = 0.7$, Range = 13.0–16.2 years, 67% females) and 61 adults ($M_{age} = 25.3$, $SD = 2.4$, Range = 22.1–31.1 years, 50% females). Adolescents were recruited from local high schools (college preparation level) and adults were recruited from Leiden University and colleges in The Hague. All participants provided informed consent. In case of minors, consent was also obtained from primary caregivers. Participation was compensated with gift vouchers, money, or course credits. All procedures were approved by the Internal Review Board of Leiden University Institute of Psychology.

The data was gathered in two waves separated by 15 months. In both waves adolescents and adults were recruited and randomly assigned to one of the training conditions (creative ideation; general ideation; rule-switching). There were two drop-outs. During the pretest and posttest not all data was available for all participants on all tasks. In some cases this was due to technical errors and in other cases students were absent from a testing session. Because the data was missing at random and not due to selection bias or systematic error, the validity of the statistical tests was not affected (Schafer and Graham, 2002). The number of subjects used in statistical analyses is reported separately per task and, as recommended, and Maximum Likelihood estimation was used when appropriate.

General cognitive ability

Creativity is associated with verbal fluency (Gilhooly et al., 2007), fluid reasoning (Nusbaum and Silvia, 2011), and working memory (De Dreu et al., 2012). Tasks that measure these constructs were administered at pretest in order to check for any differences between training conditions. The verbal fluency test (subtest of the Groningen Intelligence Test, GIT-2, Luteijn and Barelds, 2004) was used to measure general verbal ideation ability. Fluid reasoning was measured with the Raven Advanced Progressive Matrices (APM, Raven et al., 1998). Working memory was assessed using the mental counters task (Huizinga et al., 2006). Analyses of Variance were conducted with Age (adolescent, adult) and Training Condition (creative ideation, general ideation and rule-switching) as between-subjects factors to assess any differences in performance on these three tasks. See **Tables 1**, **2** for descriptive statistics and *F*-test results, respectively. No age group or training condition differences were found with regard to fluid reasoning. Adults outperformed adolescents on the measures of verbal fluency and working memory; however, there were no significant effects for training condition or age-group by training condition.

DESIGN AND PROCEDURE

A pretest-training-posttest design with three training conditions (creative ideation, general ideation, rule-switching) and two age groups (adolescents, adults) was employed, yielding a 2 (pre/post) × 2 (Age group) × 3 (training) factorial with the second and third factor between-subjects.

During the pretest session, all participants were administered two tasks measuring creative ideation, the AUT "Tin Can" task and the Alternative Uses part of a combined Alternative Uses/Ordinary Characteristics task (AU/OC task). General ideation was assessed using the Ordinary Characteristics part of the AU/OC task. A rule-switching task was also administered. In addition, verbal fluency, working memory, and fluid reasoning were assessed in order to ascertain whether the three training × two age groups did not differ on these control variables prior to training.

In the 2 weeks following the pretest session, participants followed an online training during their free time at home or at school. Participants were randomly assigned to one of three different trainings: creative ideation, general ideation, or rule-switching. Participants were asked to train eight times with a minimum of 1 day and a maximum of 2 days between training sessions and received an email or text message when needed to prompt them to train on time.

The posttest session comprised of the same tasks as the pretest and was administered 1 or 2 days following the last training session.

INSTRUMENTS

Creative ideation

Alternative Uses Test: pretest and posttest. A computerized 4-min version of the Alternative Uses Test (AUT; Guilford, 1950, 1967) was administered to measure creative ideation. Participants were given the name of an object and asked to generate as many alternative uses for the object as possible within a 4 min period (e.g., Friedman and Förster, 2001). At pretest the object was "Tin Can" and at posttest the object was "Brick." Participants were instructed to type in their solutions one at the time. After submitting the solution the text was no longer shown on the screen. From the generated ideas, we derived indices of fluency, flexibility, and originality after removing erroneous solutions (e.g., empty solutions, random strings such as "asdfjk;" and non-sense solutions such as "blah"). O*riginality* was rated on a 5-point scale (from 1 = "not original" to 5 = "highly original") by trained raters according to a pre-specified scheme (Rietzschel et al., 2006; De Dreu et al., 2008). The interrater reliability of the originality scores of this task were ICC = 0.91. *Fluency* scores were the sum of correct solutions provided. *Flexibility* was measured by the number of solution-categories per participant after trained raters assigned each solution to a set of predefined solution-categories (e.g., building aspect; load; toy; Rietzschel et al., 2006; De Dreu et al., 2008). *Unicity* provides an indication of how unique a

Table 1 | Descriptive statistics of pretest and posttest measures per training condition and age group on control variables: fluid reasoning, verbal fluency, and working memory.

	Creative ideation training			General ideation training			Rule-switch training		
	N	***M***	***SD***	***N***	***M***	***SD***	***N***	***M***	***SD***
VERBAL FLUENCY									
Adolescents	25	23.16	3.44	23	22.96	5.09	21	23.38	5.18
Adults	21	27.24	5.07	19	26.84	8.30	19	24.79	6.72
RAVEN APM									
Adolescents	23	9.26	2.01	21	9.38	3.14	20	8.45	3.58
Adults	19	9.68	1.60	18	10.11	3.32	16	10.00	1.97
WORKING MEMORY									
Adolescents									
Accuracy	19	0.88	0.08	16	0.86	0.09	18	0.84	0.19
Reaction time*	19	574	98	16	594	122	18	534	89
Adults									
Accuracy	20	0.90	0.09	19	0.91	0.09	18	0.92	0.05
Reaction time*	20	487	115	19	555	152	18	502	106

**Reaction time is reported in milliseconds.*

Table 2 | *F*-test results for comparisons of general cognitive ability measures verbal fluency, fluid reasoning, and working memory per training condition and age group.

	F	***df***	***p***	η_p^2
VERBAL FLUENCY				
Age	9.54	1, 122	<0.01	0.07
Condition	0.43	2, 122	0.65	0.01
Age × Condition	0.70	2, 122	0.50	0.01
RAVEN APM				
Age	3.17	1, 111	0.08	0.03
Condition	0.34	2, 111	0.71	0.01
Age × Condition	0.43	2, 111	0.65	0.01
WORKING MEMORY				
Accuracy				
Age	5.95	1, 104	0.02	0.05
Condition	0.05	2, 104	0.95	0.00
Age × Condition	0.68	2, 104	0.51	0.01
Reaction time				
Age	5.55	1, 104	0.02	0.05
Condition	2.34	2, 104	0.10	0.04
Age × Condition	0.65	2, 104	0.53	0.01

VF, verbal fluency; WM, working memory. Reaction time is reported in milliseconds.

particular solution was and was scored as the number of persons who provided the same solution, where higher scores indicate less unique solutions.

Combined Alternative Uses/Ordinary Characteristics Task: pretest and posttest. In the combined Alternative Uses (AU) and Ordinary Characteristics (OC) task the participant was presented with an object and requested to list object properties according to the rules of the task. During AU trials participants were asked to name as many novel uses of a common object as possible (e.g., "umbrella," example answer: "baseball bat"). During OC trials as many typical characteristics of a common object (e.g., "shoe," example answer: "fits on a foot") were requested. The AU trials measures creative ideation similar to the traditional Alterative Uses Test (AUT, Guilford, 1950, 1967), but now for multiple objects within a shorter time period. The OC part of the task is described in Section General Ideation.

For each trial the participant was shown an instruction screen (3 s) identifying the trial type ("alternative uses" or "ordinary characteristics"). In the next screen the target object name appeared in the middle of the screen with the instruction "alternative uses" or "ordinary characteristics" reiterated at the top of the screen (see **Figure 1**). The participant was given 20 s to list solutions out loud. The solutions were recorded and later transcribed. Per session 30 items (15 AU and 15 OC) were in random order, divided across two blocks (7 min each) separated by a short break. There were 60 items in total; the allocation to session (pretest, posttest) and type (AU, OC) were counterbalanced over participants and training conditions.

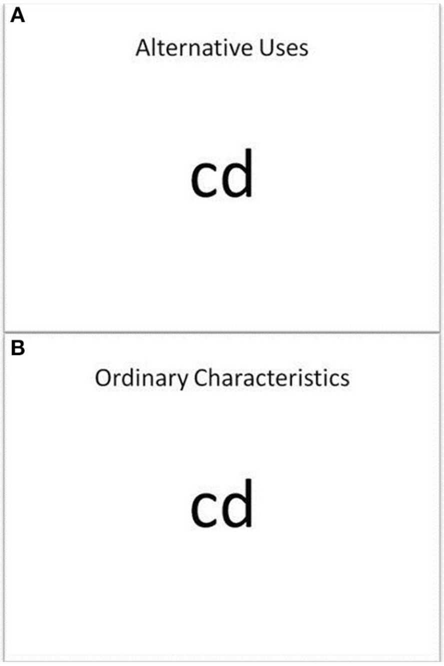

FIGURE 1 | Alternative Uses/Ordinary Characteristics task: (A) example Alternative Uses item and (B) example Ordinary Characteristics item. Participants were asked to list as many alternative uses for *or* ordinary characteristics of an everyday object as possible.

The AU responses were coded for creative fluency (average number of unique solutions across trials), and originality (the average rating across AU trials per stimulus). Two independent trained raters assessed originality on this measure with interrater reliability ICC = 0.73.

Alternative Uses: training. Participants in the AU training condition trials were administered 10 AU items during each of the eight training sessions. The items lasted 2 min each. A short break was provided halfway through the training. Each session began with a brief: "Generate as many alternative uses for each presented object." This was followed by one screen per item with the instruction briefly reiterated at the top of the screen. The participant typed the solutions into a text box and each submitted solution was posted below on the same screen. After 2 min the next item was shown. A total of 80 stimuli were presented in random order across trials over training sessions. The total duration of training was approximately 20 min.

The AU training sessions were coded for *originality* (the average rating across trials per stimulus) and creative *fluency* (average number of unique solutions across trials within one session). *Flexibility* (the number of categories used from a set of predefined solution-categories) was also measured for the first trial per training session.

General ideation

Combined Alternative Uses/Ordinary Characteristics Task: pretest and posttest. General ideation is the second skill assessed in the combined Alternative Uses (AU) and Ordinary Characteristics (OC) task. The OC task was based on Fink et al. (2009) and served as a general control for the creative ideation training, appealing to memory retrieval processes. For each OC trial the participant was shown an instruction screen (3 s) identifying the trial type ("ordinary characteristics"). In the next screen the target object name appeared in the middle of the screen with the instruction "ordinary characteristics" reiterated at the top of the screen (see **Figure 1**). The participant was given 20 s to list solutions out loud. The solutions were recorded and later transcribed. Per session 15 OC trials (and 15 AU trials) were presented in random order. There were 30 OC items in total across pretest and posttest; the allocation to session (pretest, posttest) and type (AU, OC) was counterbalanced over participants and training conditions.

Ordinary Characteristics: training. Participants in the general ideation condition were asked to solve 10 OC items lasting 2 min each, with a short break halfway, during each of the eight training sessions. Each session began with a brief instruction "List as many ordinary characteristics as possible for the object on the screen." This was followed by one screen per item with the instruction briefly reiterated at the top of the screen. The participant typed solutions into a text box and each submitted solution was posted below on the same screen. After 2 min the next item was shown. A total of 80 stimuli were presented in random order across trials over sessions. The total duration of the general ideation training was approximately 20 min. The OC responses were coded for fluency, i.e., the average number of correct solutions across all OC trials within the session.

Rule-switching

Rule-switching was measured and trained with the global/local rule-switch (RS) task (Huizinga et al., 2010). Participants were shown a rule comprising of two objects: (1) a large square and a rectangle (global rule) or (2) a small square and a small rectangle (local rule). Next the stimulus, a large square or rectangle composed of smaller squares or rectangles (2 × 2 possible stimuli), was presented in between the two rule objects. During this time the participant was asked to indicate which rule the stimulus belonged to. The decision rule was based on the size of the square and rectangle on either side of the target. If the side figures were large the "global" rule was to be applied—i.e., indicate the stimulus as a whole was a large square or rectangle. If the side figures were small then the "local" rule was required—i.e., indicate whether the stimulus was composed of small squares or rectangles. See **Figure 2** for an example. During the first and second blocks of this task decisions were based on only one rule ("global" or "local"). During the remaining blocks the two rules were mixed and the participant had to switch between the rules. The switching costs for accuracy and reaction time computed using the ration between rule repeat trials and trials directly following a rule-switch.

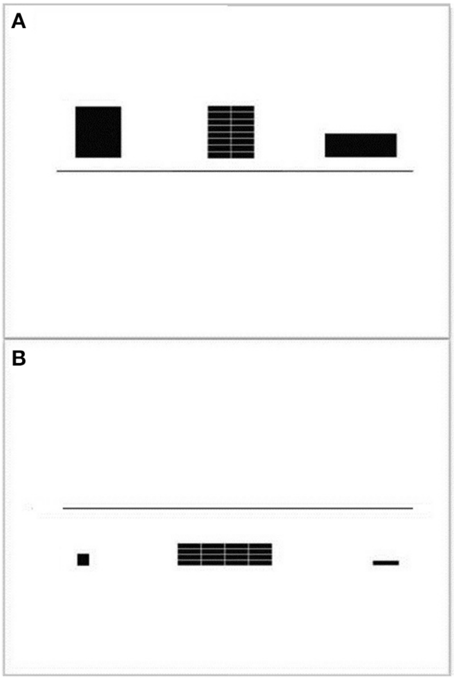

FIGURE 2 | Rule-switching task example items: (A) global rule and (B) local rule. The participant was cued to apply the global rule to the figure in the middle when the two side figures were large. The local rule was applied if the side figures were small. Switch blocks involved applying both rules in random order. In both figures above the correct solution is on the left-hand side, thus the participant would press the left button.

Rule-switching: pretest and posttest. Four blocks of 50 trials were administered. The task lasted approximately 10 min.

Rule-switching: training. Four blocks of 80 trials each were administered. The total duration of a RS training session was approximately 20 min, including a short break between blocks two and three.

RESULTS

DESCRIPTIVE STATISTICS

Descriptive statistics for all pretest and posttest measures per age group (adolescent, adult) and training condition (creative ideation, general ideation, and rule-switching) are shown in **Table 3**. Correlations between each of the pretest and posttest measures are shown in **Table 4**.

Initial comparisons

Initial comparisons were conducted on each of the pretest tasks between the two age groups and three training conditions to examine whether differences prior to training were present. The results of the Analysis of Variance (ANOVAs) with Age and Condition as between-subjects factors are presented in **Table 5**. Here we see that age effects emerged on the combined AU/OC task for the measures of AU originality and OC fluency. In both cases adults obtained higher scores than adolescents. No further main effects for Age or Training Condition were found on any of the pretest creative ideation, general ideation and rule-switching tasks. Age × Training Condition effects were not present on the AUT or rule-switching tasks; however, an interaction was present on the combined AU/OC task for the AU originality and AU fluency measures. *Post-hoc* analyses with Bonferroni correction revealed that these interaction effects emerged because of Age effects in some but not all Training Conditions (see **Figure 3**). For AU originality Age effects, with higher scores for adults, were present for the AU and RS conditions [AU condition: $F_{(1,\,42)} = 6.12$, $p = 0.02$, $\eta_p^2 = 0.13$; RS condition: $F_{(1,\,37)} = 15.40$, $p < 0.001$, $\eta_p^2 = 0.29$] but not for the OC condition ($p > 0.10$). For AU fluency we found a significant Age effect for the OC condition [$F_{(1,\,39)} = 4.65$, $p = 0.04$, $\eta_p^2 = 0.11$], where adults obtained higher scores, but not for the AU and RS conditions. In sum, age-group differences were present on the combined AU/OC task; however, these initial differences were accounted for in our main analyses as we applied repeated measures ANOVAs.

Correlations

Associations between the pretest measures were in the expected directions. Firstly, AU originality measures (AUT and combined AU/OC version) were all positively correlated, although the expected association between originality on the 4-min AU Tin test and the AU/OC task was not significant. Secondly, the associations between the AU and OC fluency measures were all moderate to strong. Finally, rule-switching performance during pretest was strongly related to rule-switching performance during the RS training condition participants' first training session. In sum, the pretest correlations support the validity of our tasks.

Correlations between each of the posttest measures were generally as expected and these correlations were often stronger than

Table 3 | Descriptive statistics of pretest and posttest measures per training condition and age group on the combined Alternative Uses/Ordinary Characteristics task (AU/OC task), the Alternative Uses test and the Rule-Switching task.

	Creative ideation training			General ideation training			Rule-Switch training		
	N	***M***	***SD***	***N***	***M***	***SD***	***N***	***M***	***SD***
					Pretest				
COMBINED AU/OC PRETEST									
Adolescents									
AU originality	23	2.08	0.36	22	2.19	0.41	22	1.99	0.40
AU fluency	23	2.46	0.81	22	2.25	0.73	22	2.76	1.13
OC fluency	23	3.53	1.30	22	3.69	0.85	22	3.75	1.26
Adults									
AU Originality	21	2.37	0.41	19	2.25	0.28	17	2.49	0.39
AU fluency	21	2.65	0.87	19	2.83	0.99	17	2.27	0.71
OC fluency	21	4.16	1.24	19	4.63	1.49	17	4.43	0.89
ALTERNATIVE USES PRETEST									
Adolescents									
Fluency	25	11.92	5.53	23	12.83	6.55	23	12.70	6.72
Flexibility	25	6.16	2.17	23	5.91	2.17	23	6.17	2.76
Originality	25	1.68	0.35	23	1.64	0.27	23	1.69	0.34
Adults									
Fluency	22	11.41	3.45	20	11.65	5.71	19	12.74	5.51
Flexibility	22	6.91	1.82	20	5.70	3.08	19	6.95	2.12
Originality	22	1.73	0.37	20	1.75	0.33	19	1.67	0.29
RULE-SWITCHING PRETEST									
Adolescents									
Accuracy	17	0.00	0.09	14	0.03	0.06	14	0.02	0.04
Reaction time*	17	104	115	14	81	76	14	70	35
Adults									
Accuracy	21	0.00	0.04	19	0.00	0.08	18	0.00	0.05
Reaction time*	21	55	54	19	79	52	18	100	88
					Posttest				
AU/OC POSTTEST									
Adolescents									
AU originality	25	2.46	0.18	19	2.50	0.27	18	2.47	0.24
AU fluency	25	2.99	1.35	19	2.55	0.85	18	3.15	1.12
OC fluency	25	3.69	0.96	19	4.20	1.02	18	4.23	1.30
Adults									
AU Originality	21	2.61	0.22	20	2.58	0.19	17	2.62	0.23
AU fluency	21	3.07	0.93	20	2.80	0.79	17	2.49	1.28
OC fluency	21	3.96	0.98	20	4.76	1.09	17	3.99	1.10
ALTERNATIVE USES POSTTEST									
Adolescents									
Fluency	23	14.35	7.99	19	11.32	7.37	20	17.25	7.15
Flexibility	23	8.48	2.11	19	7.53	2.46	20	9.85	2.80
Originality	23	1.66	0.34	19	1.79	0.49	20	1.75	0.44
Adults									
Fluency	18	13.39	4.47	15	12.20	4.16	16	10.81	5.74
Flexibility	18	9.44	2.18	15	8.33	2.16	16	7.38	2.96
Originality	18	1.70	0.30	15	1.60	0.24	16	1.67	0.32
RULE-SWITCHING POSTTEST									
Adolescents									
Accuracy	18	−0.03	0.04	15	−0.01	0.04	16	−0.02	0.06
Reaction time*	18	89	68	15	45	80	16	30	28
Adults									
Accuracy	20	0.00	0.04	18	0.00	0.03	20	0.02	0.07
Reaction time*	20	26	34	18	53	38	20	30	30

Both versions of the alternative uses task measure creative ideation. The ordinary characteristics task measures general ideation.

AU, alternative uses; OC, ordinary characteristics; RS, rule-switching,

The rule-switching task reports switch costs.

**Reaction time is reported in milliseconds.*

during the pretest. The two AU originality measures (AUT and combined AU/OC version) were positively correlated.

Correlations between pretest and posttest measures of the same task were generally all positive but varied in strength. The correlation between the AUT originality pretest and posttest was not significant; however, as we will see in the next section this is most likely due to changes taking place in some groups but not others as will be discussed in the next Section Pretest to Posttest Change.

PRETEST TO POSTTEST CHANGE

We had two main inquiries concerning pretest to posttest change on the three training-related measures of creative ideation, general ideation and rule-switching. Our first research question concerned the effectiveness of the intervention; we expected participants within a training condition to improve more on the task they practiced than participants in the other two training conditions. Our second research question focused on differential progression from pretest to posttest between age groups; we examined whether adolescents showed greater improvement in performance than adults on all tasks.

In order to test our hypotheses concerning pretest to posttest change on the measures of creative ideation (AU tasks), general ideation (OC task) and rule-switching (RS task), repeated measures ANOVAs were conducted with Age (adolescent, adult) and Training Condition (creative ideation, general ideation, rule-switching) as between-subjects factors and Session (pretest, posttest) as within-subjects factor. Homogeneity of variance between factors was examined with Levene's test. For the AUT, equal task difficulty for the Tin Can (pretest) and Brick (posttest) versions could not be assumed. Accordingly, ANCOVAs with Age and Condition as between-subjects factors and the AUT pretest score as covariate was conducted to test our hypotheses.

Creative ideation

Two tasks measured creative ideation: (1) the alternative uses part of the combined Alternative Uses/Ordinary Characteristics (AU/OC) task and (2) the Alternative Uses Test. Pretest to

Table 4 | Correlations between the pretest and posttest measures on the Alternative Uses test (AUT), combined Alternative Uses/Ordinary Characteristics task (AU/OC task), and rule-switch task (RS).

	Pretest								**Posttest**							
	AU/OC			**AUT**			**Rule-Switch**		**AU/OC**			**AUT**			**Rule-Switch**	
	AU orig	**AU flu**	**OC flu**	**orig**	**flu**	**flex**	**acc**	**rt**	**AU orig**	**AU flu**	**OC flu**	**orig**	**flu**	**flex**	**acc**	**rt**
PRETEST TASKS																
Combined AU/OC																
AU originality	1															
AU fluency	0.09	1														
OC fluency	0.36**	0.49**	1													
Alternative uses																
Originality	0.11	0.17	0.06	1												
Fluency	0.19*	0.21*	0.21*	0.05	1											
Flexibility	0.27**	0.19*	0.28**	0.13	0.72**	1										
Rule-switch																
Accuracy	−0.20*	0.01	−0.05	0.18	−0.05	−0.05	1									
Reaction time	−0.05	−0.16	−0.11	−0.14	−0.13	−0.13	−0.04	1								
POSTTEST TASKS																
Combined AU/OC																
AU originality	0.23*	−0.07	0.11	0.08	0.10	0.10	−0.03	−0.03	1							
AU fluency	−0.02	0.53**	0.27**	0.03	0.25**	0.20*	−0.03	−0.05	−0.04	1						
OC fluency	−0.08	0.35**	0.54**	0.09	0.27**	0.27**	0.02	−0.05	0.09	0.42**	1					
Alternative uses																
Originality	0.00	0.03	−0.01	0.14	0.09	0.10	0.01	−0.10	0.18	0.15	0.07	1				
Fluency	−0.05	0.39**	0.11	0.11	0.21*	0.14	−0.08	−0.03	−0.04	0.61**	0.30**	0.16	1			
Flexibility	0.01	0.39**	0.14	0.15	0.21*	0.25**	−0.08	−0.03	−0.02	0.58**	0.30**	0.03	0.79**	1		
Rule-switch																
Accuracy	0.15	−0.22*	0.04	−0.29**	−0.07	−0.04	−0.03	0.18	0.22*	−0.03	−0.04	0.01	−0.12	−0.15	1	
Reaction time	0.02	−0.04	−0.09	−0.17	−0.11	−0.21*	0.07	0.41**	−0.11	−0.09	−0.16	−0.15	0.06	0.03	−0.11	1

Orig, originality; flu, fluency; flex, flexibility; acc, accuracy; rt, reaction time. $^{*}p < 0.05$, $^{**}p < 0.01$.

posttest change on these two tasks was examined separately and is described in the following subsections. We hypothesized that participants trained in creative ideation would improve more in originality, fluency (number of valid creative solutions) and flexibility (ability to change categories during creative ideation) on the AU tasks than participants trained in general ideation or rule-switching.

Alternative Uses: AU/OC task. The alternative uses part of the combined AU/OC task comprised of measures of AU originality and AU fluency. The first set of analyses tested for training effects on AU originality scores. A main effect of Session showed that participants generally improved on the AU originality measure from pretest to posttest [$F_{(1,\ 98)} = 64.02, p < 0.001, \eta_p^2 = 0.395$]. A main effect of Age showed that adults obtained higher scores on the AU originality measure on the whole [$F_{(1,\ 98)} = 22.53$, $p < 0.001, \eta_p^2 = 0.187$]. A Session × Age interaction showed that adolescents progressed more from pretest to posttest on AU originality [$F_{(1,\ 51)} = 61.42, p < 0.001$] than adults [$F_{(1,\ 47)} = 14.19$, $p < 0.001$]: Session × Age effect: $F_{(1,\ 98)} = 5.14$, $p = 0.03$, $\eta_p^2 = 0.05$ (see **Figure 3A**). Pretest to posttest change in AU originality did not differ between training conditions [Session × Training Condition effect: $F_{(2,\ 98)} = 0.13$, $p = 0.88$, $\eta_p^2 = 0.00$]; Session × Age × Training Condition effect: $F_{(2,\ 98)} = 0.23$, $p = 0.79$, $\eta_p^2 = 0.01$.

The same analyses for AU fluency showed that in general, participants improved in AU fluency from pretest to posttest [Session effect: $F_{(1,\ 102)} = 8.91$, $p < 0.01$ $\eta_p^2 = 0.09$]. No significant differences in AU fluency progression were observed for Age [Age effect: $F_{(1,\ 98)} = 0.01, p = 0.91, \eta_p^2 = 0.00$ or Session × Age effect: $F_{(1,\ 102)} = 0.10$, $p = 0.76$, $\eta_p^2 = 0.00$; see **Figure 3B**], Condition [Session × Condition effect: $F_{(2,\ 102)} = 0.90$, $p = 0.41, \eta_p^2 = 0.02$] or Age × Condition [Session × Age × Condition effect: $F_{(2,\ 102)} = 1.20, p = 0.31, \eta_p^2 = 0.02$].

Alternative Uses Tin Can and Brick. The AU Brick task was the posttest counterpart of the AU Tin Can pretest task. Originality, fluency, flexibility, and unicity (inverse of uniqueness) were measured on the AUT. Results are shown in **Figure 4**.

No main effects for Condition or Age were found for originality [Condition: $F_{(2,\ 104)} = 0.10$, $p = 0.91$, $\eta_p^2 = 0.00$, Age: $F_{(2,\ 104)} = 1.48$, $p = 0.23$, $\eta_p^2 = 0.01$]. Also, no Age × Training Condition interaction was found on the measure of originality [$F_{(2,\ 104)} = 1.01, p = 0.37, \eta_p^2 = 0.02$].

For fluency there were no main effects for Condition [$F_{(2,\ 104)} = 1.44$, $p = 0.24$, $\eta_p^2 = 0.03$] or Age [$F_{(2,\ 104)} = 3.33$, $p = 0.07$, $\eta_p^2 = 0.03$]. There was a significant interaction effect between Age and Condition on fluency [$F_{(2,\ 104)} = 3.16$, $p = 0.047$, $\eta_p^2 = 0.06$]. Therefore, an additional ANCOVA per

Table 5 | *F*-test results for pretest and posttest measures per training condition and age group on the combined Alternative Uses/Ordinary Characteristics task (AU/OC task), the Alternative Uses test (AUT), and the Rule-Switching task.

	F	*df*	*p*	η_p^2
AU/OC TASK				
AU originality				
Age	**16.08**	**1, 118**	**<0.001**	**0.12**
Condition	0.14	2, 118	0.87	0.00
Age × Condition	2.79	2, 118	0.07	0.05
AU fluency				
Age	0.30	1, 118	0.58	0.00
Condition	0.01	2, 118	0.99	0.00
Age × Condition	**4.01**	**2, 118**	**0.02**	**0.06**
OC fluency				
Age	**12.75**	**1, 118**	**<0.001**	**0.10**
Condition	0.77	2, 118	0.47	0.01
Age × Condition	0.17	2, 118	0.85	0.00
ALTERNATIVE USES TEST				
Originality				
Age	0.57	1, 126	0.45	0.00
Condition	0.04	2, 126	0.96	0.00
Age × Condition	0.37	2, 126	0.69	0.01
Fluency				
Age	0.30	1, 126	0.58	0.00
Condition	0.38	2, 126	0.69	0.01
Age × Condition	0.12	2, 126	0.89	0.00
Flexibility				
Age	1.10	1, 126	0.30	0.01
Condition	1.39	2, 126	0.25	0.02
Age × Condition	0.60	2, 126	0.55	0.01
RULE-SWITCHING TASK				
Switch costs accuracy				
Age	1.47	1, 97	0.23	0.02
Condition	0.44	2, 97	0.65	0.01
Age × Condition	0.49	2, 97	0.62	0.01
Switch costs reaction time				
Age	0.14	1, 97	0.71	0.00
Condition	0.02	2, 97	0.98	0.00
Age × Condition	1.99	2, 97	0.14	0.04

$p < 0.05$ appears in bold.

age-group with Bonferroni-corrected *post-hoc* comparisons was conducted. These analyses revealed a marginally greater fluency in adolescents in the rule-switching condition vs. the general ideation condition ($\Delta M = 5.62$, $SE = 2.31$, $p = 0.05$). No other significant differences between the training conditions were found.

For flexibility there were also no main effects for Condition [$F_{(2,\ 104)} = 1.19$, $p = 0.31$, $\eta_p^2 = 0.02$], or Age [$F_{(2,\ 104)} = 1.33$, $p = 0.25$, $\eta_p^2 = 0.01$], The Condition × Age effect was significant: $F_{(2,\ 104)} = 6.42$, $p < 0.01$, $\eta_p^2 = 0.11$. This was investigated further with an ANCOVA per age-group with Bonferroni corrected *post-hoc* tests for Condition. These revealed greater flexibility for the Rule-switching than General ideation training condition in adolescents ($\Delta M = 2.18$, $SE = 0.74$, $p = 0.01$) and marginally greater flexibility for the Creative ideation vs. Rule-switching condition in adults ($\Delta M = 2.09$, $SE = 0.84$, $p = 0.05$). No other significant differences between training conditions were found.

Adolescents had marginally lower scores for unicity (i.e., higher scores infer less unique solutions) compared to adults [$F_{(1,\ 104)} = 3.82$, $p = 0.05$, $\eta_p^2 = 0.03$], indicating greater uniqueness of solutions for adolescents. There was no main effect for Condition [$F_{(2,\ 104)} = 0.25$, $p = 0.78$, $\eta_p^2 = 0.00$], nor was there an interaction effect for Condition × Age [$F_{(2,\ 104)} = 0.98$, $p = 0.38$, $\eta_p^2 = 0.02$].

AU Tin Can performance was positively related to AU Brick performance; although it was not a significant covariate for originality [$F_{(2,\ 104)} = 2.58$, $p = 0.11$, $\eta_p^2 = 0.02$], it did form a significant covariate for fluency [$F_{(2,\ 104)} = 5.78$, $p = 0.02$, $\eta_p^2 = 0.05$], flexibility [$F_{(2,\ 104)} = 8.78$, $p < 0.01$, $\eta_p^2 = 0.08$], and unicity [$F_{(2,\ 104)} = 8.04$, $p = 0.01$, $\eta_p^2 = 0.07$]. In general this shows that individuals with high pretest "Tin Can" scores also obtained high posttest "Brick" scores.

General ideation

Repeated measures ANOVAs for OC fluency revealed no significant changes across sessions [Session effect: $F_{(1,\ 98)} = 1.69$, $p = 0.20$, $\eta_p^2 = 0.02$]. There was a main effect of Age [$F_{(1,\ 102)} = 5.71$, $p = 0.02$, $\eta_p^2 = 0.05$; see **Figure 5**] where adults obtained higher OC fluency scores compared to adolescents. No significant differences in OC fluency progression were observed for the two age groups [Session × Age effect: $F_{(2,\ 102)} = 3.54$, $p = 0.06$, $\eta_p^2 = 0.03$] or training conditions [Session × Condition effect: $F_{(2,\ 102)} = 2.20$, $p = 0.12$, $\eta_p^2 = 0.04$] or Age × Condition [Session × Age × Condition effect: $F_{(2,\ 102)} = 0.15$, $p = 0.87$, $\eta_p^2 = 0.00$].

Rule-switching

Performance on the RS task comprised measures of switch costs (mean repeat trial minus mean switch trial) for accuracy and reaction time. Participants trained with the RS task were expected to improve more than those trained in AU or OC.

Switch costs decreased for accuracy from pretest to posttest [Session effect: $F_{(1,\ 76)} = 5.36$, $p = 0.02$, $\eta_p^2 = 0.07$]. A Session × Age interaction was found for accuracy [$F_{(1,\ 76)} = 9.40$, $p < 0.01$, $\eta_p^2 = 0.11$], where adolescents decreased more in switch costs than adults (see **Figure 6**). No Session × Condition or Session × Condition × Age effects were found for accuracy [$F_{(1,\ 76)} = 0.61$, $p = 0.55$, $\eta_p^2 = 0.02$. or $F_{(1,\ 76)} = 0.07$, $p = 0.93$, $\eta_p^2 = 0.00$]. There were no main effects for Age [$F_{(1,\ 76)} = 0.02$, $p = 0.89$, $\eta_p^2 = 0.00$] or Condition [$F_{(1,\ 76)} = 0.59$, $p = 0.56$, $\eta_p^2 = 0.02$] or Age × Condition [$F_{(1,\ 76)} = 1.29$, $p = 0.28$, $\eta_p^2 = 0.03$].

For reaction time, switch costs also decreased from pretest to posttest [Session effect: $F_{(1,\ 76)} = 10.97$, $p < 0.01$, $\eta_p^2 = 0.13$]. No Session × Age or Session × Age × Condition interactions were present [$F_{(1,\ 76)} = 1.42$, $p = 0.24$, $\eta_p^2 = 0.02$ and $F_{(1,\ 76)} = 0.60$, $p = 0.55$, $\eta_p^2 = 0.02$, respectively]. No main effects for Age [$F_{(1,\ 76)} = 3.16$, $p = 0.09$, $\eta_p^2 = 0.04$] or Condition [$F_{(1,\ 76)} = 1.45$, $p = 0.24$, $\eta_p^2 = 0.04$] were present. A marginal Session × Condition interaction effect was present [$F_{(1,\ 76)} = 3.01$, $p =$

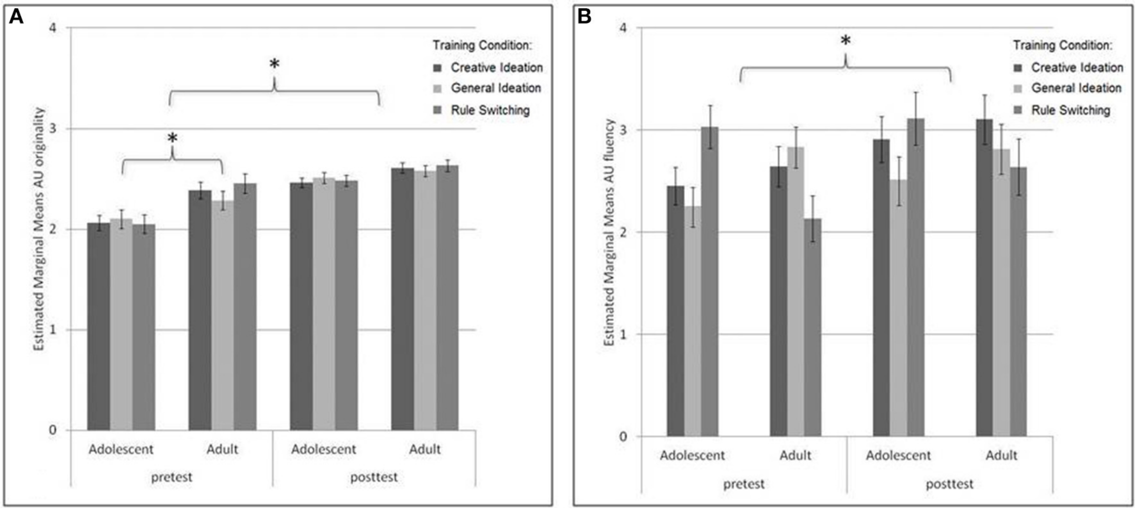

FIGURE 3 | Pretest to posttest progression for adults and adolescents on the creative ideation measure of the combined Alternative Uses/Ordinary Characteristics task: (A) originality (1 = "not original" to 5 = "highly original") and (B) fluency (number of alternative uses listed). In general participants improved in AU originality from pretest to posttest. Adults had higher mean originality scores than adolescents; however, adolescents showed greater gains from pretest to posttest than adults in AU originality. Participants generally had higher mean AU fluency scores on the posttest compared to pretest; however, no age group or training condition differences were found. $^{*}p < 0.05$.

0.06, $\eta_p^2 = 0.07$] and a significant Age × Condition interaction was present for reaction time [$F_{(2,\ 76)} = 5.76$, $p < 0.01$, $\eta_p^2 = 0.13$]. Follow-up repeated measures analyses for reaction time were conducted per age group in order to further investigate the role of training condition. These *post-hoc* comparisons with Bonferroni correction revealed no significant differences within age groups between training conditions.

PROGRESSION DURING TRAINING

We used repeated measures ANOVAs with Age (adolescent, adult) as between-subjects factor and Session (1–8) as within-subjects factor to examine the participants' progression during training. Homogeneity of variance between factors was examined with Levene's test. Greenhouse-Geisser correction for any violations of sphericity was applied when required. In some cases training data for one session was incomplete due to loss of Internet connection or early closing of the training software Internet browser ($N_{AU} = 6$, $N_{OC} = 11$, $N_{RS} = 10$); when this occurred the session score was computed based on the mean of the previous and next session. Participants for whom data from more than one consecutive session was incomplete were excluded from the analyses ($N_{AU} = 2$, $N_{OC} = 2$, $N_{RS} = 2$).

Creative ideation training

A depiction of the participant's progression on the measures of originality and fluency, flexibility on the Alternative Uses (AU) training task is shown in **Figure 7**. Adults on average had higher scores on the originality measure [$F_{(1,\ 44)} = 9.01$, $p < 0.01$, $\eta_p^2 = 0.17$], whereas as adolescents on average had marginally higher scores for flexibility [$F_{(1,\ 44)} = 3.93$, $p = 0.05$, $\eta_p^2 = 0.09$]. There were no differences between age groups on the fluency measure [$F_{(1,\ 44)} = 0.57$, $p = 0.46$, $\eta_p^2 = 0.01$].

Although there was no main effect for Session on originality [$F_{(1,\ 44)} = 0.12$, $p = 0.73$, $\eta_p^2 = 0.01$], a significant quadratic Session effect emerged for flexibility [$F_{(1,\ 44)} = 29.92$, $p < 0.001$, $\eta_p^2 = 0.42$] and a significant cubic Session effect was present for fluency [$F_{(1,\ 44)} = 5.55$, $p = 0.02$, $\eta_p^2 = 0.11$]. Session × Age interactions were not present for originality [$F_{(1,\ 44)} = 1.23$, $p = 0.30$, $\eta_p^2 = 0.42$], fluency [$F_{(1,\ 44)} = 0.18$, $p = 0.88$, $\eta_p^2 = 0.00$] or flexibility [$F_{(1,\ 44)} = 0.60$, $p = 0.65$, $\eta_p^2 = 0.01$]. In short, results indicate that although training does not affect originality, it does impact both fluency and flexibility in creative ideation, two critical antecedents of original thinking and insight performance.

General ideation training

Fluency performance for adults and adolescents on the Ordinary Characteristics (OC) training task is shown in **Figure 8**. Analyses do not show a main effect for Age [$F_{(1,\ 39)} = 0.64$, $p = 0.46$, $\eta_p^2 = 0.01$] nor a Session × Age interaction [$F_{(1,\ 39)} = 0.96$, $p = 0.54$, $\eta_p^2 = 0.02$]. Thus, no discernible differences were present in adolescents and adults progression on the OC task during the training sessions. Training does not affect general ideation.

Rule-switch training

Switch costs remained relatively steady across Sessions for both accuracy and reaction time [accuracy: $F_{(1,\ 39)} = 1.73$, $p = 0.10$, $\eta_p^2 = 0.04$; reaction time: $F_{(1,\ 39)} = 1.67$, $p = 0.19$, $\eta_p^2 = 0.04$], as can be seen in **Figure 9**. Adults and adolescents did not differ in average switch costs during training [accuracy: $F_{(1,\ 39)} = 1.35$, $p = 0.25$, $\eta_p^2 = 0.03$; reaction time: $F_{(1,\ 39)} = 0.51$, $p = 0.48$, $\eta_p^2 = 0.01$] throughout the training sessions. No interaction between Session and Age is present for accuracy [$F_{(1,\ 39)} = 0.67$, $p = 0.66$, $\eta_p^2 = 0.02$] or reaction time [$F_{(1,\ 39)} = 0.64$, $p = 0.54$, $\eta_p^2 = 0.02$]. As for training creative ideation, training

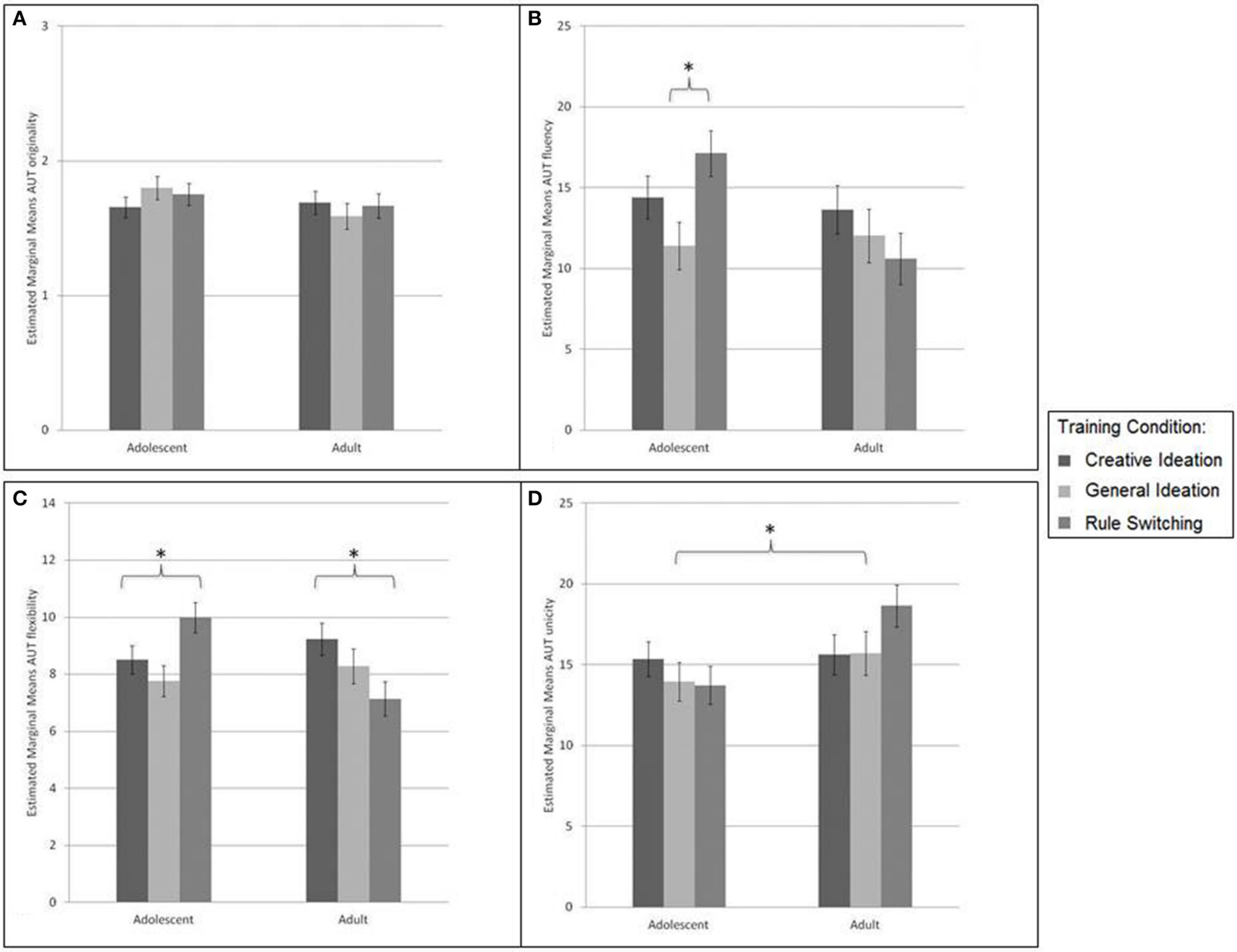

FIGURE 4 | Alternative Uses "brick" posttest performance for adults and adolescents per training condition on measures: (A) originality (1 = "not original" to 5 = "highly original"), (B) fluency (number of solutions), (C) flexibility (number of categories used in solutions), and (D) unicity (inverse of uniqueness, i.e., mean frequency of provided solution in dataset). No differences were found in originality between age groups and training conditions. Fluency was marginally greater in adolescents trained in rule-switching vs. those trained in general ideation. Adolescents the rule-switch training condition had greater flexibility scores than the adolescents in the creative and general ideation conditions. In adults, the opposite was observed for flexibility, where adults trained in creative ideation outperformed the active control groups in flexibility. For unicity, adolescents had marginally lower scores indicating greater uniqueness of solutions. $^*p < 0.05$.

does affect rule-switching ability yet not differently for age groups.

DISCUSSION

The aim of the current study was to examine the effects of creative ideation training in adolescents and adults. To this end, participants followed one of three training types; alternative uses generation (creative ideation condition), general ideation, or rule-switching. A set of tasks measuring both creative ideation and general cognitive functions were administered before and after 2 weeks of training. There were two main findings: (1) participants improved in creative ideation and rule-switching, and (2) adolescents benefitted more from training than adults, although this was independent of the type of training provided. The results are organized along these findings.

INITIAL DEVELOPMENTAL DIFFERENCES

Before interpreting the effects of training, it is important to consider potential age differences prior to training. The prediction was that adults and adolescents would perform equally well on most creativity measures, but that adults would outperform the adolescent group on originality (Wu et al., 2005; Kleibeuker et al., 2013a). We anticipated additional differences for general ideation with better performance for adults compared to adolescents, based on prior research (Kleibeuker et al., 2013b) and its close relation to verbal fluency performance (Romine and Reynolds, 2005). No initial differences were expected for RS performance (Huizinga et al., 2006).

Results for creative ideation in the 4-min AUT resembled previous findings in which adolescents performed at a mature level on most aspects of creativity, including fluency and flexibility.

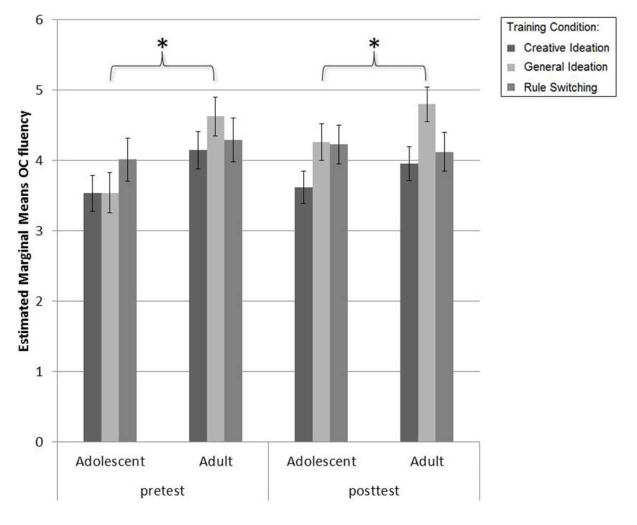

FIGURE 5 | Pretest to posttest progression for adults and adolescents on the general ideation measure of the combined Alternative Uses/Ordinary Characteristics task. Adults had higher mean OC fluency scores (number of ordinary characteristics listed) on average; however, no other main or interaction effects for session, age group or training condition were found in OC fluency performance. $^*p < 0.05$.

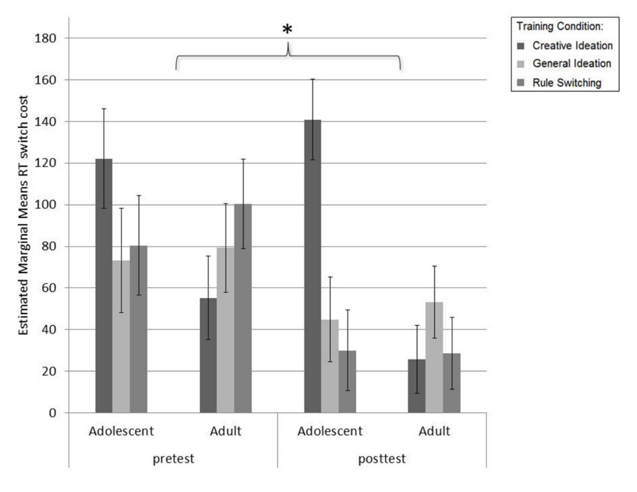

FIGURE 6 | Reaction time switch costs (ms) from pretest to posttest for adults and adolescents per training condition. Switch costs were significantly lower on posttest than pretest. Adolescents decreased marginally more in switch costs than adults. Individuals trained in rule-switching decreased marginally more than those trained in creative ideation or general ideation. *Post-hoc* comparisons of a significant Age × Condition effect did not reveal further differences. $^*p < 0.05$.

Also fitting earlier work, significant developmental differences were apparent on the measure of originality, with more original and unique solutions for adults compared to adolescents (see also Kleibeuker et al., 2013b). Different factors may account for these developmental differences. First, given their greater knowledgebase and more lifetime experience (e.g., Weisberg, 1999), adults have a greater chance of retrieving original and unique associations with presented objects. Also, individual lifestyles of adults generally involve larger inter-individual variance in experiences in comparison to adolescents. Consequently, adults are more likely to create relatively infrequent and unique associations and ideas. A second possible explanation for differences between age groups concerns developmental changes in flexible coordination between analytic and associative processing (Martindale and Hasenfus, 1978; Martindale, 1999; Christoff et al., 2009a,b), which is associated with functioning of prefrontal brain regions that develop throughout adolescence and into adulthood (Kerns et al., 2004; Kerns, 2006). Both analytic and associative processing are believed to lead to numerous creative ideas (Nijstad et al., 2010; De Dreu et al., 2012; Kleibeuker et al., 2013c); however, the quality of generated ideas has been related to the ability to flexibly coordinate between analytic and associative processing. Thus, adolescent participants may not yet have fully developed the ability to successfully shift between the two types of processing (Smolucha and Smolucha, 1986; see also Runco, 1991).

As predicted, we found developmental differences in fluency on general ideation. As with age related differences in creative ideation, and originality in particular, this effect could be explained by age related differences in experiences and knowledge base. A second explanation concerns the development of processes that are related to memory retrieval. These processes are associated with lateral prefrontal cortex activations (e.g., Buckner et al., 2008) and other brain regions that develop relatively late and mature throughout adolescence (Giedd et al., 1999; Fair et al., 2007). Consistent with prior studies no age related differences were observed for performance on the RS task (Huizinga et al., 2006), suggesting that cognitive flexibility is already at adult level in middle adolescence.

TRAINING EFFECTS

The applied training paradigm revealed several interesting findings. Participants improved in creative ideation and rule-switching. More specifically, the RS training group improved on the RS task, with larger performance increases relative to the other two training groups (e.g., Karbach and Kray, 2009). Training effects were also observed for creative ideation; however, contrary to what was observed for the RS training, these benefits were not specific to the creative ideation group. There were general increases for all training conditions on originality and fluency on the multiple object AUT. No improvements were observed for general ideation.

The general improvement in fluency and originality could be interpreted as follows. First, given that these effects were non-specific for training conditions, it is possible that the improvements for all three conditions, including the creative ideation training, simply reflect retesting effects instead of training effects. Indeed, some crucial aspects of the creative ideation task differed from the training paradigm such as duration (20 s vs. 2 min), way of answering (audio recording, typing), and task switches (alternative uses to ordinary characteristics vs. only one task during training). The task might therefore test processes that are different from those applied during the creative ideation training sessions. However, the correlations between the alternative uses training task and the two AUTs administered during pretest and posttest suggest that the improvements for the alternative uses

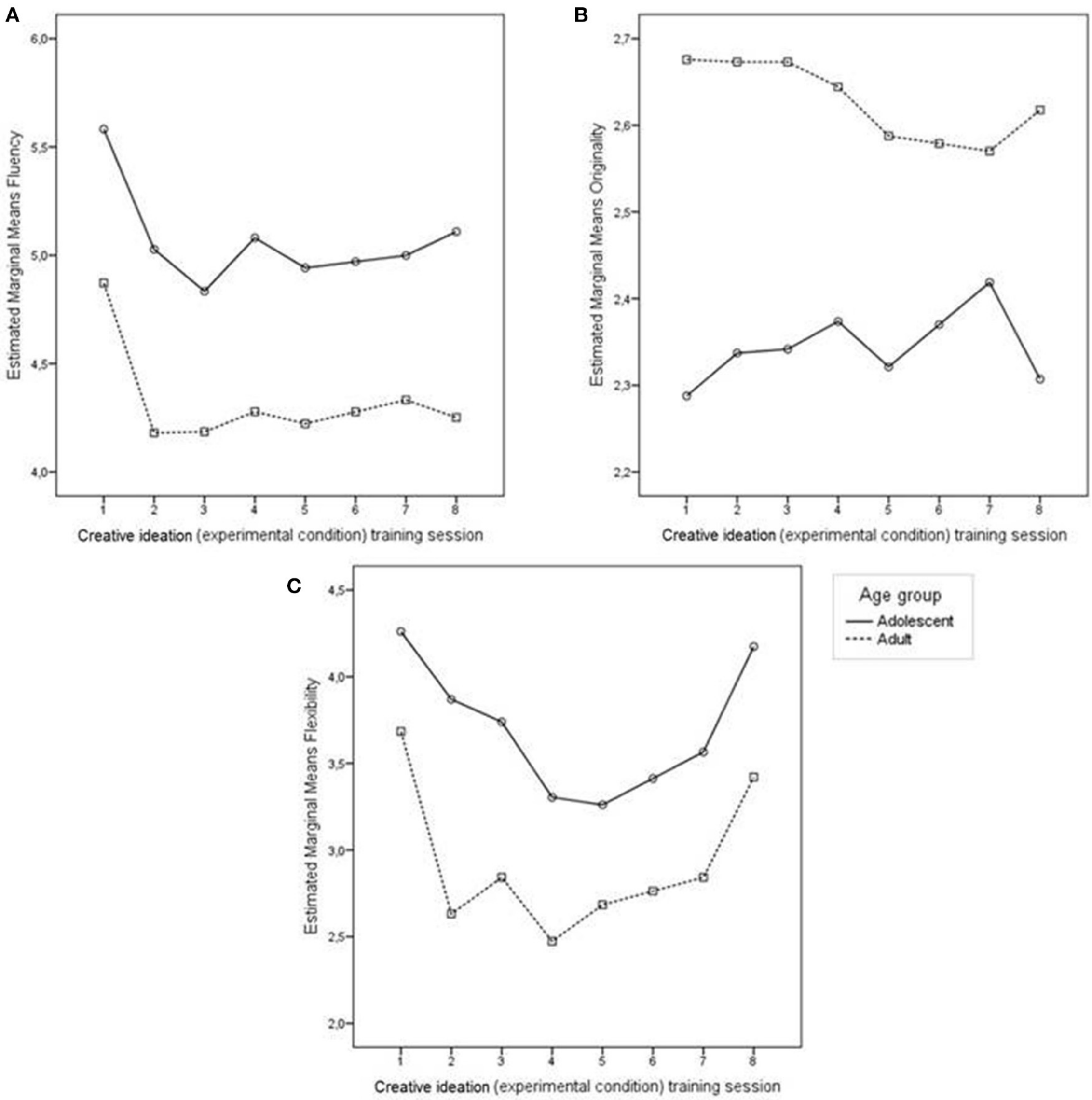

FIGURE 7 | Progression during Alternative Uses (experimental) training across sessions for adults and adolescents: (A) fluency (number of solutions), (B) originality (1 = "not original" to 5 = "highly original"), (C) flexibility (number of categories used in solutions). There were no significant age group differences in fluency. Adults scored higher on originality throughout the training sessions. Adolescents displayed greater flexibility during the course of the training.

training group are at least to some degree related to their practice with the AUT. Perhaps simply practicing with the AUT was not enough to elicit a discernible effect and more extensive training informing people about the nature of creativity and strategies for creative thinking (e.g., Speedie et al., 1971; Clapham, 1997; Scott et al., 2004) or providing exposure to ideas of others (Dugosh and Paulus, 2005; Fink et al., 2010) would improve the impact of creative ideation training. This hypothesis can be studied in future research by examining the effect of different types of training programs with AUTs of varying lengths. A second explanation may be that practice generating ordinary characteristics or with the rule-switching task may benefit generating alternative uses (performance) through improvements of processes that support creative ideation. Improvements in cognitive flexibility as practiced in the rule-switching condition may benefit generating alternative uses as well as switching between tasks during the combined alternative uses and ordinary characteristics task. Indeed, cognitive flexibility is thought to be important for creative performance (e.g., Warren and Davis, 1969; Gilhooly et al., 2007; Baas et al., 2008; De Dreu et al., 2008; Nusbaum and Silvia, 2011; Bott et al., 2014). Furthermore, originality and fluency in the generation of alternative uses could be enhanced by improving the ability to successively retrieve relevant semantic information from memory, i.e., general fluency as was the case during the ordinary characteristics task training. For example, creativity training in which participants were instructed to retrieve information about

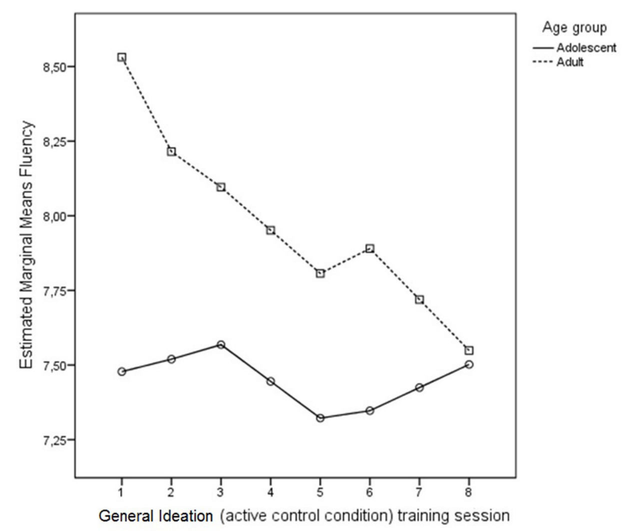

FIGURE 8 | Progression in number of solutions (fluency) during Ordinary Characteristics (active control) training across sessions for adults and adolescents. No age differences in fluency of ordinary characteristics ideation were found.

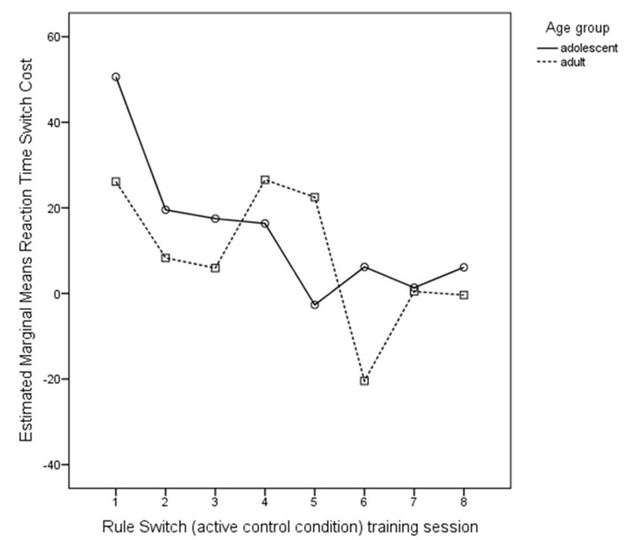

FIGURE 9 | Progression in reaction time switch costs (ms) during Rule-Switch (active control) training across sessions for adults and adolescents. No age differences in reaction time switch costs were found.

the parts that make up the object appeared to be effective (Warren and Davis, 1969). This role of our two active control tasks can be examined by administering the alternative uses and ordinary characteristics tasks separately.

DEVELOPMENTAL DIFFERENCES IN TRAINING EFFECTS

An important question in this study concerned whether training benefits would be larger for adolescents than adults. Interestingly, greater increases in originality and uniqueness were observed for adolescents compared to adults independent of training condition. These findings suggest that adolescence is a period of enhanced susceptibility for training effects. Indeed, prior research on cognitive training indicates that at least for certain higher cognitive functions, adolescents have greater potential for improvement than adults (Jolles and Crone, 2012). These developmental differences can be attributed to developmental changes in brain structure and function. Increasing specialization and integration of brain regions with age are argued to result in decreased plasticity of cognitive functions in adults compared to adolescents (Huttenlocher, 2003; Johnson, 2011; see also Jolles and Crone, 2012). Moreover, adolescence is a period associated with the reorganization of the prefrontal cortex and related regulatory systems (Keating, 2004; Steinberg, 2005). Given the strong associations between creative ideation, prefrontal cortex and cognitive control functionality (e.g., Groborz and Necka, 2003; Dietrich, 2004; Keating, 2004), adolescence provides a favorable time window for progression in creative ideation.

Another explanation concerns developmental differences in flexibility in learning. Recent rodent studies indicate that (young) adolescents, in comparison to adults, learn more flexibly; they are less prone to training induced perseverance and show greater flexibility in reversing learned associations (Johnson and Wilbrecht, 2011). Indeed, generating original ideas, especially through the *flexibility pathway,* is associated with flexible switching between (distant) associations and overcoming perseverance of cognitive biases or “functional fixedness” (Baas et al., 2008; Nijstad et al., 2010). This latter explanation particularly concerns training effects within the same domain, but also likely operates on associations formed during practice with the ordinary characteristics task. According to the flexibility hypothesis, adolescents would not or at least be less susceptible to training induced automaticity and perseverance.

A second age related finding concerns different effects of training paradigm for adults and adolescents on divergent thinking fluency and flexibility. More specifically, the current results indicate that task switch training in adolescents has a larger effect on creative ideation flexibility than in adults. These results suggest that adolescents and adults employ different processes or strategies to generate alternative uses, with more reliance on cognitive flexibility functions for the adolescent age group. Thereby, these findings provide further support for the hypothesis that adolescence is a developmental stage of increased flexibility optimized for adaptive and explorative behavior during this life phase of instability (Johnson and Wilbrecht, 2011; Crone and Dahl, 2012).

LIMITATIONS

Some limitations of this study deserve mention and can be informative for future research. First, the absence of a control group without training made it difficult to distinguish between re-test effects and training effects as well as examine the existence of transfer effects to posttests. Future studies should therefore incorporate a passive control group. Second, task choices may have obscured some of the training effects. The single object AUT (Tin Can and Brick) differed in difficulty and coding scheme and could not be directly compared to examine pretest to posttest change. Future studies would most likely benefit from implementing a multiple object assessment at each time point, which may represent a purer measure of creative ideation as individual differences in the necessary knowledge of the different objects is spread out thus reducing measurement error. Third, the current study does not provide information about long-term effects of the training. Retesting after, for example, a 6 month period would provide additional information on the effects of the different training paradigms and plasticity in adolescents, which might be especially informative for educational purposes. Fourth, the results were not controlled for motivation differences. Adolescence has been argued to be a developmental stage where motivation effects are more prominent than adulthood (Steinberg, 2005); therefore, incorporation of motivation questionnaires might provide insight into possible side effects of individual differences in motivation. Finally, this study focuses only on creative ideation in the verbal domain; in future studies other domains such as figural divergent thinking or visual insight should be investigated.

CONCLUSIONS AND FUTURE DIRECTIONS

In future research, it would be interesting to gain better understanding of the observed developmental differences in training effects also reflect underlying changes. It would be of particular interest to test whether the observed changes in creative thinking performance for the different types of training (alternative uses generation, ordinary characteristics retrieval, and rule-switching) are the consequence of changes in similar or perhaps different underlying functions. As such, future research could focus on training-related neuronal changes using (f)MRI, especially in prefrontal regions, known to be related to creative thinking (Keating, 2004). Moreover, it would be interesting to focus on age related effectiveness of different training paradigms. In the current study, 13–15 year olds were compared to 22–30 year olds. Testing a larger range of ages, including pre-adolescents and late adolescents, would provide a more detailed perspective of development-related limitations and opportunities in training of creative ideation. For the current study, our aim was to better understand the effects of practice only in adults and adolescents. An interesting addition could be informing people about the nature of creativity and strategies for creative thinking, or use an adaptive design, distinguishing between levels of task difficulty, both of which have been shown to be effective interventions (e.g., Speedie et al., 1971; Clapham, 1997), but knowledge about developmental differences in effectiveness is still lacking. Interestingly, the amount of feedback provided by the trainer had a substantial negative impact on the divergent thinking training effectiveness in earlier studies (Scott et al., 2004). However, peer feedback in the form of idea sharing (Paulus and Nijstad, 2003) and exposure to ideas from others (Dugosh and Paulus, 2005; Fink et al., 2010) does appear to enhance creativity. Adolescents react differently to feedback from peers than adults (Albert et al., 2013), thus an investigation into developmental differences in the effect of peer feedback could be another interesting addition to the creativity training literature.

The results of the current study not only contribute to the fundamental knowledge of cognitive development, but also provide possible implications with regard to creativity education and training. Indeed, the present results imply that adolescence is an advantageous period to enhance “out of the box” thinking and creative processes. Given the importance of creative thinking to individual life success and societal improvement (e.g., Ward et al., 1999), educators should take advantage of this sensitive period to improve divergent thinking skills.

In conclusion, the results support earlier findings in showing that practice in creative ideation is successful within the same domain (Scott et al., 2004) and supports the hypothesis that adolescence is a developmental stage of increased flexibility optimized for adaptive and explorative behavior during this instable life stage (Johnson and Wilbrecht, 2011; Crone and Dahl, 2012).

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Effects of optimism on creativity under approach and avoidance motivation

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Focusing on avoiding failure or negative outcomes (avoidance motivation) can undermine creativity, due to cognitive (e.g., threat appraisals), affective (e.g., anxiety), and volitional processes (e.g., low intrinsic motivation). This can be problematic for people who are avoidance motivated by nature and in situations in which threats or potential losses are salient. Here, we review the relation between avoidance motivation and creativity, and the processes underlying this relation. We highlight the role of optimism as a potential remedy for the creativity undermining effects of avoidance motivation, due to its impact on the underlying processes. Optimism, expecting to succeed in achieving success or avoiding failure, may reduce negative effects of avoidance motivation, as it eases threat appraisals, anxiety, and disengagement—barriers playing a key role in undermining creativity. People experience these barriers more under avoidance than under approach motivation, and beneficial effects of optimism should therefore be more pronounced under avoidance than approach motivation. Moreover, due to their eagerness, approach motivated people may even be more prone to unrealistic over-optimism and its negative consequences.

Keywords: optimism, motivation, approach, avoidance, creativity

In today's competitive and dynamic world, designing an environment that is optimal for creativity is a main concern of many organizations, workplaces, and educational settings. Creativity—i.e., generating ideas, insights, or solutions that are both novel and useful (Amabile, 1996), is a key ingredient of innovation, and is needed to adapt to changing technologies and demands, and to distinguish oneself or one's company from others (Oldham and Cummings, 1996; Simonton, 1999). Not surprisingly therefore, scientists and practitioners strive to identify conditions that influence creativity. One critical factor that impacts peoples' creative performance is the type of goals that drive their behavior. Previous research demonstrates that striving for positive outcomes or success (approach motivation) enhances creativity, whereas striving to avoid negative outcomes or failure (avoidance motivation) undermines it (Friedman and Förster, 2005; Elliot et al., 2009; Mehta and Zhu, 2009).

AVOIDANCE MOTIVATION AND CREATIVITY

Goals give direction to people's behavior toward positive outcomes or away from negative outcomes. The goals people adopt are influenced by individual differences; some people tend to focus more on avoidance goals and others more on approach goals (Elliot et al., 1997; Elliot and Thrash, 2010), but goals are also influenced by fluctuating situations. Whereas safe situations in which potential rewards or other positive outcomes are salient typically evoke approach motivation, threatening situations in which potential losses or other negative outcomes are dominant usually evoke avoidance motivation. Compared to approach motivation, avoidance motivation is associated with a host of psychological processes that undermine creativity. Indeed, evidence that avoidance motivation reduces creativity is abundant (e.g., Friedman and Förster, 2002, 2005; Elliot et al., 2009; Mehta and Zhu, 2009; Lichtenfeld et al., 2012). For example, in one study Friedman and Förster (2002) asked people to perform motor actions associated with approach motivation (i.e., arm flexion, a movement resembling bringing objects closer) or avoidance motivation (i.e., arm extension, resembling distancing objects). People in the approach compared to avoidance condition came up with more creative ways for using a brick.

Because creative solutions can be useful, and sometimes even necessary, to avert threats—for example, to repel an enemy or avoid bankruptcy—the relation between avoidance motivation and decreased creativity can be problematic. Consequently, identifying strategies to reduce the negative effects of avoidance motivation on creativity is important. Addressing the core psychological processes that underlie creativity, we propose that optimism may play a crucial role in remedying these negative effects. Our main argument is that optimism—i.e., expecting to succeed in achieving success or avoiding failure, moderates the relationship between motivational orientation and creativity. Specifically, we expect that optimism reduces the negative effects of avoidance motivation on creativity, as it reduces problematic psychological processes such as threat appraisals, anxiety, and disengagement. Because avoidance motivation is less problematic for non-creative tasks (e.g., those that require attention to detail), the positive effects of optimism should be less pronounced outside the domain of creativity. Additionally, the positive effects of optimism on creativity should be less pronounced when people

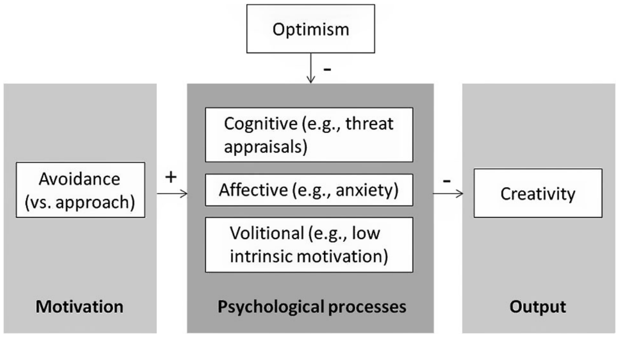

FIGURE 1 | By influencing the psychological processes that are evoked by avoidance motivation, optimism reduces the undermining effect of avoidance motivation on creativity.

are approach motivated. Approach motivation may even make people prone to over-optimism, and lead to reduced creativity (see **Figure 1** for the theoretical model).

In the following sections, we discuss optimism, approach and avoidance motivation, and creativity, and provide the rationale underlying our model. Specifically, we discuss: (1) the nature and consequences of optimism; (2) the psychological processes associated with approach and avoidance motivation and their relation to creativity; and (3) how optimism taps into each of these processes and moderates the relationship between motivation and creativity.

WHAT IS OPTIMISM?

The tendency to positively perceive the future seems to be an inherent aspect of human nature (Varki, 2009; Sharot, 2011). Indeed, people often overestimate potential positive events in their future, while underestimating negative events (e.g., Hoorens et al., 2008; Waters et al., 2011; Shepperd et al., 2013). Scheier and Carver (1985) describe optimism as a generalized tendency to expect positive outcomes even in the face of obstacles. According to this view, optimists expect good things to happen in the future and therefore actively strive to achieve their goals. Buchanan and Seligman (1995) describe optimism in terms of how people explain bad events in their past. According to this view, optimists explain bad events with external, unstable, and specific causes, whereas pessimists explain bad events with internal, stable, and global causes. The extent to which people tend to be optimistic varies across individuals (e.g., Carver and Scheier, 2002; Icekson and Pines, 2012). Additionally, situational factors influence optimism. For example, asking people to generate positive thoughts about their future boosts optimism temporarily (Fosnaugh et al., 2009).

Optimistic individuals believe they can overcome obstacles and perceive difficult tasks as challenges rather than threats (Smith et al., 1993; Chang, 1998). Optimism stimulates persistence in goal pursuit (Brown and Marshall, 2001), and enhances psychological and physical adjustment to stressful events (Carver et al., 2010). Beyond the obvious benefits to health and wellbeing, optimism enhances performance in the academic (Chemers et al., 2001; Nes et al., 2009), athletic (Gould et al., 2002; Gordon, 2008), work (Seligman and Schulman, 1986; Kluemper et al., 2009), and creative domain (Rego et al., 2012).

Despite the notable advantages of having a positive lookout, overly positive expectations sometimes have negative consequences and lead to poorer performance. Optimistic individuals tend to underestimate potential threats and obstacles, take risks, and persist in investing in hopeless endeavors (Felton et al., 2003; Trevelyan, 2008; Hmieleski and Baron, 2009). Optimists, for example, are more likely than pessimists to continue gambling after losing money (Gibson and Sanbonmatsu, 2004).

Optimism thus can have positive but also negative effects on performance. Here, we propose that for creative performance the positive effects of optimism are particularly likely to manifest themselves when people are avoidance motivated. When people are approach motivated, these positive effects should be less prominent, and negative effects of over-optimism are more likely to occur. It is likely that there is a negative relation between trait avoidance motivation and trait optimism. However, even when people are avoidance motivated (due to individual differences or situational cues), levels of optimism about successfully avoiding specific negative outcomes vary across situations. For example, someone may be rather optimistic about the likelihood of not failing an exam, but less optimistic about the likelihood of not getting hurt on a skiing trip. In the following, we review the psychological processes that are evoked by avoidance motivation, and discuss how optimism may reduce negative effects of these processes on creativity.

OPTIMISM, A RECIPE FOR CREATIVITY UNDER AVOIDANCE MOTIVATION

Compared to approach motivation, avoidance motivation is associated with a host of cognitive, affective, and volitional processes that can undermine creative performance (for a thorough review of these processes see Elliot et al., 2013). Here we discuss why these processes influence creativity, and how optimism impacts each of these processes and may thereby mitigate negative effects of avoidance motivation.

COGNITIVE PROCESSES

According to *Cognitive Appraisal* theories (Lazarus and Folkman, 1984) demanding tasks or situations are evaluated according to subjective perceptions of demands and available resources. When demands exceed resources, situations are evaluated as threats. However, when situations are taxing yet rewarding, they are perceived as challenges. When people are approach motivated, they tend to appraise situations in terms of challenges, whereas when they are avoidance motivated they tend to appraise situations in terms of threats. Approach motivation and the associated challenge appraisals evoke flexible and associative information processing, which enhances creativity (Baas et al., 2008; Gutnick et al., 2012). Avoidance motivation and the associated threat appraisals, on the other hand, evoke persistent and systematic information processing (Friedman and Förster, 2002; Friedman and Elliot, 2008). This persistent processing style does not render creativity impossible, but makes it more difficult and effortful. In order to achieve creative output, people need to exert focused effort to compensate for their inflexible processing style (Roskes et al., 2012, 2013). Therefore, avoidance motivation often reduces creativity (Friedman and Förster, 2002, 2005; Mehta and Zhu, 2009). In the best case scenario, when avoidance motivated people are willing to go the extra mile and invest effort into creative performance, they are as creative as approach motivated people (at least in the short term) but end up tired and depleted (Roskes et al., 2012; Ståhl et al., 2012). Threat appraisals, thus, are suboptimal when striving for creative output.

Optimism increases the likelihood of perceiving demanding situations as challenging rather than threatening (Smith et al., 1993; Chang, 1998). Consequently, when people are avoidance motivated, optimism about the likelihood of avoiding negative outcomes may reduce threat appraisals and enhance challenge appraisals (e.g., using cognitive therapy; Gardner et al., 2005). These reduced threat and enhanced challenge appraisals, in turn, should stimulate cognitive flexibility, thereby increasing creativity (Gutnick et al., 2012). When people are approach motivated, they already tend to appraise situations as challenges and engage in flexible processing. Therefore, optimistic beliefs about their abilities to attain positive outcomes should not enhance their creativity as much.

AFFECTIVE PROCESSES

Approach motivation is experienced as a positive state in which positive emotions such as joy and excitement are easily elicited (Pekrun et al., 2009).

In contrast, striving to avert negative outcomes evokes anxiety, worry, and fear of failure (Gable et al., 2000; Eysenck et al., 2007). These negative emotions narrow people's attention scope and impede cognitive flexibility (Baas et al., 2008; De Dreu et al., 2008). Optimism may enhance creativity among avoidance motivated people by moderating the hedonic tone of affective reactions, thereby broadening the attention scope. Optimism is inversely related to tension and worry. First, it influences neuroendocrine regulation by decreasing the secretion of stress hormones (Lai et al., 2005; Endrighi et al., 2011). For example, optimism decreases the association between stress perceptions and elevated levels of cortisol (Jobin et al., 2013). Second, optimism intensifies positive emotions such as enthusiasm and happiness (Hodges and Winstanley, 2012) and attenuates negative emotions such as sadness and fear (Lucas et al., 1996; Siddique et al., 2006). When people are avoidance motivated, stimulating optimism about the likelihood of achieving avoidance goals can mitigate negative affect and in doing so increase creativity. Again, when people are approach motivated, and are already experiencing little negative affect, this positive effect of optimism should be reduced.

VOLITIONAL PROCESSES

When people strive to avoid negative outcomes (e.g., avoid losing one's job, embarrassing oneself, or performing worse than others), there is no positive end state to look forward to. The best outcome of avoidance goal achievement is the absence of negative outcomes, which can be important, but doesn't provide much fuel for excitement or intrinsic motivation. Avoidance goal striving can therefore be experienced as an obligation—something one *has* to do (Higgins, 1997; Carver et al., 2000; Ryan and Deci, 2006). For creativity, intrinsic motivation, the feeling that one's actions have meaning and purpose, is crucial (Amabile, 1983; Friedman, 2009). The low intrinsic motivation involved in avoidance goal pursuit, is thus another factor undermining creativity. Additionally, because creativity is relatively effortful for them, avoidance motivated people only invest in creativity when this is perceived as necessary for avoiding failure or averting losses (Roskes et al., 2012). When people are avoidance motivated, they need to be actively stimulated and convinced that their creative efforts will be useful. Finally, when people focus on avoiding negative outcomes rather than achieving positive ones, they are more liable to engage in simple tasks in which failure is unlikely and to withdraw effort (i.e., "self-handicapping") to protect themselves from demonstrating low ability (Alicke and Sedikides, 2009; Righetti et al., 2011).

Optimism may buffer against the negative effects of avoidance motivation on these volitional processes. Optimism enhances proactive and persistent goal pursuit, and reduces the urge to disengage or give up. For example, highly optimistic HIV, cancer, and cardiac patients were more likely to seek information about their condition and make plans for recovery than less optimistic patients (Carver et al., 2010; Forgeard and Seligman, 2012). Moreover, optimism increases willingness to invest effort and persist, even when facing adversity (Carver et al., 2010). Optimism may thus increase engagement, proactive goal pursuit, and willingness to invest effort, which should particularly benefit creativity when people are avoidance motivated.

To summarize, avoidance motivation is associated with cognitive, affective, and volitional processes that can be problematic when striving for creativity. Due to its impact on each of these processes, optimism is a good candidate for stimulating creativity under avoidance motivation.

OPTIMISM, A SUPPRESSOR OF CREATIVITY UNDER APPROACH MOTIVATION?

Both approach motivation and optimism are associated with challenge appraisals, cognitive flexibility, excitement, and intrinsic motivation, which are conducive to high levels of creativity. Intuitively, we may therefore expect the combination of approach motivation and optimism to be optimal for creativity. However, a closer look at the processes involved suggests that this may not always be the case. When people are approach motivated, they tend to focus on potential gains and overlook obstacles and dangers. They pay less attention to threatening cues and feel more confident about achieving their goals (Elliot, 1999). Under avoidance motivation, optimism may provide balance, and help to see beyond threats and difficulties. However, under approach motivation optimism may tip the scales into the direction of over-optimism with its associated negative consequences.

Indeed, high levels of optimism are related to an attentional bias toward positive stimuli, ignoring contradictions, and neglecting threatening information (Segerstrom, 2001; Geers and Lassiter, 2002; Geers et al., 2003; Isaacowitz, 2005). This prevents people from taking precautionary behaviors. For example, Weinstein and Lyon (1999) found that highly optimistic homeowners living in a high radon risk area underestimated their personal health risks, and consequently were less likely to purchase radon test kits. Moreover, over-optimism can be detrimental for performance; for instance, overly optimistic students perform worse than moderately optimistic students. Similarly, negative effects of high levels of optimism on academic performance only occurred for students that have low conscientiousness, a personality trait characterized by self-discipline (Icekson and Kaplan, working paper). Additionally, discounting of negative feedback when working on creative tasks, may lead to the generation of original, but not very useful ideas. This is problematic, because to be considered creative, ideas need to be both novel and useful. These pieces of evidence suggest that the risk for over-optimism may be greater when people are approach rather than avoidance motivated.

When people are approach motivated, high optimism may undermine creative performance, due to reduced preparation, effort, and discounting of negative but relevant information. In sum, we suggest that the risk for unrealistic positive expectations may be larger when people are approach motivated and have their eyes on the prize, rather than on the obstacles along the way. Consequently, their creativity may be undermined.

IMPLICATIONS AND DIRECTIONS FOR FUTURE RESEARCH

Avoidance motivation makes creativity difficult and often undermines it, due to a variety of psychological processes that are discussed in this paper. Thorough understanding of the processes that enhance and impair creativity under approach and avoidance motivation, will enhance creativity and motivation theory, and enable to develop interventions aimed at stimulating creativity (also see Roskes, in press; Roskes et al., in press).

From a practical perspective, eliciting optimism among people who are avoidance motivated should stimulate creativity. This can be done by designing environments in ways that enhance optimism, or by directly training individuals to adopt more optimistic views. For example, managers can adapt their leadership style to communicate their positive vision to followers. Such positive expectations of leaders can instill optimism in their subordinates (McColl-Kennedy and Anderson, 2002). Optimism can also be stimulated by individual level interventions, as demonstrated by cognitive therapy or by exercises like "the best possible self" (BPS), which requires to envision oneself in an imaginary future where everything turned out in the most optimal way (King, 2001; Gardner et al., 2005; Meevissen et al., 2011). When people are approach motivated, stimulating optimism is less needed to stimulate creativity. First, because approach motivated people are inherently more likely to be optimistic, and second because they may be at risk for the negative consequences of over-optimism. While optimism should be boosted among avoidance motivated people, approach motivated people may instead benefit from being cautioned.

From a theoretical perspective, it is important to study the processes that play a role in predicting creativity under approach and avoidance motivation more thoroughly. For clarity, cognitive, affective, and volitional processes involved in creativity have been discussed separately in this paper. However, many of these processes are inherently interdependent. Threat appraisals, for example, are closely related to negative emotions (Lazarus, 1999), physiological stress responses (Seery, 2011), and reduced intrinsic motivation (Drach-Zahavy and Erez, 2002), whereas challenge appraisals are related to positive affect (Skinner and Brewer, 2002) and enhanced effort and motivation (Drach-Zahavy and Erez, 2002). Future research is needed to disentangle the roles of the various processes in shaping effects of approach and avoidance motivation on creativity, and to deepen our understanding regarding optimal levels of optimism. This will help to build theory, and to identify potential factors that impact these processes and can ameliorate the negative effects of avoidance motivation on creativity.

CONCLUSION

Focusing on avoiding failure or negative outcomes can undermine creativity, due to cognitive (e.g., threat appraisals), affective (e.g., anxiety), and volitional processes (e.g., low intrinsic motivation). This can be problematic for people who are avoidance motivated by nature and in situations in which threats or potential losses are salient. Optimism positively impacts each of the problematic processes evoked by avoidance motivation, and should thus reduce the undermining effect on creativity. We further suggest that optimism may suppress the positive relation between approach motivation and creativity. More broadly, we propose that for effectively stimulating creative performance, it is important to address the core psychological processes underlying creativity and identify factors that influence these processes.

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The scientific study of inspiration in the creative process: challenges and opportunities

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Inspiration is a motivational state that compels individuals to bring ideas into fruition. Creators have long argued that inspiration is important to the creative process, but until recently, scientists have not investigated this claim. In this article, we review challenges to the study of creative inspiration, as well as solutions to these challenges afforded by theoretical and empirical work on inspiration over the past decade. First, we discuss the problem of definitional ambiguity, which has been addressed through an integrative process of construct conceptualization. Second, we discuss the challenge of how to operationalize inspiration. This challenge has been overcome by the development and validation of the Inspiration Scale (IS), which may be used to assess trait or state inspiration. Third, we address ambiguity regarding how inspiration differs from related concepts (creativity, insight, positive affect) by discussing discriminant validity. Next, we discuss the preconception that inspiration is less important than "perspiration" (effort), and we review empirical evidence that inspiration and effort both play important—but different—roles in the creative process. Finally, with many challenges overcome, we argue that the foundation is now set for a new generation of research focused on neural underpinnings. We discuss potential challenges to and opportunities for the neuroscientific study of inspiration. A better understanding of the biological basis of inspiration will illuminate the process through which creative ideas "fire the soul," such that individuals are compelled to transform ideas into products and solutions that may benefit society.

Keywords: inspiration, creativity, insight, effort, approach motivation

INTRODUCTION

Describing his creative process, Mozart observed, "Those ideas that please me I retain in memory, and am accustomed, as I have been told, to hum them to myself. If I continue in this way," he writes, "it soon occurs to me how I may turn this or that morsel to account so as to make a good dish of it... All this fires my soul" (Harding, 1948). Mozart's depiction of inspiration possesses all of the core elements of the modern scientific inspiration construct—appreciation of new or better possibilities ("ideas that please me"), passive evocation ("it...occurs to me"), and motivation to bring the new possibilities into fruition (turning a morsel into a dish; "fires my soul"). Like Mozart, writers, artists, and other creators commonly emphasize the importance of inspiration in the creative process (Harding, 1948). Despite this, until recently, scientists have given little attention to inspiration.

Perhaps it is not surprising that inspiration has received little attention within the scientific community, given the numerous challenges that the inspiration concept has presented. Among these challenges have been (a) a lack of clarity about the meaning of inspiration; (b) difficulty of operationalization; (c) ambiguity about whether inspiration is distinct from related constructs; (d) preconceptions that inspiration is unimportant relative to "perspiration," and (e) a variety of barriers to neuroscientific investigation. The overarching goal of this article is to address each of these challenges and to point to opportunities for expanding upon the emerging scientific literature on inspiration. We address the first challenge, ambiguity of definition, in the next section.

CONCEPTUALIZATION

The term "inspiration" has been used in a variety disciplines (e.g., literary criticism, theology, psychology) and literatures within psychology (e.g., social comparison, humanism, creative process; for a review, see Thrash and Elliot, 2003). Often the term is not defined, is used interchangeably with other constructs, or is referenced only to be critiqued as mythical, unimportant, or unscientific. Further complicating matters, inspiration historically has been studied in a domain-specific manner, with little communication between researchers across domains. Recognizing the need for a unified, integrated definition of the inspiration construct, Thrash and Elliot (2003, 2004) undertook the task of developing a domain-general conceptualization that drew upon the core commonalities across diverse literatures. These efforts have yielded three complementary frameworks for conceptualizing inspiration that focus on different aspects of construct definition: core characteristics, component processes, and the transmission model. In this section, we review these domain-general conceptualizations and then show how they may be applied specifically to the case of inspiration to create.

TRIPARTITE CONCEPTUALIZATION

The *tripartite conceptualization* (Thrash and Elliot, 2003) specifies the three core characteristics of the state of inspiration: *evocation*, *transcendence*, and *approach motivation*. Evocation refers to the fact that inspiration is *evoked* rather than initiated volitionally by the individual. In other words, one does not feel directly responsible for becoming inspired; rather, a stimulus object, such as a person, an idea, or a work of art, evokes and sustains the inspiration episode. During an episode of inspiration, the individual gains awareness of new possibilities that *transcend* ordinary or mundane concerns. The new awareness is vivid and concrete, and it surpasses the ordinary constraints of willfully generated ideas. Once inspired, the individual experiences a compelling *approach motivation* to transmit, actualize, or express the new vision. This set of three characteristics is intended to be minimally sufficient to distinguish the state of inspiration from other states.

COMPONENT PROCESSES

Inspiration may be conceptualized not only in terms of the characteristics of the inspired state, but also in terms of the temporally and functionally distinct processes that compose an episode of inspiration. Thrash and Elliot (2004) argued that inspiration involves two distinct processes—a relatively passive process that they called being inspired *by*, and a relatively active process that they called being inspired *to*. The process of being inspired *by* involves appreciation of the perceived intrinsic value of a stimulus object, whereas the process of being inspired *to* involves motivation to actualize or extend the valued qualities to a new object. For example, one might be inspired by a breathtaking sunrise, or by the elegance of a new idea that arrives during an insight or "aha" moment. Thereafter one might be inspired to paint or undertake a new research project. The individual can, at any time, look to (or recall) the evoking stimulus for motivational sustenance. Thrash and Elliot (2004) further proposed that the process of being inspired *by* gives rise to the core characteristics of evocation and transcendence, whereas the process of being inspired *to* gives rise to the core characteristic of approach motivation.

These component processes are posited to be present across diverse manifestations of inspiration. Thrash and Elliot (2004) asked participants to produce narratives recalling either a time when they were inspired or a baseline experience (control condition). The inspiration narratives spanned topics such as becoming animated by a scientific or artistic insight, discovering one's calling, being influenced by a role model to succeed or live virtuously, and realizing that greatness is possible in response to an unexpected success. Despite superficial differences in narrative content, the inspiration narratives shared the underlying themes of having one's eyes opened during an encounter with a person, object, event, or idea (i.e., being inspired "by"), and wishing to express or actualize one's new vision (i.e., being inspired "to").

TRANSMISSION MODEL

From a less descriptive and more theoretical standpoint, inspiration may be conceptualized in terms of its purpose or function (Thrash and Elliot, 2004; Thrash et al., 2010b). Whereas simpler forms of approach motivation serve the function of movement toward and attainment of desired goal objects (e.g., food or affiliation), inspiration is posited to serve a unique approach function: it motivates the transmission or expression of the newly appreciated qualities of the evoking object (Thrash and Elliot, 2004; Thrash et al., 2010b). Inspiration thus serves the role of a mediator in a statistical sense. For instance, certain virtues that one observes in another person may lead to inspiration, which, in turn, leads the inspired individual to pursue these same virtues in a future self. Similarly, a creative seminal idea may inspire the individual, compelling him or her to bring the idea into fruition in the form of a creative invention, poem, or other tangible product.

INSPIRATION TO CREATE

The general inspiration construct as conceptualized above may be applied straightforwardly to the specific domain of creative activity. From the perspective of the tripartite conceptualization, the general characteristic of transcendence takes the form of *creativity*—the new or better possibilities are appreciated specifically for their creative potential. Regarding the component process conceptualization, the process of being inspired *by* is prompted by the emergence of creative ideas in consciousness, often during a moment of insight. Under optimal conditions (e.g., if the idea is actionable, and the person has the capacity for approach motivation), the process of being inspired *by* gives way to the process of being inspired *to*, which motivates action. Regarding the transmission model, creative inspiration often takes a specific form of transmission called *actualization* (Thrash et al., 2010b), in which one is inspired to bring a creative idea into fruition (i.e., the desirable features of the elicitor are transmitted from a seminal idea to a completed product).

We emphasize that, according to our conceptualization, inspiration is not posited to be the *source* of creative ideas. Instead, inspiration is a motivational *response* to creative ideas. Thus inspiration explains the transmission, not the origin, of creativity. This distinction is critical for at least three reasons. First, claiming that creativity comes from inspiration would not aid scientific understanding, much as attributing creativity to a "muse" would be an exercise in labeling a mysterious cause, not a scientific explanation. Second, scientists have already developed a variety of scientific constructs and theories to explain the origins of creative ideas, which include situational, dispositional, self-regulatory, cognitive, historical, and neurological processes (e.g., Koestler, 1964; Rothenberg, 1979; Martindale, 1990; Finke et al., 1992; Sternberg and Davidson, 1995; Amabile, 1996; Feist, 1998; Bowden and Jung-Beeman, 2003; Simonton, 2003; Baas et al., 2013). In contrast, scientists have given relatively little attention to the processes through which creative ideas are transformed into creative products. The inspiration construct helps fill this gap in the research literature. Finally, because this conceptualization of creative inspiration is derived from a general conceptualization, it is consistent with usage of the inspiration construct in other literatures. For instance, creative inspiration is a response to (not the cause of) creative ideas, much as interpersonal inspiration is a response to (not the cause of) virtuous qualities in others.

OPERATIONALIZATION

Given the personal nature and elusiveness of the experience of inspiration, how can it possibly be measured in the laboratory? One might be tempted to throw up one's hands and turn instead to something that is more amenable to direct experimental control.

THE VALUE OF SELF-REPORT

We maintain that self-report is a straightforward and appropriate method for operationalizing inspiration, because the inspiration construct is inextricably intertwined with a distinctive phenomenological experience. Numerous creators have claimed—through conscious self-reports—that they experience inspiration and that this experience is critical to their creative process (Harding, 1948). Operationalizing inspiration through self-report allows researchers to put such claims to the test.

Thrash and Elliot (2003) developed a trait measure of inspiration called the Inspiration Scale (IS). Although the term "trait" has a variety of connotations, trait inspiration refers to nothing other than individual differences in the tendency to experience the state of inspiration. Because inspiration is a construct that is meaningful in individuals' lives but underappreciated by psychologists, the measure was designed to be straightforward and face valid. Items include statements such as, "Something I encounter or experience inspires me" and "I am inspired to do something." The IS has two internally consistent 4-item subscales: inspiration frequency and intensity. Both subscales are internally consistent, with Cronbach's αs equal to or greater than 0.90. The two subscales have been demonstrated to be highly correlated ($r = 0.60$ to 0.80), and therefore scores may be summed to form an internally consistent 8-item index of overall inspiration. The IS demonstrates measurement invariance across time (2 months) and across populations (patent holders, university alumni), indicating that the underlying latent constructs have comparable meaning at different points in time and in different populations. Two-month test-retest reliabilities for both subscales are high, $r = 0.77$. In short, the IS has excellent psychometric properties. Notably, the intensity subscale has been adapted for use as a state measure (e.g., Thrash and Elliot, 2004; Thrash et al., 2010a).

Some may worry that self-reported inspiration cannot be trusted, that it is not objective, or that it does not provide a full explanation. We respond to each of these potential limitations. First, inspiration, as assessed with the IS, tends to be unrelated or weakly related to social desirability, and its predictive validity is robust when social desirability is controlled[1] (Thrash and Elliot, 2003; Thrash et al., 2010a). Second, although the IS provides a subjective indicator of inspiration, scores on this measure have been linked to a variety of external criteria and objective outcomes, as reviewed in the following section. Moreover, consciousness plays a critical role in the simulation of future action in humans (Baumeister and Masicampo, 2010) and may be necessary for inspired action. Accordingly, conscious self-report is intrinsically appropriate to the construct. Finally, we recognize that self-report measures may leave some researchers with a hunger for lower-level explanations, such as those involving physiological or neurological processes, but we see this as an opportunity rather than a problem—the inspiration construct may see an exciting second generation of research regarding neural underpinnings. In this case, self-reported inspiration provides a "bootstrap" that may guide researchers to underlying process. Although it is true that the self-report method is limited in some ways, it offers a well-validated starting point for neuroscientific investigations. Moreover, not investigating inspiration on the grounds that it is measured by self-report would lead researchers to overlook a critical predictor of creative output, the biological underpinnings of which would remain undiscovered.

THE PLACE OF INSPIRATION IN CREATIVITY RESEARCH PARADIGMS

The field of creativity assessment is active and dynamic, and thus a review of the literature is well beyond the scope of this article (for a review, see Plucker and Makel, 2010). We note, however, that the dominant research paradigms used in the study of creativity have unwittingly precluded attention to inspiration. Creativity is most often assessed using tests of creative ideation (e.g., Alternate Uses) or creative insight (e.g., Remote Associates Test). While such tests are very practical in laboratory contexts and allow researchers to focus on the processes underlying the emergence of creative ideas, they do not allow participants to transform creative ideas into creative products. Failure to accommodate the idea actualization process—that is, creation *per se*—renders inspiration speciously immaterial to the creative process. If the function of inspiration within the context of creativity is the actualization of creative ideas into creative products, useful paradigms must allow for idea actualization. Product-based assessments, such as the Consensual Assessment Technique (CAT; Amabile, 1982) and analysis of patent data, are the gold standard if one wishes to investigate the unique contribution of inspiration to the creative process.[2] In fact, relevance to inspiration aside, assessment of creative products is considered by some to be the most appropriate and valid operationalization of creativity (Baer et al., 2004; Baer and McKool, 2009).

DISCRIMINANT VALIDITY

Ambiguity about whether inspiration is distinct from other constructs has been another impediment to research activity. If one presumes that inspiration is the same thing as, for example, creativity or insight, then one has no reason to study it. In this section, we clarify the distinctions between inspiration and several other constructs (creativity, insight, and positive affect).

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[1] In these instances, social desirability was assessed using either the Marlowe-Crowne Social Desirability Scale (Crowne and Marlowe, 1960) or the Paulhus Deception Scales (Paulhus, 1998).

[2] We note that the Consensual Assessment Technique has also been used to assess the creativity of ideas (e.g., Faure, 2004). Here, we refer specifically to the use of this technique in assessing the creativity of products.

INSPIRATION AND CREATIVITY

While there is considerable variability in the definition and usage of the term creativity within psychology (Silvia and Kaufman, 2010), there is some degree of consensus that creativity implies two qualities: novelty and usefulness (e.g., Feist, 1998; Plucker et al., 2004). We find it useful to explicitly conceptualize creativity as an *appraisal* of novelty and usefulness that may be applied to any of a variety of objects, particularly ideas and resulting products. Depending on the aims of the research, this appraisal may be made by the creator herself, by gatekeepers within a field, by an audience, or through various other operationalizations available to the researcher. We note that researchers often appear to have either ideas or products in mind as the ultimate objects of creativity appraisals, even when the term "creative" precedes other nouns (e.g., creative activity (Simonton, 2000), creative insights (Csikszentmihalyi and Sawyer, 1995), creative personalities (Feist, 2010), creative states (Jamison, 1989), or creative processes (Kris, 1952)).

Although the terms inspiration and creativity have occasionally been used synonymously (e.g., Schuler, 1994; Chamorro-Premuzic, 2006), our conceptualizations of inspiration and creativity involve a clear delineation. Creativity is an appraisal of novelty and usefulness that may apply (to various degrees) to content at any point in the creative process, from a seminal idea to the completed product. Inspiration, in contrast, is a motivational state. We posit that inspiration is often elicited when a creator appraises his or her idea as creative, and it is posited to motivate actualization of the idea in the form of a product that is likewise appraised (by its creator and perhaps others) as creative. We discuss empirical support for these proposals below.

INSPIRATION AND INSIGHT

Conflation of inspiration with insight is common in everyday language.[3] An individual might exclaim, "I had an inspiration," where "inspiration" refers to the idea itself, not to the motivational response. In the scientific context, the term insight has been used to describe the process by which a problem solver suddenly moves from a state of not knowing how to solve a problem to a state of knowing how to solve it (Mayer, 1992). Within the creativity context, insight has also been conceptualized as the cognitive content that enters consciousness suddenly; the "aha!" moment (Csikszentmihalyi and Sawyer, 1995). Regardless of its exact usage, insight can be differentiated from inspiration in terms of its theoretical function. Whereas insight research is an attempt to explain the cognitive mechanisms, such as restructuring (Ohlsson, 1984), by which ideas enter awareness, inspiration research is an attempt to explain the motivational response that often (but not always) follows creative insight (see Thrash et al., 2010b).

If inspiration always followed from insight, then perhaps the inspiration construct would be superfluous. However, inspiration does not always follow. Thrash et al. (2010b) found that creative ideation tends to lead to inspiration but that this effect is moderated by individuals' approach temperament (i.e., sensitivity to reward; Elliot and Thrash, 2010). Individuals with a strong approach temperament tend to get inspired to create in response to creative insight, whereas individuals with a weak approach temperament report feeling a lack of inspiration in spite of their insight. Inspiration thus has important implications for the behavioral transmission of a creative insight into a creative product.

Recent work on the phenomenology of insight offers hints about how insight may lead to inspiration. Abrupt changes in processing fluency during insight have been found to endow an individual with elevated levels of positive affect (PA) and perceived truth regarding his or her solution (Topolinski and Reber, 2010). Given that PA is involved in both the insight "aha" experience and inspiration, it may facilitate a fluid transition from insight to inspiration. Moreover, perceiving one's solution as true, a consequence of insight, may bolster inspired motivation. As we have noted, however, insight can occur without inspiration. Dispositional factors of the individual (e.g., low approach temperament) and situational factors (e.g., contexts in which opportunities for transmission are not available) can impede inspiration. Likewise, inspiration can occur outside of the problem-solving context and without a discrete and sudden insight.

INSPIRATION AND POSITIVE AFFECT

Activated PA, a high-arousal form of pleasant affect, is the strongest known correlate of inspiration (Thrash and Elliot, 2003). Indeed, the term "inspired" appears on the PANAS measure of activated PA (Watson et al., 1988). Because activated PA is often present during states of approach motivation (Watson et al., 1999), it particularly resembles the inspired *to* component process.

Although inspiration and activated PA overlap to some degree empirically and conceptually, considerable evidence supports their discriminant validity. First, inspiration and activated PA are factorially distinct (Thrash and Elliot, 2003). Second, consistent with the tripartite conceptualization of inspiration, experiences of inspiration involve greater levels of transcendence and lower levels of volitional control and ascriptions of personal responsibility (indicative of "evocation") compared to experiences of activated PA (Thrash and Elliot, 2004). Third, inspiration and activated PA have different proximal and distal antecedents (Thrash and Elliot, 2004). Activated PA is triggered proximally by reward salience (environmental cues and perceptions that something desired is attainable) and distally by approach temperament. In contrast, inspiration is triggered proximally by experiences of insight and distally by openness to experience. Finally, inspiration and activated PA have different distributions across days of the week; on Fridays, for instance, activated PA is at its peak while inspiration is at its trough (Thrash, 2007).

INSPIRATION, PERSPIRATION, AND CREATIVITY

Perhaps the most pernicious obstacle to research on inspiration has been the longstanding belief that it is perspiration, and not inspiration, that is critical for creative output. Thomas Edison,

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[3] The language of the items and response options of the Inspiration Scale (IS) eliminate this problem by clearly using the term "inspiration" to mean a state, not a cognition or idea.

regarding his work, once remarked that, "what it boils down to is one per cent inspiration and ninety-nine per cent perspiration" (Edison, 1903). This comment has sometimes been offered in support of the idea that effort is important to creativity and that inspiration, by comparison, is unimportant (e.g., Martindale, 1989, 2001; Sawyer, 2006). Furthering this line of reasoning, Fehrman and Petherick (1980) offered an account of why inspiration nonetheless endures as a folk explanation of creativity: when individuals are exposed to creative works, they misattribute creators' effort to inspiration, unaware how much effort was required to produce the work. It appears that reasoning such as this has precluded attention to a legitimate role of inspiration in the creative process.

Empirical data related to inspiration, perspiration, and creativity are now available for consideration. A number of studies indicates that inspiration is a robust predictor of creativity. At the between-person (i.e., trait) level, inspiration and creative self-concept are positively correlated, and inspiration predicts longitudinal increases in creative self-concept (Thrash and Elliot, 2003). Trait inspiration also predicts objective indicators of creative output. In a sample of U.S. patent holders, inspiration frequency was found to predict the number of patents held (Thrash and Elliot, 2003). Inspiration also predicts creativity at the within-person level, such that inspiration and self-reported creativity fluctuate together across days (Thrash and Elliot, 2003).

In three studies of different types of writing (poetry, science, and fiction), self-reported state inspiration during the writing process uniquely predicted creativity of the final product, as assessed by expert judges using the CAT (Thrash et al., 2010b). These findings held when a variety of covariates (e.g., openness to experience, effort, activated PA, awe) were controlled. Finally, inspiration has been shown to mediate between the creativity of seminal ideas and the creativity of final products in a manner consistent with the posited transmission function[4] of inspiration (Thrash et al., 2010b). Covariates of inspiration (effort, activated PA, awe) failed to mediate transmission, indicating that the transmission function is unique to inspiration.

Having established a relation between inspiration and creativity, we now consider the role of "perspiration" in the creative process. Notably, Thrash et al. (2010b) documented a positive relation, rather than a negative relation, between inspiration and effort, indicating that these constructs are not mutually exclusive as the Edison quote may imply. The assumption that the presence of effort indicates low levels of inspiration is further challenged by a positive relation between inspiration and the work-mastery component of need for achievement (Thrash and Elliot, 2003). Both of these findings were documented at two statistically independent levels of analysis (between-persons, within-persons).

Certainly effort is important to the creative process, but its role is different than that of inspiration. Whereas writers' inspiration predicts the creativity of the product, writers' effort predicts the technical merit of the product (Thrash et al., 2010b). Thus inspiration and effort are unique predictors of different aspects of product quality. Moreover, screen capture data indicate that inspiration is involved in the automatic/generative aspects of the writing process (e.g., inspired writers produce more words and retain more of their original typing), whereas effort is related to controlled self-regulation (e.g., writers who exert effort delete more words and pause more to think; Thrash et al., 2010b). In short, inspiration and "perspiration" are not mutually exclusive, and they contribute in qualitatively different ways to the creative process and product.

The question of whether the audience correctly infers the presence of inspiration remains. The misattribution hypothesis states that it is the creator's *effort* that predicts the creativity of the product but that the audience incorrectly attributes this creativity to *inspiration* in the creator. An alternative to this model is the possibility that the audience correctly infers inspiration (Bowra, 1977). Thrash et al. (2010b) tested these competing hypotheses. Readers were found to correctly attribute creativity to writers' inspiration; likewise, they correctly attributed technical merit to writers' effort. These results, in addition to providing the first empirical evidence that readers can make veridical inferences about writers' motivational states, indicate that folk notions of the importance of inspiration are borne out by empirical data.

The psychological science of inspiration, as well as its relation to creativity, is now well-established. Inspiration has been conceptualized through integration of usages in diverse literatures, operationalized using a well-validated measure, discriminated from related constructs, and linked to creativity in multiple populations, contexts, and levels of analysis. Prior work provides a solid foundation on which investigations into the neuroscience of inspiration can rest.

INSPIRATION IN THE NEUROSCIENCE LABORATORY

In most respects, the challenges associated with studying creative inspiration are similar regardless of whether one approaches the topic as a neuroscientist, a psychologist, etc. Therefore, the preceding general challenges and solutions are also relevant specifically in the neuroscience context. However, we reiterate the importance of attending carefully to construct definition, because the term "inspiration" has occasionally been used in the neuroscience literature to refer to constructs that are quite different than the inspiration construct that we have discussed. In their classic EEG studies of the creative process, for instance, Martindale and Hasenfus (1978) used the terms inspiration and elaboration to refer to the stages that precede and follow, respectively, creative insight (see Kris, 1952, for a precedent for such usage in psychoanalysis). Inspiration as we have defined it—i.e., as a conscious motivational state rather than as a stage—is more likely to occur during Martindale and Hasenfus's elaboration stage than during the inspiration stage. We now turn to challenges that are particularly relevant within a neuroscience context.

One obstacle in studying inspiration in the laboratory is the impossibility of direct manipulation through exposure to

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[4] The authors empirically tested the *transmission model*, which specifies that inspiration mediates the relation between the creativity of the seminal idea and the creativity of the product. Two alternate theoretical models, the *epiphenomenon model* and the *self-perception model*, which suggest that creativity of the idea influences both inspiration and creativity of the product, or that creativity of the idea influences creativity of the product which in turn influences reports of inspiration, respectively, were also tested using structural equation modeling. The authors found support for the transmission model of inspiration over the epiphenomenon and self-perception models.

exogenous elicitors. If one seeks to elicit inspiration through use of some kind of "inspiring" stimulus, then the manipulated elicitor is the independent variable and inspiration is a dependent variable. Thus caution is needed regarding causal inference, despite use of the experimental method (Thrash et al., 2010a). Although inspiration cannot be directly manipulated through exposure to exogenous stimuli, a researcher may build a case for causality using manipulation of elicitors in combination with statistical controls and cross-lagged analyses, as demonstrated by Thrash et al. (2010a). We note that these problems are not unique to the study of inspiration. Emotions, insight, and many other constructs elude strict experimental control; at best, they may be "elicited" rather than "manipulated".

A related challenge is that it may be difficult to capture authentic or intense experiences of inspiration in a laboratory setting, given that inspiration is elusive for certain individuals or under certain circumstances. One solution may be to, in effect, lower the threshold for what constitutes an episode of inspiration. Thrash and Elliot (2004), for instance, studied "daily inspiration" using experience sampling methods, and we suggest that such tolerance for less intense manifestations of inspiration can be extended to a laboratory study. Much as creativity is not the same thing as genius (Bruner, 1962), inspiration is a matter of degree, and moderate levels might be achievable even in some invasive neuroscience paradigms.

A third challenge is the need for repeatable trials and time-locking. Brain imaging techniques (e.g., fMRI, EEG, MEG) require designs in which the mental event under consideration may be (a) temporally isolated so that the recorded data and the mental event can be time-locked to an eliciting stimulus and (b) elicited repeatedly during a recording session in order to improve the signal-to-noise ratio (Dickter and Kieffaber, 2013). One possible method to address these requirements is to use participant self-report (indicating the onset of inspiration) as the time-locking event. Suppose, for example, participants invent captions for each of a series of photographs (a highly-repeatable activity) and report on levels of inspiration at the moment of getting an idea for each caption. Bowden and Jung-Beeman (2007) used a method similar to this in order to identify processes that distinguish solutions involving the experience of insight from those that do not. We caution, however, that inspiration generally is more prolonged in time than is insight (particularly when considerable activity is needed to actualize an idea), and therefore methods that capture subsequent variability in inspiration across time—not just the level of inspiration at the moment of insight—will be particularly valuable.

One such method for capturing variability in inspiration across time, while simultaneously reducing the burden of eliciting inspiration repeatedly, is to record electrical brain activity using a non-invasive technique (such as EEG) during the creative process. For instance, if researchers record screen capture data during the writing process as in Thrash et al. (2010b), they can subsequently play back the recording to participants and collect continuous measures of recalled inspiration during the creative process (e.g., using a dial or slider input device). These ebbs and flows of inspiration can then be linked to variability in neural processes.

The difficulties associated with eliciting inspiration in order to study it at the within-person level may also be addressed by simply focusing on the individuals who are likely to be inspired (i.e., those who are high in trait inspiration). Elicitation may be circumvented altogether by examining structural brain differences between groups known to be high versus low in trait inspiration. One may separate groups into "more inspired" and "less inspired" using the IS. Additionally, as individuals higher in trait inspiration tend to exhibit greater levels of openness and extraversion, one might expect, for example, reduced latent inhibition and increased activity in the ventral tegmental area dopamine projections (Ashby et al., 1999; Depue and Collins, 1999; Peterson et al., 2002) for these individuals. Thus, inspiration's nomological network can serve as an informative starting point for between-person neurological analyses.

Next, we consider the question of where to look in the nervous system. While at present there is no neuroscience of the inspiration construct *per se*, literatures on related constructs can offer us some hints.

Insight relates to inspiration within the tripartite conceptualization in terms of both evocation and transcendence, and within the component processes model as the initial event that often leads one to become inspired *by*. During "Aha!" moments, one *transcends* a mental set and experiences a conceptual expansion (Abraham et al., 2012), and the experience feels automatic and unexpected; it feels *evoked* (Bowden et al., 2005). Therefore, certain neural components involved in insight experiences may be present at the onset of an inspiration episode. However, given that the literature on the neural correlates of insight is complex and that neural processes are under debate (Dietrich and Kanso, 2010), we caution against relying too heavily upon any one finding in guiding work on inspiration.

As inspiration involves not only transcendence and evocation, but also approach motivation, we may also look to the neuroscience literature on states of approach motivation (Elliot, 2008). There exists a burgeoning literature on approach motivation and appetitive affect, with attention to underlying neuronal circuitry (e.g., Bradley et al., 2001; Aron et al., 2005; Junghöfer et al., 2010), subcortical reward systems (e.g., Rosenkranz and Grace, 2002; Wise, 2004; Alcaro et al., 2007), neurotransmitters (e.g., Bassareo et al., 2002; Hoebel et al., 2008), and neurohormones (e.g., Frye and Lacey, 2001; Frye and Seliga, 2003; Frye, 2007). Findings in this area may offer suggestions for the neural underpinnings of the inspired *to* process.

Although the neurological findings regarding certain aspects of the inspiration construct can offer clues, the neural components of these pieces alone are unlikely to tell the full story. After all, we have already argued above that inspiration is not the same thing as insight or activated PA, nor is it the sum of these parts. For instance, an individual could be in an appetitive motivational state at the same time that he or she gets a creative insight, but he or she would not be inspired if the appetitive state reflects anticipation of eating, rather than of bringing the idea into fruition. The evoking object, in this case, the insight, does not meaningfully relate to the motivational object. The critical question for neuroscience is how processes related to generation of creative ideas recruit appetitive motivational processes, such that individuals respond to creative ideas not with indifference, but rather with a feeling of being compelled to act. How exactly does the prospect of turning a morsel into a dish fire the soul, as Mozart put it (in the opening quotation)?

In the initial stages of research on the neurological basis of inspiration, it may be useful to begin with a focus on overall inspiration instead of particular aspects or component processes. Inspiration as a unified concept can be measured quite efficiently using the 4-item intensity subscale of the IS (Thrash and Elliot, 2004). If necessary, inspiration could be assessed with a single item from the IS. Such items are surprisingly effective at capturing the full inspiration construct as we have defined it (Thrash et al., 2010b).

CONCLUSION

Writers, artists, and other creators have long argued that inspiration is a key motivator of creativity. Over the past decade, scientists have tested and found strong support for these claims. Scientific progress has required overcoming a number of challenges, including definitional ambiguity, difficulties of operationalization, ambiguities about discriminant validity, and skepticism about the importance of inspiration relative to perspiration. By developing an integrative conceptualization, operationalizing inspiration with the IS, establishing discriminant validity, and addressing skepticism with empirical evidence, these challenges have been largely overcome. Although additional challenges face the neuroscientist who wishes to study inspiration, similar challenges have already been overcome in relation to insight and other constructs. We believe that the stage has been set for a rigorous neuroscience of inspiration.

Brain-level explanations of an inspiration episode can then be integrated with explanations at other levels of analysis to produce a richer and more holistic understanding of inspiration. This deeper understanding will aid in determining how and why individuals sometimes feel (or do not feel) compelled to act on their creative ideas. Inspiration has the power to effect change not just for individuals, but also for societies. Technological advancements, cures for diseases, and solutions to environmental problems first emerge as promising ideas. It is difficult to overstate the importance of figuring out why, how, and for whom creative ideas to societal problems fire the soul and inspire the idea actualization process.

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The interplay between spontaneous and controlled processing in creative cognition

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Neural studies of creativity have yielded relatively little consistent results. For example, in functional neuroanatomical studies, the prefrontal cortex (PFC) has often been implicated as a critical neural substrate. However, results in electrophysiological (EEG) studies have been inconsistent as to the role of the PFC. EEG results have more often implicated widespread alpha synchronization, particularly in posterior regions, in creative cognition. Recent fMRI evidence has indicated that the PFC may be activated as a part of and together with other components of a deliberate control brain network. Controlled processing is neurologically dissociated from, but may co-occur with, spontaneous cognition mediated by a subset of the default-mode network (e.g., the angular gyrus [BA 39] in the posterior parietal cortex, which has been increasingly implicated in creative cognition). When the demand for controlled processing is substantially increased, default-mode processing may be suppressed. There is now preliminary evidence to suggest an association between alpha synchronization and default-mode processing. Creative cognition likely emerges from an *optimal* balance between spontaneous processing and controlled processing.

Keywords: creativity, spontaneous cognition, angular gyrus, lateral posterior parietal cortex, default-mode network, deliberate control, prefrontal cortex, multiple-demand network

The advent of neuroimaging methodologies in the last two decades has seen an increase in studies of creativity from a cognitive neuroscience perspective. However, there is hitherto relatively little evidence for a clear and consistent pattern of brain activity that is associated with creative information processing in general, or with a particular proposed stage of it (see e.g., Arden et al., 2010; Dietrich and Kanso, 2010; Kaufman et al., 2010; Sawyer, 2011). Recent cognitive neuroscience evidence has supported the role that a subset of the brain's default mode network (DMN) plays in spontaneous cognition (e.g., the angular gyrus, Brodmann Area [BA] 39, in the posterior parietal cortex; Mok, 2012). Default network activity may be suppressed when there is a substantial demand for controlled processing. However, spontaneous processing and controlled processing may co-occur. This article aims to highlight how these findings may be integrated with the existing creative cognition literature to offer a preliminary unifying perspective.

INTEGRATION WITH EXISTING THEMES

Neural studies of creativity have typically employed the standard, bipartite definition of creativity (Runco and Jaeger, 2012). Creativity is regarded as an ability that enables one to produce behavior or work that is *novel* and *useful*; useful creative behaviors and products would be appropriate and relevant to one's social context (e.g., Amabile, 1982; Sternberg and Lubart, 1999). The focus is to illuminate the neurocognitive operations that occur during the creative *process* (Kaufman et al., 2010). In experimental studies of creativity, tests of divergent thinking have been widely used. It has been reasoned that cognitive processes that give rise to creative ideas are more likely generative and divergent in nature, where the thinker searches in various directions, leading to numerous varied possibilities and possibly novel combinations. Commonly used tests of divergent thinking include variants of the Alternate Uses Test (AUT), which requires the respondent to self-generate as many alternative or unusual uses for common objects as possible such as a paper clip or a brick; and the Torrance Tests of Creative Thinking (TTCT; Torrance, 1974), which is a battery of standardized verbal and figural tests. Despite a relative lack of consistent results, functional neuroanatomical studies using functional magnetic resonance imaging (fMRI) or positron emission tomography (PET) have often implicated the prefrontal cortex (PFC) as a critical neuroanatomical substrate of divergent thinking (e.g., Folley and Park, 2005; Goel and Vartanian, 2005; see Dietrich and Kanso, 2010). The PFC has long been thought to play a critical role in top-down cognitive control (Miller and Cohen, 2001). It has, thus, been deemed essential for common cognitive functions such as working memory, attentional control, cognitive flexibility and cognitive evaluation, all of which are thought to be important to creative information processing (Dietrich, 2004). However, when brain electrical activity was measured using electroencephalography (EEG), the divergent thinking paradigm did not yield comparable results in frontal regions (see e.g., Dietrich and Kanso, 2010).

In another line of cognitive neuroscience research, it has been demonstrated that the PFC, especially the dorsolateral aspect, may be activated as a part of and together with other components of (what is now known as) the multiple-demand network[1] (Duncan, 2006). This form of cognitive processing is more deliberately engaged, attention-demanding, controlled and goal-directed, and is neurologically dissociated from, but may be concurrently experienced with, more spontaneous cognition mediated by a subset of the brain's DMN (Mok, 2012). A default brain region that is particularly involved in spontaneous processing (e.g., spontaneous prospection) is the angular gyrus (BA 39) of the lateral posterior parietal cortex (LPPC), whether of events and experiences in the short-term (Mok, 2012) or the long-term (Andrews-Hana et al., 2010).

On a fundamental and individual level, real-life creative activities may be substantially facilitated by spontaneous cognition, mediated by a subset of the brain's DMN and operating in the background as our concentration on the outside world is relaxed. However, when one is more focused on meeting more explicit and deliberate response demands such as in a test or timed situation, the demand for controlled processing may substantially increase, leading to a suppression of default processing (Mok, 2012). The differentiation between two processing modes—spontaneous vs. deliberate—for creative cognition has also been addressed in Dietrich (2004). More recent evidence is converging to indicate that creative cognition emerges from everyday cognitive abilities (Sawyer, 2011). Productive creative cognition may likely be facilitated by a delicate balance between more spontaneous processing vs. more controlled processing, both of which may be experienced concurrently to the extent that default activity does not become suppressed due to a substantial demand for controlled processing (Mok, 2012). In the literature, terms such as daydreaming and mind-wandering (e.g., Dietrich, 2007; Sawyer, 2011) have been used to describe mental states conducive to creative cognition. Such states are known to be mediated by the brain's DMN. Default network activity increases when we are asleep or when we are undisturbed and left to ourselves to daydream and/or mind-wander (Mason et al., 2007; Buckner et al., 2008). Default-mode processing reflects the brain's resting-state activity when our focus on the external environment is relaxed (Buckner et al., 2008). This corresponds to cognitive states described by disinhibition or relaxation of constraints (Dietrich, 2007; Kaufman et al., 2010) deemed to be facilitative of creativity.

Previously, in a PET study, BA 39 of the LPPC has been implicated in the performance of a verbal creativity task (Bechtereva et al., 2004). Participants generated a story using a difficult vs. an easy word list. The difficult list comprised remotely associated words, whereas the easy list comprised semantically-related words. Two other task conditions controlled for the syntactic vs. memory-related aspects of the task. When a task condition operationalized as requiring a greater degree of creativity to problem solve was contrasted against a task condition operationalized as requiring a lesser degree of creativity, at least a left BA 39 region within the LPPC (Cho, 2010) was implicated. A very recent fMRI study has also implicated the LPPC, including the angular gyrus, in creative cognition when participants generated alternate uses, as opposed to ordinary characteristics, for common objects (Kleibeuker et al., 2013). In a structural neuroanatomical MR study, a positive correlation has been found between cortical thickness in a right angular gyral region and self-reported real-life creative achievements (Jung et al., 2010).

The inconsistent pattern of results in neural studies of creativity has often been attributed to a lack of psychometrically sound assessment instruments and/or a definitional issue of the various concepts under investigation (e.g., Arden et al., 2010; Dietrich and Kanso, 2010). Below I outline two factors that may influence the observed results. A key aspect of the experimental tasks commonly used in neural studies of creativity such as those based on the AUT and the Torrance Tests is that they are administered in timed conditions, much like a test situation in which the participant may feel the stress of having their responses critically evaluated. Such external task demands may require more attention and control, leading to an increase in control network activity and a suppression of default network activity. Plucker and Makel (2010) have also raised concerns about a timed testing condition. Moreover, in an unpublished set of data, Mok and colleagues observed that the MR scanning environment such as the continuously loud scanner noise may lead to a decrease in size of experimental effects that are dependent on default network processing. To cope with the effect of environmental noise, there may be a greater demand for controlled processing, leading to a relative suppression of default network activity. These factors may contribute to why fMRI studies of creativity were in general rather consistent in implicating the PFC when timed tasks were used or when a study session felt like a test situation. Studies employing the EEG methodology with timed task administrations appeared to have yielded inconsistent results with regard to the role of frontal regions in creative cognition. The superior temporal resolution of the EEG methodology (1 ms, as opposed to 2 s for fMRI and 40 s for PET; Sawyer, 2011) may have afforded a greater potential to capture transient task-related activity such as default network activity, rather than possibly more persistent control network activity.

It is noteworthy that EEG studies have, in fact, been more consistent in showing that divergent thinking (measured by the AUT and/or the Torrance Tests) is associated with strong alpha activity and alpha synchronization, particularly in the parietal regions but also in the frontal and central regions (e.g., Fink et al., 2007, 2009a,b; Grabner et al., 2007). More recent studies employing simultaneous resting-state EEG/fMRI measurements have found a positive correlation between blood-oxygen-level dependent (BOLD) signals in components of the brain's DMN, including the LPPC, and global alpha power (Mantini et al., 2007) and global alpha synchronization (Jann et al., 2009), respectively. Global measures of alpha activity were based on all electrode sites (frontal, central, temporal and posterior channels). Mantini et al. (2007) additionally found global alpha power

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[1] Components of the multiple-demand network include the pre-supplementary motor area, the inferior frontal sulcus and the lateral PFC around it [BA 9], the anterior insula and the intraparietal sulcus (Duncan, 2006). The multiple-demand network has been found to be activated in a wide range of cognitive activity, from working memory storage/manipulation, executive control to response selection (Woolgar et al., 2011).

to correlate negatively with an intrinsic connectivity network more involved in dorsal attention, which included the PFC. This line of research appears to provide preliminary support for an association between global alpha synchronization and a state of mind corresponding to the brain in default mode. In default mode, active processing in control, and related sensory and motor brain regions is depressed. This harks back to the traditional interpretation of alpha synchronization as reflective of "cortical idling" (Pfurtscheller et al., 1996). A modern interpretation of alpha synchronization may be that it is related to the brain's default-mode processing.

Caution should be exercised in interpreting event-related alpha synchronization (ERS) as reflective of an inhibitory or top-down control process (cf. Klimesch et al., 2007). For example, alpha ERS observed over a short memory delay (1800 ms) in a working memory scanning task (a modified Sternberg task) has been interpreted as evidence against cortical idling but reflective of inhibition of brain areas not being used in processing (Schack and Klimesch, 2002). On close scrutiny, delay-period memory processing in this task might have been more spontaneously experienced than deliberately engaged, for the possibility that the probe stimulus, presented after the delay, would be contained in the (memory) set of simple stimuli presented before the delay. Delay-period memory processing of an (easy to discern) identity match stimulus may be facilitated, at default processing levels, concurrently by an LPPC region (for a prospective perspective) and a hippocampal region (for a retrospective perspective; Mok et al., 2009; Mok, 2012). When the memory set size was increased, delay-period ERS over posterior regions was stronger (Jensen et al., 2002; Schack and Klimesch, 2002). Upon presentation of the probe, event-related alpha desynchronization was observed (Klimesch et al., 2007). Participants likely engaged deliberately in controlled processing as they responded to the probe.

Alpha activity has also been taken as reflective of active inhibition of external sensory information during mental imagery (e.g., Cooper et al., 2003). More recent fMRI results, however, have supported the core, modality-independent role of the DMN in mental imagery (e.g., Mok et al., 2009; Daselaar et al., 2010). Another paradox was the simultaneous synchronization and desynchronization of different alpha responses in a recognition memory task (Klimesch et al., 2000). While transient evoked alpha synchronization may be observed at parieto-occipital sites, widespread induced alpha desynchronization may be observed at most recording sites. More spontaneously experienced cognitive processing in the LPPC, a DMN region, may co-occur with more controlled processing (Mok, 2012). The EEG signature of this co-occurrence warrants further investigation, as does a more systematic evaluation of the functional significance of alpha activity in general for spontaneous cognition mediated by a subset of the DMN.

A PRELIMINARY UNIFYING PERSPECTIVE AND SOME DEFINITIONAL ISSUES

As reviewed, the LPPC of the DMN is particularly involved in spontaneous cognition and it has increasingly been implicated in creative processing. Spontaneous processing in the LPPC is particularly of a prospective, or rather future-oriented, perspective. In the delay task used in Mok (2012), participants experienced spontaneous delay-period prospection of a cue-unique response outcome, mediated by the angular gyrus in the LPPC; there appeared to be individual differences in which hemisphere might be more involved. In accounting for semantic priming in cognitive psychology, the presentation of the prime stimulus that precedes the target stimulus has also been thought to initiate a prospective memory process, leading to spontaneous semantic spreading activation (Neely and Keefe, 1989). Divergent thought processes that underlie creative cognition, elicited by the initial stimulus of concern, may be quite similar in nature to spontaneous semantic spreading activation. Such thought processes allow one to access remote associates, which are important for the generation of novel possibilities and new associations (Kaufman et al., 2010). Functional neuroimaging studies have supported the role of the angular gyrus in a wide range of semantic tasks (e.g., Seghier et al., 2010). The subregion within the human angular gyrus most involved in spontaneous prospective memory processing at default activity level appears to be the posterior subdivision (PGp; Mok, 2012; Seghier, 2013).

The PFC activated as a part of a control network is well-poised to facilitate the evaluation and judgment of the social appropriateness of a novel idea, and the implementation of goal-directed plans (Dietrich, 2004). These processes will likely tap into contextual knowledge/memory whether social, cultural or historical. Depending on the content being processed, additional circuitries may be activated, e.g., sensory-perceptual cortices and related neural regions (for sensory-perceptual content such as visual and/or auditory content), emotional and associated limbic regions (for affective content), motivational systems (for appetitive or aversive content), and motor-related regions (for motor content). If additional neurocognitive analysis is involved, other relevant neural circuitries may be activated. Affective and/or motivational processes may modulate the balance between the deliberate and spontaneous processing modes and the efficacy of semantic associative processes (e.g., Shemyakina and Dan'ko, 2004), influencing the quality of ideational complexity vs. the effectiveness of judgment and implementation processes.

Runco (2010) introduced the notion of *optimization* and argued that it allows simplicity and parsimony in conceptualizing and defining creativity. Productive creative cognition likely emerges from an optimal balance between deliberate and spontaneous cognition. Runco (2010) further suggested that there is a single capacity, rather than two where one is for originality of thought and the other is for judiciousness, that underlies creative processing. On a neurocognitive level, in the service of everyday activities, this single capacity would correspond to the capacity to achieve, on a moment to moment basis, optimal balance between control network activity and default network activity, and optimal coordination between these respective networks and other brain regions involved in content processing. Evaluative and judgmental processes would be optimized to the extent of one's understanding of the social, cultural and historical context. Morality and empathy, and how the social brain interacts with other components of the DMN (Mars et al., 2012) can potentially influence evaluative and judgmental processes and bear on eventual implementation of creative endeavors. The moment-to-moment optimization of spontaneous vs. controlled processing, whether the moment serves idea generation, verification or implementation (cf. Wallas, 1926), may be modulated by individual differences such as personality and intelligence. An empirical question is whether it would be more viable to define optimization relative to a self-norm or a population norm.

Novel ideas are rare, or rather deviant from the norm (Runco, 2004). Thought processes such as divergence and free association that give rise to deviant ideas are productively creative only to the extent that they are optimal but not excessive (Runco, 2004). The concept of deviance can be applied to accommodate documented links between creativity and deviant neurocognitive processes that underlie certain mental disorders (Kaufman et al., 2010), altered states of consciousness such as those induced by drugs, meditation, or long-duration exercise (Dietrich, 2007), and the "dark-side" of creativity such as the creation of weapons of mass destruction. Creativity studies with a developmental perspective (cf. Kleibeuker et al., 2013) should consider the developmental trajectory of the DMN vs. the control network and their respective connectivity with other brain regions; and the transition from relatively non-symbolic, language-free, and possibly innate abilities existing in infancy to symbolic or language-dependent abilities that may be modifiable and can benefit from training.

IMPLICATIONS FOR FUTURE RESEARCH AND PRACTICE

To better measure default network activity, study sessions that feel like a test (e.g., with timed administrations) should be reconsidered. Study designs could bias participants toward different levels of creativity within-subject, carefully matching/controlling for as many of the other aspects of the experimental task as is possible. A concurrent-task design could allow for a better estimate of the relative levels of default network activity vs. control network activity. The potential influence of the MR scanning environment on default network suppression should also be systematically studied.

In the mainstream school system, the assessment of learning remains critical. A curricular emphasis on an end-product to be delivered by a certain deadline and its assessment as an outcome of learning may create a learning environment (akin to a test situation) that regularly heightens the brain's control activity and suppresses default activity. Class activities should not engender persistent suppression of default processing on the individual level. Instead, with appropriate structuring and scheduling, more opportunities could be provided for developing minds and brains to spontaneously experience default-mode processing. Learning environments could be designed to enhance and/or maintain relevant default network activity despite existing external task demands. An appropriate use of prime stimuli to initiate optimal spontaneous semantic spreading activation could be a good starting point.

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Creative thinking as orchestrated by semantic processing vs. cognitive control brain networks

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Creativity is primarily investigated within the neuroscientific perspective as a unitary construct. While such an approach is beneficial when trying to infer the general picture regarding creativity and brain function, it is insufficient if the objective is to uncover the information processing brain mechanisms by which creativity occurs. As creative thinking emerges through the dynamic interplay between several cognitive processes, assessing the neural correlates of these operations would enable the development and characterization of an information processing framework from which to better understand this complex ability. This article focuses on two aspects of creative cognition that are central to generating original ideas. "Conceptual expansion" refers to the ability to widen one's conceptual structures to include unusual or novel associations, while "overcoming knowledge constraints" refers to our ability to override the constraining influence imposed by salient or pertinent knowledge when trying to be creative. Neuroimaging and neuropsychological evidence is presented to illustrate how semantic processing and cognitive control networks in the brain differentially modulate these critical facets of creative cognition.

Keywords: creative cognition, divergent thinking, semantic cognition, cognitive control, inhibitory control, fronto-striatal network, fronto-parietal network

The interest in uncovering the brain mechanisms underlying creative thinking, or the ability to generate original yet relevant responses in a given context (Stein, 1953), has a lengthy scientific history that dates back at least to the 1940s (Reitman, 1947; Ashby and Bassett, 1949). The most influential issues that have guided investigations on creativity and brain function include enhanced creative ability following brain damage (Miller and Miller, 2013), the dominance of right over left hemisphere function in creative thinking (Mihov et al., 2010), and the brain basis of exceptional ability among experts in creative domains such as music, art and dance (Bengtsson et al., 2007). The general (although not necessarily unanimous) picture that emerges from the literature is that creative performance and/or ability is particularly associated with frontal lobe (FL) function (Dietrich and Kanso, 2010), higher right brain activity (Mihov et al., 2010), greater EEG alpha power which reflects high internal processing demands (Fink and Benedek, 2012), and that it can be inadvertently boosted as a consequence of specific types of brain damage (Seeley et al., 2008).

Such generalizations regarding creativity and brain function primarily arise from adopting a somewhat unitary approach in investigating creativity where it is assessed as an undifferentiated general construct, as opposed to process-differentiated one. This is customarily achieved by contrasting brain activity (neuroimaging or EEG studies) or behavioral performance (neuropsychological studies) during creative vs. non-creative tasks. Several researchers have critically addressed theoretical and methodological concerns that arise in the context of neuroscientific investigations of creative thinking, such as the inability to prompt creativity in a reliable or valid manner and the suboptimal nature of comparison tasks in creativity paradigms (Dietrich, 2007; Arden et al., 2010; Sawyer, 2011; Abraham, 2013). The advantage of a unitary approach is that it delivers the "big picture" regarding our creative brains. However, the unitary approach is too generalized, and hence insufficient, if the overarching aim is to uncover the neural and information processing mechanisms by which creativity occurs. As several cognitive operations work in unison when we are engaged in creative idea generation, adopting a "process" approach to creativity (Kozbelt et al., 2010) in investigating the brain correlates of these different operations would allow us to realize such an objective.

COGNITIVE COMPONENTS OF CREATIVITY

The Geneplore model of creativity (Ward et al., 1995; Finke et al., 1996; Ward et al., 1997), which sought to characterize the different mental operations that are involved during creative thinking, was driven by the process approach. Although diverse in nature, these operations were proposed to have two components in common. First, they involve the generation of potential ideas or "preinventive" structures (e.g., the analogical transfer of information from one domain to another). Second, this initial generation phase is followed by extensive exploration of these preinventive structures (e.g., search for conceptual limitations).

According to this model, the essential difference between creative and "non-creative" or normative cognition does not lie in the type of mental operations themselves, but in the contexts to which these information processing toolboxes are applied

(Abraham, in press). The contexts or problem solving situations that prompt creative cognition (e.g., compose a haiku) are relatively more open-ended, ambiguous, non-linear, abstract and unpredictable compared to those that primarily necessitate normative cognition (e.g., devise a weekly exercise regime). Creative cognition can therefore be assessed by examining normative cognitive processes under explicitly generative conditions. In fact, a number of such mental operations have been described (**Figure 1**; Abraham and Windmann, 2007). These include the ability to broaden the framework of established conceptual structures (conceptual expansion), mental visualization during creative idea generation (creative imagery), the ability to surpass the constraining influence of recently activated knowledge (overcoming knowledge constraints), and the sudden occurrence of a solution during problem solving as a result of a fundamental perspective shift (insight). So, how do these operations work in combination with one another during creative idea generation?

Imagine the following scenario. You are asked to imagine new uses for a shoe, beyond the object's customary use of foot protection. Allow yourself a few minutes to carry out this task before reading further and make note of the uses you generate.

Typically, other common uses for a shoe, such as using it to kill a cockroach, will occur to you automatically. As these familiar options are quickly exhausted, the task becomes increasingly cognitively demanding. While trying to come up with novel ideas, you probably generated mental images to explore a shoe's physical parameters in terms of weight, volume, dimensions, materials, type: stilettos vs. sneakers, and so on (creative imagery). During this process, it may have become apparent to you that a shoe can be used as a make-shift container (conceptual expansion) and that the brutally angled sole of a stiletto lends itself to different uses than the flat sole of a sneaker. While exploring potential uses for a shoe as a highly angled container in the case of a stiletto, you may inadvertently recollect uses that are closely related to those you have already generated, such as using the stiletto's heel to impale a spider, and you strive to inhibit this tendency to rehash known associations (overcoming knowledge constraints). Then, seemingly out of the blue, the different elements that are being explored suddenly come together in a novel manner while you undergo some form of an "aha-experience" (insight) as you become aware of this new use of, for instance, using a shoe as a hamster slide (**Figure 1**).[1]

The focus in the present opinion article will be limited to evaluating the similarities and differences in brain function that are associated with conceptual expansion and overcoming knowledge constraints as these operations have received little to no attention thus far within the literature, unlike the processes of insight (Kounios and Beeman, 2009; Dietrich and Kanso, 2010) and imagery (Farah, 1989; LeBoutillier and Marks, 2003; Bartolomeo, 2008).

CONCEPTUAL EXPANSION

The ability to expand acquired conceptual structures to include novel elements is investigated in tasks that assess conceptual expansion (Ward, 1994). The original task involved having participants generate animals that lived on another planet that was very different from Earth. How far these alien creatures deviated from generic Earth animals in terms of the absence of typical features and the presence of atypical features was assessed. As this animal task cannot be optimally implemented in its original form for neuroimaging research, three alternative experimental paradigms were developed to assess conceptual expansion. These have now been implemented in fMRI (Abraham et al., 2012b; Kröger et al., 2012; Rutter et al., 2012b) and EEG settings (Rutter et al., 2012a; Kröger et al., 2013).

The paradigms were devised with the objective of uncovering the brain correlates of conceptual expansion. Brain regions that were commonly activated across all three paradigms would be considered to be reliably involved in creative conceptual expansion. Two approaches were adopted when developing these paradigms[2] where one was devised to assess "active" conceptual expansion (Abraham et al., 2012b) while the other assessed "passive" conceptual expansion (Kröger et al., 2012; Rutter et al., 2012b). Participants shouldered the task of expanding the concepts themselves (generate novel uses for a newspaper) in the volitionally generated or active conceptual expansion paradigm. In contrast, during the involuntarily induced or passive conceptual expansion paradigms, participants were presented with object-use combinations (Shoe → Plant pot) or metaphors (The clouds danced over the city), to which they reported experiences of conceptual expansion. This occurred when they encountered an object-use combination or metaphor that was deemed by them to be both novel (previously unknown to them) and appropriate.

The brain regions that were found to be activated across all three paradigms were limited to the left hemisphere and included the anterior inferior frontal gyrus (IFG: BA 45/47), the temporal pole (TP: BA 38) and the lateral frontopolar cortex (FPC: BA 10). The IFG is central to semantic information processing in the brain (Bookheimer, 2002; Binder and Desai, 2011; Jefferies, 2013) with anterior aspects of this structure being involved in semantic selection and controlled semantic retrieval (Thompson-Schill, 2003; Badre and Wagner, 2007). The TP is also key structure of relevance in semantic cognition as it is widely held to underlie the domain-general or amodal repositories of conceptual knowledge of the brain (Lambon Ralph et al., 2009; Simmons and Martin, 2009). It is involved in the combination and integration of lexical representations to a context (Lau et al., 2008), as well as in the acquisition of new conceptual knowledge (Hoffman et al., 2014).

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[1] This example is only presented for illustrative purposes to showcase differences between select cognitive operations during the creative act. As such, it not to be construed as a prototype that represents the manner in which the creative process typically unfolds. The list of selected operations is by no means exhaustive. Moreover, the occurrence, temporal order and interrelation between these operations would be expected to differ as a function of intraindividual, interindividual and contextual factors.

[2] The alternate uses task is widely employed in investigations of creativity where divergent thinking is assessed in terms of fluency or originality of the responses. Just as in studies of other facets of cognition, the same task can be implemented in different ways depending on the microlevel of study to allow for specific inferences to be made regarding creative function. Within the neurocognitive approach, the microlevel is centered on the brain correlates of the cognitive process. So the brain response when performing the alternate uses task is assessed relative to brain response when performing a closely matched control task that does not necessitate conceptual expansion, but nonetheless requires reasoning, fluency, semantic judgments, cognitive control, and so on.

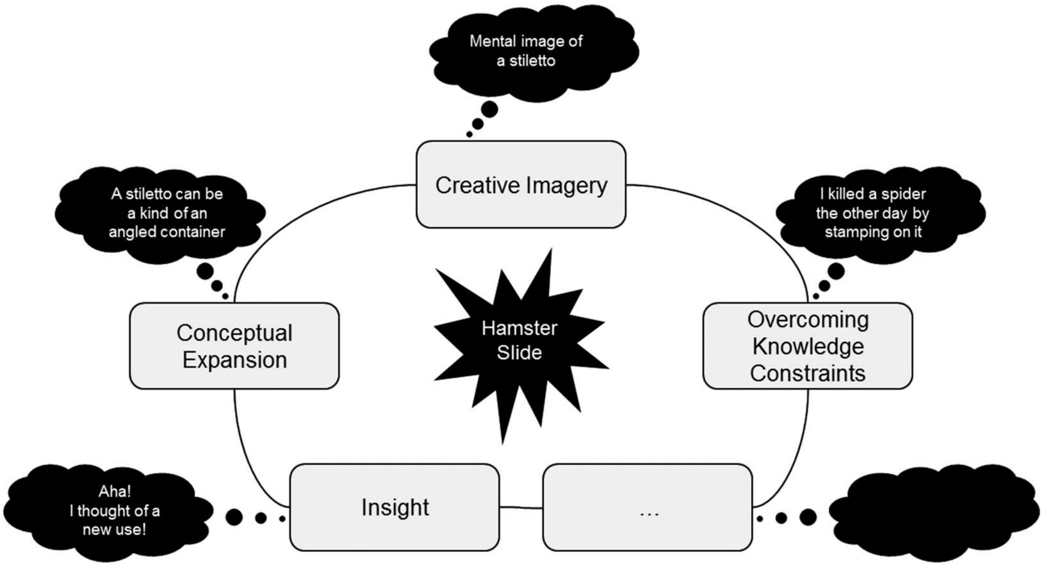

FIGURE 1 | A schematic diagram to highlight four of the several different mental operations that are involved in creative thinking with a hypothetical example of how different aspects of creative cognition work in unison during creative idea generation.

The lateral FPC, in contrast, is held to mediate cognitive control at the most abstract level of information processing (Badre, 2008; Christoff et al., 2009) and plays a key role during relational reasoning (Christoff et al., 2001; Wendelken et al., 2008) as well as when combining information from two or more separate cognitive operations (Ramnani and Owen, 2004). Although the lateral FPC is not specifically limited to semantic aspects of information processing, both this brain region and the anterior IFG are sensitive to the degree of associative strength between concepts (Bunge et al., 2005; Green et al., 2010) with greater brain activity elicited by wider semantic distances.

To summarize, neuroimaging studies on conceptual expansion have revealed that brain structures (inferior frontal, temporopolar and frontopolar) that are collectively associated with the selection, controlled retrieval, combination and integration of semantic knowledge are preferentially more strongly engaged during creative conceptual expansion relative to other types of normative semantic information processing. Although nonverbal conceptual expansion has yet to be investigated in the same manner, the same brain network would be expected to be involved in conceptual expansion regardless of the stimulus type. This is because the use of verbal and non-verbal as well as semantic and non-semantic control tasks across the different paradigms revealed that the engagement of this network of brain regions during conceptual expansion cannot be merely attributed to verbal or semantic processing.

OVERCOMING KNOWLEDGE CONSTRAINTS

The ability to override the hindering influence imposed by relevant but distracting information during creative idea generation (Smith et al., 1993) is referred to here as the process of overcoming knowledge constraints. In the original toy task that was devised to assess this operation, participants are asked to imagine and draw a novel toy that does not yet exist (previously/currently). But before they do so, they are shown examples of three novel toys that were generated by others. Unbeknownst to the participants, these novel toy examples were in actuality engineered by the experimenter to have three features in common. What is assessed after the participants generate their own responses is how many of these three elements are present in the participants' toy inventions. Higher scores reflect stronger incorporation of example elements, which in turn reflects a poorer ability to overcome knowledge constraints that were levied by a salient and distracting context.

Just as in the conceptual expansion task, the toy task cannot be optimally implemented in its original form for neuroimaging research. To date, no study has directly investigated the brain correlates of overcoming knowledge constraints during creative idea generation. Only two neuroimaging studies have an indirect bearing on this discussion where the opposite effect, of "cognitive stimulation" on creative problem solving upon being exposed to others' ideas, was assessed (Fink et al., 2010, 2012).

The behavioral findings indicated that prior exposure to common uses (generated by others) relative to no prior exposure, led to greater originality in self-generated uses. But this was not true with prior exposure to original uses. As Fink et al. (2012) did not assess the degree of similarity between self-generated vs. other-generated uses, it is not possible to speculate about how these two situations may have involved overcoming different types of knowledge constraints. When comparing the brain's response during idea generation following original-use-prior-exposure compared to no-prior-exposure or common-use-prior-exposure, heightened activity was found in the left posterior middle temporal gyrus (MTG). The posterior MTG is part of the brain's semantic system (Binder and Desai, 2011) and is held to underlie the "long-term storage of and access to information associated with lexical representations" which "serves as input to higher-order semantic processes" (Lau et al., 2008). If we were to presume that prior exposure to original ideas imposes more constraints on idea generation than no prior exposure to ideas, as has been suggested by behavioral research, one could postulate that posterior middle temporal regions are more actively recruited when having to overcome knowledge constraints.

Interestingly, neuropsychological evidence has demonstrated that damage to lateral parietal and temporal cortices (including the posterior MTG) is associated with poorer performance on the overcoming knowledge constraints toy task (Abraham et al., 2012a). Creative cognition was assessed in three neurological samples with lesions of the FL, basal ganglia (BG), or parietal-temporal lobe (PTL). The PTL group were significantly less adept at overcoming knowledge constraints, which is a pattern that fits with findings of semantic perseverative responses associated with this population, especially in the presence of semantic distractions (e.g., Corbett et al., 2011).

The BG and FL-POL (FL group with frontopolar/frontoorbital lesions) groups though were found to be better at overcoming knowledge constraints during creative idea generation compared to healthy control groups. This information processing advantage was very specific in that neither the BG group nor the FL-POL group displayed superior performance on any other aspect of creative cognition.

The BG together with the prefrontal cortex are part of the network in the brain that orchestrates executive function and cognitive control (Alexander et al., 1991; Robbins, 2007; Brocki et al., 2008). Within the prefrontal cortex, frontopolar regions underlie abstract cognitive control (Badre, 2008; Badre et al., 2009) while frontoorbital regions are associated with cognitive disinhibition (Cummings, 1993). BG lesions are accompanied by poor inhibitory control, marked inattention and increased distractibility (Fielding et al., 2006; Aron et al., 2007).

These factors would be advantageous in overcoming knowledge constraints as optimal performance on this task requires inhibiting salient information that is engineered such that increased effort must be expended to see past it. Having poor inhibitory control or being easily distractible would render one more capable of overcoming such constraints as one's attention is continually being involuntarily diverted away from any particular focus.

Further indirect support from this idea comes from a study on creative cognition in attention-deficit/hyperactivity disorder (ADHD) where adolescents with ADHD outperformed healthy matched control participants on the toy task (Abraham et al., 2006). Even within a sample of adults with chronic schizophrenia, a high degree of thought disorder symptoms (disorganization within the semantic content of thought) was associated with superior ability to overcome knowledge constraints on the toy task (Abraham et al., 2007). Indeed, both ADHD and schizophrenia are associated with dysfunctions of the fronto-striatal network in the brain (Robbins, 1990; Bradshaw and Sheppard, 2000; Robbins et al., 2012).

CREATIVE COGNITION AND THE BRAIN

The general picture that glimmers through when bringing together the findings from neuroscientific investigations of conceptual expansion and overcoming knowledge constraints during creative idea generation is that of a dynamic interplay between semantic processing and cognitive control networks in the brain.

Trying to conceive of an original idea necessarily involves broadening or expanding existing conceptual structures to include novel or previously unassociated features. When engaged in conceptual expansion, the brain's semantic processing network operates on overdrive, particularly the higher-order regions which mediate lexical selection, controlled retrieval, combination and integration processes. During this process of cogitation, when distracting but salient information threatens to throw a spanner in the works by hampering one's ability to generate truly original ideas, the cognitive control network of the brain storms into play to push these distractions out of one's mind. This can be done in one of two ways—by either inhibiting or ignoring this salient information.

Inhibiting or ignoring salient task-relevant information is in fact very difficult as our predictive brains are developed to be especially adept at efficient and effective goal-directed action (Bubic et al., 2010) and we are accustomed to operating in our daily lives within normative contexts where the distractions one may have to overcome can be unmistakably recognized and are not necessarily salient or relevant to the specific task at hand. Such distractions can therefore be (relatively speaking) easily ignored. During creative idea generation though, the distracting information can be exceedingly pertinent to the task at hand and cannot therefore go unheeded in the same manner. Under such conditions, imbalances within the fronto-striatal network seem to confer specific advantages in creative cognition, possibly owing to the manifestation of cognitive disinhibition and increased distractibility, which would allow for a greater ease in disregarding salient semantic distractors.

CONCLUSIONS

The objective of this article was to outline the potential neurocognitive mechanisms that underlie two vital aspects of creative cognition—conceptual expansion and overcoming knowledge constraints—based on neuroscientific findings that adopted a process approach to investigate the same. What was highlighted was the role of the semantic processing and cognitive control networks in the brain during creative idea generation. These insights can help inform and guide future neuroscientific investigations on creativity as well as aid in the development of more detailed and targeted information processing models of creative neurocognition. Promising future directions for exploration include the impact of training-induced plasticity effects on different aspects of creative neurocognition as well as uncovering the association between information processing biases in creative cognition with reference to variability that is manifest in real world creativity.

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The time-course of EEG alpha power changes in creative ideation

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Increases in EEG alpha power during creative ideation are among the most consistent findings in the neuroscientific study of creativity, but existing studies did not focus on time-related changes of EEG alpha activity patterns during the process of creative ideation so far. Since several cognitive processes are involved in the generation of creative ideas, different EEG correlates may result as a function of time. In this study we addressed this crucial point. Forty-five participants worked on the "Alternative Uses Task" while the EEG was recorded and changes in task-related power (relative to rest) in the upper-frequency band (10–12 Hz) for three isochronous time intervals of the idea generation period were determined. Alpha power changes during idea generation followed a characteristic time course: we found a general increase of alpha power at the beginning of idea generation that was followed by a decrease and finally by a re-increase of alpha prior to responding that was most pronounced at parietal and temporal sites of the right hemisphere. Additionally, the production of more original ideas was accompanied by increasing hemispheric asymmetry (more alpha in the right than left hemisphere) with increasing duration of the idea generation period. The observed time course of brain activity may reflect the progression of different but well-known stages in the idea generation process: that is the initial retrieval of common and old ideas followed by the actual generation of novel and more creative ideas by overcoming typical responses through processes of mental simulation and imagination.

Keywords: EEG, alpha power, creative ideation, divergent thinking, time-course

Research on creativity—commonly defined as "the ability to produce work that is both novel and appropriate" (Sternberg and Lubart, 1996, p. 677)—has recently attracted great attention in psychology and particularly in the field of neuroscience. It is often dated back to Guilford's well-known presidential address at the American Psychological Association, where he highlighted the crucial importance of research on creativity which has been neglected for a comparatively long period of time (Guilford, 1950). Since then, creativity as a research topic has become more and more popular and has been addressed in various scientific disciplines by adopting a broad variety of different perspectives and methodological approaches (cf. Simonton, 2000; Runco, 2004).

The underlying neural basis of creative cognition is a major area of interest in creativity research. Based on the conceptualization of creative thought as the combination or interplay of different cognitive processes (e.g., Guilford, 1950), it is unlikely that there is just one "center of creativity" in the brain (cf. Dietrich, 2004). To come up with a creative idea, people need to be aware of a certain problem, to be able to analyze the situation and to redefine it. Then, possible alternatives or solutions resulting from cognitive processes such as flexible thinking have to be developed and are finally needed to be evaluated (cf. Guilford, 1950). Moreover, the generation of a novel idea is thought to involve the meaningful recombination of previously unrelated semantic concepts or frames of thought (Mednick, 1962; Koestler, 1964; Benedek et al., 2012). Thus, various cognitive processes such as attention, memory retrieval, working memory etc. could be considered as being crucially involved in the idea generation process. In this particular context it is hypothesized that the same combination of neural networks that is recruited in non-creative cognition (e.g., working memory) is implicated in creative cognition as well (e.g., Cabeza and Nyberg, 2000; Dietrich, 2004).

As a consequence of the broad variety of different approaches and methods that were used to investigate creativity, previous findings on neural correlates of creativity have been heterogeneous and often inconsistent (cf. Arden et al., 2010; Dietrich and Kanso, 2010). In reviewing relevant findings in this field, Dietrich and Kanso (2010) concluded that the results differ widely because of the diversity of possible assessments of creativity, including varying research foci (divergent thinking, artistic creativity, problem solving with insight) and neuroscientific methods (e.g., EEG, fMRI). Fink and Benedek (2012) suggested that comparing findings across different studies might be more reasonable by specifically looking at studies in which similar tasks and measurement methods were used. In doing so, Fink and Benedek (2012) reviewed EEG studies which specifically focused on the relationship between creative ideation (i.e., divergent thinking) and power in the alpha frequency band (8–12 Hz). Their review revealed robust evidence of EEG alpha power being particularly sensitive to various creativity-related demands: alpha power varies as a function of creativity-related task demands (the more creative a task the higher the level of alpha), as a function of originality (higher originality is accompanied by more alpha), and as a function of an individuals' creativity level (more alpha in higher creative individuals, see Fink and Benedek, 2012, 2013). Additionally, alpha power has also been observed to increase as a result of verbal creativity interventions (Fink et al., 2006, 2011). On the basis of these findings Fink and Benedek (2012) concluded that the observed alpha findings are among the most consistent findings in the neuroscientific study of creativity, and we might therefore assume that the study of alpha power changes is a valuable and powerful tool to study brain activity patterns during the process of creative idea generation. Traditionally, increases in EEG alpha power (hereinafter referred to as alpha synchronization) have been interpreted as sign of "cortical idling" (cf., Pfurtscheller et al., 1996). More recent studies suggested that alpha synchronization may indicate a state of high internal processing demands that are characterized by "the absence of bottom-up processing (Ray and Cole, 1985; Cooper et al., 2003) and thus can be classified a pure form of top-down activity" (von Stein and Sarnthein, 2000, p.311). This top-down process may have an attentional control function leading to inhibition of task-irrelevant stimuli (Klimesch et al., 2007). Therefore, alpha synchronization is probably associated with selective and active cognitive processing (Sauseng et al., 2005).

Alpha synchronization observed during creative ideation, which has consistently been observed over the prefrontal and temporo-parietal cortex (Fink and Benedek, 2012), may also reflect active cognitive processing and focused internal attention (Fink et al., 2009a; Benedek et al., 2011; Fink and Benedek, 2012; Jauk et al., 2013). Finding a creative solution requires effective memory retrieval and effective working memory processing for knowledge modulation (activation, inhibition and combination of knowledge; see e.g., Heilman et al., 2003; Dietrich, 2004). In addition, alpha synchronization at parietal sites of the right hemisphere seems to play an important role in creating ideas with high originality. In previous studies, stronger alpha synchronization at right parietal sites was found in higher creative individuals compared to less creative individuals (e.g., Martindale and Hines, 1975; Jaušovec, 2000; Razumnikova, 2007; Fink et al., 2009a,b).

Besides neuroscientific research on creativity, theoretical models were postulated to describe creative cognition and its possible stages or phases. The number of phases that are assumed as being implicated in the creative process vary (e.g., Wallas, 1926; Finke et al., 1992; Csikszentmihalyi, 1996). Exemplarily, in the "Geneplore" model two phases are hypothesized (Finke et al., 1992). According to this model, creative cognition is considered as the result of processing in circuits that consist of (reoccurring) generative and exploratory phases (Finke et al., 1992). The authors assume that idea generation starts with the construction of mental representations (generative phase) followed by interpretation and modification processes (exploratory phase). Other models propose four (preparation, incubation, illumination and verification; Wallas, 1926) or even five stages (preparation, incubation, insight, evaluation and elaboration; Csikszentmihalyi, 1996).

There were also attempts to examine the different strategies and cognitive processes involved in divergent thinking (i.e., creative idea generation) tasks. Gilhooly et al. (2007) performed a verbal protocol analysis of the alternate uses task (i.e., a common divergent thinking task that requires to generate creative new uses for common objects) and categorized the processes reported during the task. The study revealed that initial ideas were largely based on the retrieval of known uses from memory, whereas later ideas were based on more complex strategies such as focusing on specific object properties or using imagery (cf. Benedek et al., 2014a). As a result, ideas are generally observed to become more creative over time (e.g., Beaty and Silvia, 2012; Benedek and Neubauer, 2013). It was proposed that the generation of creative ideas involves executive processes such as prepotent response inhibition in order to overcome initial dominant responses and to provide top-down control of attention during strategic semantic search processes (Gilhooly et al., 2007; Beaty and Silvia, 2012; Benedek et al., 2012). This notion is further substantiated by studies reporting a close link of divergent thinking ability with higher-order cognitive ability (Nusbaum and Silvia, 2011; Beaty and Silvia, 2013; Jauk et al., 2013, 2014).

Until now, there is only very little evidence on the time-course of creativity-related processes on the neurophysiological level. Studies which investigated neural correlates of insightful problem solving (i.e., problem solving accompanied by subjective experience of insight or the "AHA moment") reported an increase of alpha power at parietal and temporal sites of the right hemisphere shortly before solving tasks with insight (Jung-Beeman et al., 2004; Kounios et al., 2006; Sandkühler and Bhattacharya, 2008; Sheth et al., 2009). Time-related neural responses during the process of creative ideation (i.e., the generation of creative ideas) are yet unknown.

The aim of this study was therefore to investigate the time-course of EEG alpha power during the process of creative ideation. Theoretical accounts assume the involvement of different phases or processes in creative idea generation (e.g., Wallas, 1926; Finke et al., 1992; Csikszentmihalyi, 1996), which is why we expect different patterns of EEG alpha power as a function of time. In order to address this question we reanalyzed a recent EEG study of our laboratory in which alpha power activity during idea generation was investigated (Fink et al., 2011). In that study participants were required to generate alternative uses to everyday objects (i.e., AU task) after being stimulated via affective and cognitive interventions, whereas during the control condition they performed the task without any intervention. As a measure of brain activity, only alpha power during the entire idea generation period was quantified. In the present study we focused on the time course of alpha power during different phases of idea generation. Therefore we determined alpha power estimates for three subsequent time intervals within the idea generation period of the AU task in order to get first insights whether or to which extent alpha power during creative ideation changes as a function of time. Based on recent evidence on the relationship between alpha power and creative ideation (Fink and Benedek, 2012), we expected time-related alterations of alpha power at prefrontal as well as over parietal and temporal sites (of the right hemisphere) as a possible indication of varying demands on memory retrieval and working memory processing during the process of idea generation. In addition, we also investigated whether ideas of varying originality show different time-related changes of EEG alpha power. Recent research revealed that alpha power at right parietal sites may be important in originality (Fink and Benedek, 2012), and given the manifold cognitive processes that are required to generate originality, we expected that the association between alpha power and originality may also vary as a function of time.

METHOD

PARTICIPANTS

Forty-eight students participated in the study (cf. Fink et al., 2011). Three participants had to be excluded from data analyses due to technical problems during EEG recording. The final sample included 45 participants (22 women, 23 men) aged 18 to 32 years ($M = 23.09$, $SD = 3.48$). They were right-handed as assessed by a standardized handedness test (Steingrüber and Lienert, 1971; Papousek and Schulter, 1999). The participants indicated no history of medical, psychiatric or neurological disorders or treatment that could have interfered with any of the behavioral and neurophysiological measures. This study was approved by the local ethics committee of the University of Graz.

TASK AND PROCEDURE

Participants worked on the Alternative Uses (AU) task (cf. Wilson et al., 1953; Fink et al., 2007) while the EEG was measured. In the AU conventional everyday objects such as “shoes” or “toothpaste” were presented on the screen, and participants were instructed to come up with original and unconventional uses for these objects. Participants worked on three different experimental conditions, each of them consisting of 15 items. In two experimental conditions participants were stimulated via brief cognitive and affective intervention during idea generation (see Fink et al., 2011) while in the control condition no intervention was applied. The data presented in this paper are based on the 15 AU items of the control condition. At the beginning, two 2 min EEG sequences under resting conditions were recorded, the first with eyes closed, the second with eyes open. Before EEG recording, participants were carefully instructed how to perform the AU task.

The AU task started with the presentation of a fixation cross for the duration of 10 s (reference period, see **Figure 1**). Then the stimulus word (everyday object) appeared for 4 s on the screen. Subsequently, a white question mark appeared on the screen, indicating that participants had to think about useful and original ideas for the given stimulus for a time period of 10 s (idea generation period). Afterwards, the question mark changed its color into green signalizing the participants to articulate their idea within a time period of 4 s. For further analysis, the oral responses were recorded and transcribed (cf., Fink et al., 2007). At the end of each trial, participants were asked to evaluate their response either as “original” or “not original” via mouse click on the corresponding choice box on the screen. Then the next trial started. The presentation of the AU stimuli during EEG recording was fully randomized.

ANALYSIS OF AU PERFORMANCE DATA

Originality of creative idea generation in the AU task was assessed via self-rating and external ratings (Fink et al., 2007; Benedek et al., 2013). For the external ratings, nine experienced raters were instructed to judge the originality of each response of a participant on a five-point rating scale ranging from 1 (“highly original”) to 5 (“not original at all”). Inter-rater agreement was satisfactory (*intra-class correlation coefficient* = 0.76). The ratings for each response were averaged over raters to obtain a measure of idea originality. For each participant, we then divided (via median-split) the total number of ideas into trials in which more vs. less original ideas (assessed via external ratings) were generated. This distinction was used as a within-subjects factor in further analysis. A paired samples t-test ($t_{44} = 24.28$; $p < 0.001$; $M_{\text{less original ideas}} = 3.54$, $M_{\text{more original ideas}} = 2.66$) revealed that the average score of more original ideas was significantly lower (denoting higher originality) than the average score of less original ideas.

EEG DATA RECORDING AND ANALYSIS

The EEG was measured with a BrainVision BrainAmp Research Amplifier (Brain Products) with Ag/AgCl electrodes and a stretchable electrode cap from the following 19 positions after the international 10–20 system (Jasper, 1958): FP_1, FP_2, F_3, F_7, F_Z, F_4, F_8, T_7, C_3, C_Z, C_4, T_8, P_7, P_3, P_Z, P_4, P_8, O_1, O_2. The midline electrodes (F_Z, C_Z, P_Z) were not included in the statistical analysis (given that we were also interested in potential hemispheric differences). The ground electrode was located at FP_Z, the reference electrode was placed on the nose. To register eye movements, an electrooculogram (EOG) was recorded bipolarly between two electrodes diagonally placed above and below the inner and the outer canthus of the right eye. The EEG signals were filtered between 0.1 Hz and 100 Hz. An additional 50 Hz notch filter was applied. Electrode impedances were kept below 5 kΩ for the EEG and below 10 kΩ for the EOG. All signals were sampled at a frequency of 500 Hz.

EEG data were preprocessed by removing drifts and low pass filtering (50 Hz). The data were visually inspected for artifacts and artifactual epochs caused by muscle tension, eye blinks or eye movements were excluded from further analyses. Also, only trials with a valid answer were included in statistical analysis. In a next step, EEG signals were filtered by applying an FFT filter for the upper alpha frequency band (10 and 12 Hz). Power estimates were obtained by squaring filtered EEG signals, and then band power values (μV^2) were (horizontally) averaged for each single trial.

As in previous studies (e.g., Fink et al., 2009a, 2011), we quantified task-related power (TRP) changes in the upper alpha band during creative ideation. In computing TRP, 8 s time segments (out of 10 s) in the middle of the reference period (starting 1 s after the onset of the fixation cross) as well as the 8 s segment in the middle of the activation period (starting 1 s after the onset of the white question mark, cf. **Figure 1**) were

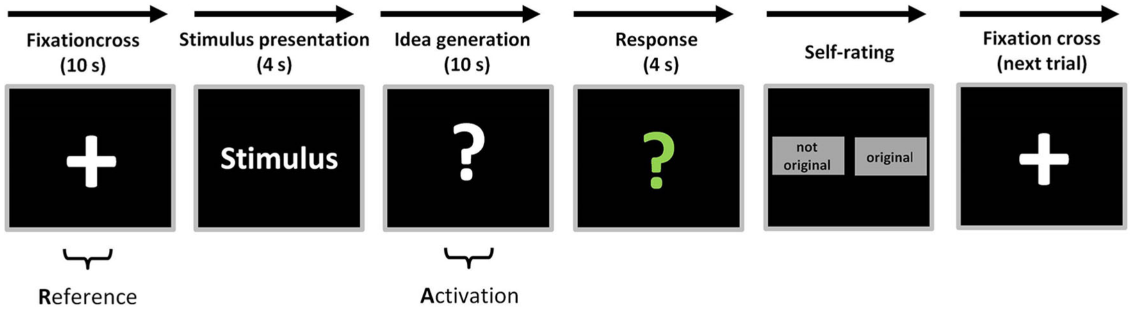

FIGURE 1 | Overview of experimental task and measurement intervals. Each AU trial started with a fixation cross for the duration of 10 s (reference period) before the stimulus word appeared for 4 s on the screen. During the presentation of the white question mark participants had to think about useful and original ideas for the stimulus for a time period of 10 s (activation period). Subsequently, the question mark changed its color into green and the participants had to articulate their most original idea within 4 s. Finally, participants were asked to evaluate their response either as “original” or “not original” via mouse click on the corresponding choice box on the screen (figure adapted from Fink et al., 2011).

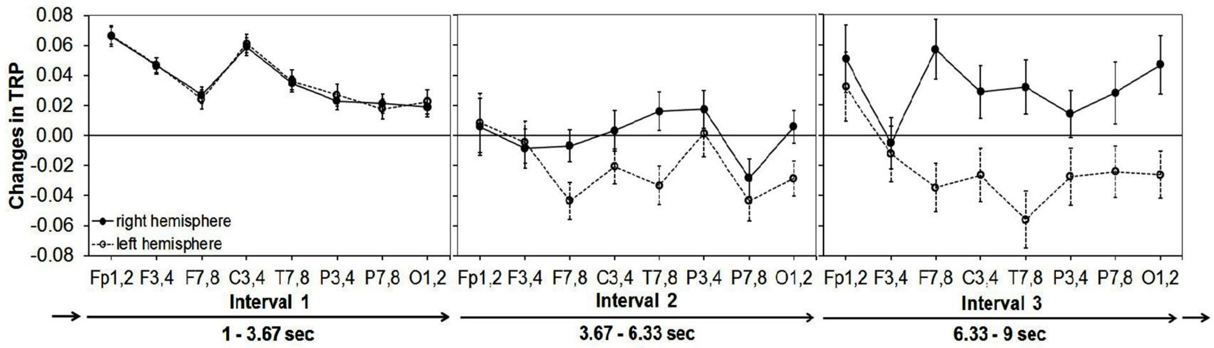

FIGURE 2 | Means and standard error bars of task-related alpha power changes (10–12 Hz) during creative idea generation for eight cortical areas of the right vs. the left hemisphere (abbreviations for cortical sites after the international 10–20 system (Jasper, 1958): FP = frontopolar, F = frontal, C = central, P = parietal, O = occipital, T = temporal; odd numbers stand for cortical sites of the left hemisphere, even numbers for corresponding cortical sites of the right hemisphere).

used. The TRP for each electrode position (i) was computed according to the formula: TRP(logPow$_i$) = log [Pow$_{i\ \text{activation}}$] − log [Pow$_{i\ \text{reference}}$] (Pfurtscheller, 1999). That means that the (log-transformed) power during the reference period (fixation cross) was subtracted from the (log-transformed) power during the activation period (creative ideation). Hence, increases in power from the reference to the activation period are reflected in positive values (i.e., referred to as alpha synchronization) whereas negative values indicate decreases in power (i.e., desynchronization). To investigate the time-course of TRP the 8-s idea generation intervals were splitted into three isochronous time intervals of 2.67 s each.

TRP values were analyzed using repeated measurement ANOVA in considering the factors ORIGINALITY (more vs. less original ideas), TIME (interval 1 [1–3.67 s], interval 2 [3.67–6.33 s], interval 3 [6.33–9 s]), HEMISPHERE (left vs. right), and POSITION (eight positions in each hemisphere) as within-subjects variables. *Post-hoc* pairwise comparisons were performed using Tukey’s HSD. In case of violations of sphericity assumptions, the multivariate approach to the repeated measurements variables was used (Vasey and Thayer, 1987) and Bonferroni *post-hoc* tests (for $\varepsilon < 0.70$) were used.

RESULTS

The ANOVA yielded significant main effects of TIME ($F_{2,88} = 6.81$, $p < 0.00$, $\eta_p^2 = 0.13$), HEMISPHERE ($F_{1,44} = 24.68$, $p < 0.00$, $\eta_p^2 = 0.36$) and POSITION ($F_{7,38} = 2.90$, $p < 0.01$, $\eta_p^2 = 0.11$) as well as significant interaction effects of TIME $*$ HEMISPHERE ($F_{2,88} = 17.70$, $p < 0.00$, $\eta_p^2 = 0.29$, TIME $*$ POSITION ($F_{14,31} = 2.48$, $p < 0.02$, $\eta_p^2 = 0.08$), HEMI SPHERE $*$ POSITION ($F_{7,38} = 4.95$, $p < 0.00$, $\eta_p^2 = 0.13$) and TIME $*$ HEMISPHERE $*$ POSITION ($F_{14,31} = 2.63$, $p < 0.01$, $\eta_p^2 = 0.07$).

Alpha synchronization was stronger in the right than in the left hemisphere, a finding that was most pronounced at frontocentral and posterior cortical sites. Regarding the time-course of creative ideation, a characteristic trend of TRP was observed: as depicted in **Figure 2**, comparatively strong alpha synchronization occurred in the first time interval of idea generation.

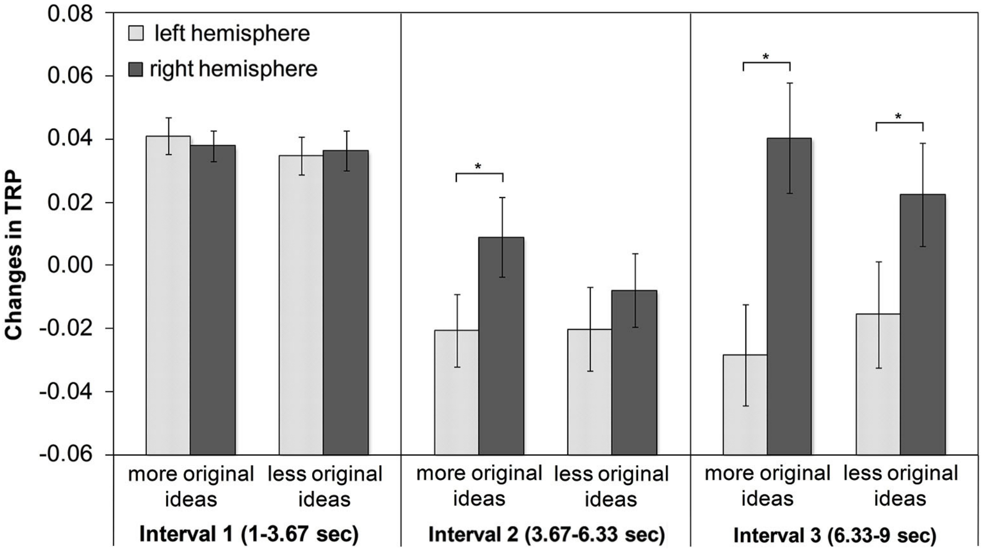

FIGURE 3 | Means and standard error bars of task-related alpha power changes (10–12 Hz) during creative idea generation for more vs. less original ideas (* Tukey HSD: $p < 0.01$)

Then, alpha power decreased (and mostly desynchronized) during the middle time segment of the idea generation period, especially over left frontal, temporal and parietal sites. In the last time interval, alpha synchronization increased again, particularly at right-hemispheric sites (see **Figure 2**). With respect to idea originality, two significant interaction effects emerged: ORIGINALITY $*$ HEMISPHERE ($F_{1,44} = 4.35$, $p < 0.05$, $\eta_p^2 = 0.09$) and ORIGINALITY $*$ TIME $*$ HEMISPHERE ($F_{2,88} = 3.10$, $p < 0.05$, $\eta_p^2 = 0.07$). The generally stronger increase in TRP in the right hemisphere was more pronounced for trials with more (vs. less) original ideas. The three-way interaction between originality, time and hemisphere is shown in **Figure 3**. During the first time interval both more and less original ideas were associated with comparatively strong alpha synchronization, similarly for both hemispheres. In the second time interval, more original ideas were associated with hemispheric asymmetry in alpha synchronization, with more TRP at right-than left-hemispheric sites. Interestingly, this asymmetry even increased at the third time interval of the idea generation period.

DISCUSSION

The findings of this study suggest that the process of creative ideation is characterized by a distinctive pattern of task-related EEG alpha power changes as a function of time. Specifically, the findings revealed a rather strong increase of alpha power at the beginning of idea generation, followed by a decrease in the middle time interval and a final re-increase of alpha that was confined to the right hemisphere. The time-course of creative ideation was also accompanied by a clear-cut pattern of increasing hemispheric lateralization: at left-hemispheric sites, alpha TRP showed a steady decline over time, whereas in the right hemisphere alpha TRP rather seemed to follow a U-shaped function. Moreover, we found significant effects related to the originality of ideas: while at the beginning of idea generation virtually no differences between more vs. less original ideas were found, at later time intervals more original ideas were associated with increases in right-, relative to left-hemispheric alpha power.

The idea generation task was preceded by a period of stimulus presentation in which the given stimulus (i.e., AU item) was read and encoded. After that, the actual idea generation took place. The initial phase of creative idea generation is typically characterized by the retrieval of dominant responses from memory such as common uses for the presented objects (Gilhooly et al., 2007; Benedek et al., 2014a). Alpha band activity is thought to be related to the controlled access and retrieval from memory (Klimesch et al., 2007; Klimesch, 2012), and this process has not been associated with hemispheric lateralization of alpha power, or, if any, with a tendency for a left-over-right difference (Klimesch et al., 1999). It appears thus reasonable to assume that the initial pattern of bilateral alpha synchronization indicates the typical first phase during idea generation, namely the recall of common ideas from memory. After this initial process of creative idea generation, a general relative decrease of alpha power was observed and also a beginning hemispheric lateralization, as this decrease was less pronounced at right-hemispheric cortical sites. This lateralization then further increased in the last time-interval, driven by a re-increase of right-hemispheric TRP that was most pronounced at frontal and posterior cortical sites. Alpha synchronization over the right posterior cortex has been observed as being specific for creative thought (Fink et al., 2009a,b; Benedek et al., 2011; Jauk et al., 2012) and has been interpreted as a sign of focused internally-directed attention in order to facilitate imaginative processes during creative thought (Benedek et al., 2011; Fink and Benedek, 2012, 2013). In the context of our findings, the middle time-interval may represent a stage of the creative process during which basic retrieval from memory is increasingly receding (as indicated by reduced bilateral alpha synchronization), at the same time paving the way for more creative, imaginative thought processes. The latter would require directed and specific memory search in semantic networks, probably mediated by alpha desynchronization over left frontal, temporal and parietal sites, accompanied by a diffuse pattern of alpha synchronization over right-hemispheric regions. For example, Jensen et al. (2002) reported a strong alpha synchronization at posterior sites of the right-hemisphere especially at the end of working on a working memory task and stated "*that the tight temporal regulation of alpha provide strong evidence that the alpha generation system is directly or indirectly linked to the circuits responsible for working memory (p.877)*". As creative idea generation proceeds, more complex processes such as mental simulation and the generation of mental images (of new and more creative object uses) are presumably going to take place (Gilhooly et al., 2007). These processes may be especially sensitive to interference from distracting irrelevant external stimulation and thus be accompanied by an even stronger right-hemispheric EEG alpha synchronization reflecting a process of task shielding (Jensen et al., 2002; Benedek et al., 2014b).

Most strikingly, the described pattern of results was more pronounced in higher original ideas compared to less original ideas (see **Figure 3**). A stronger alpha synchronization at right-hemispheric sites for higher (vs. less) original individuals or ideas has been previously reported (e.g., Grabner et al., 2007; Fink et al., 2009a). Our study extends previously reported findings (Grabner et al., 2007; Fink et al., 2009a) since we included the aspect of time-course of idea generation. Regarding the earlier increase of alpha synchronization at right-hemispheric sites for higher original ideas, we assume that ideas of high quality require the same neural circuits and mechanisms than less original ideas, but probably in a more efficient manner, as indicated by an earlier and stronger increase in alpha synchronization of right-hemispheric sites compared to ideas of lower originality. For ideas of lower originality there is also an increase in alpha synchronization of right-hemispheric sites but only in the third time interval and the underlying idea generation process seems to be less advanced compared to ideas with higher idea originality. The resulting ideas might not be as elaborated as the more original ideas and are consequently rated as less original. This finding could thus be seen as additional support for the proposed interpretation of the EEG results.

As aforementioned, the present study is a re-analyses of a previous study of our laboratory (Fink et al., 2011). Therein, participants had to work on the AU task after being stimulated via affective and cognitive interventions and without any intervention. The analyses presented in this paper are based only on the trials of the control condition (i.e., without any intervention), and in this particular context we cannot completely rule out the possibility of spill-over effects (i.e., it may be possible that the interventions of the two other conditions may also have an unsystematic impact on the trials of the control condition). However, even though such kind of effects could possibly exist, it seems less likely that they were systematic since the trials were presented in a fully randomized order. Also, we cannot completely rule out the possibility that participants thought of more than one idea. However, behavioral analyses of idea fluency in this task showed that the average number of ideas within one minute is 4 (Benedek et al., 2013). As a consequence, a 10-s task should not elicit much more than 1 idea—particularly in view of the effect that participants were instructed to produce as original ideas as possible (i.e., instruction stressed quality, rather than fluency of ideas). We concede that people may still initially generate a dominant, typical response which is, however, rejected for the sake of finding creative ideas (Gilhooly et al., 2007). The brain activation related to such an initial response tendency was discussed to be associated with the earliest time epoch during idea generation. In addition, the analysis included the comparison of brain activity patterns associated with more vs. less original ideas which allowed for stronger and more powerful conclusions about the time-course of alpha activity during the process of creative idea generation.

To summarize, this study provides first insights into the time-course of creative ideation from the neuroscience perspective. In investigating task-related alpha power changes during creative idea generation we were able to describe some of the manifold cognitive processes implicated in the process of creative idea generation at the level of brain. As the findings of this suggest, the observed time course of alpha activity may reflect the progression of different stages in the process of idea generation: the idea generation process showed an initial bilateral alpha synchronization followed by a relative decrease in alpha power and an increasing hemispheric lateralization driven by a re-increase of alpha power at right frontal and posterior cortical sites. This is an entirely novel finding and it is proposed that the distinctive patterns of task-related alpha activity as a function of time reflect the sequence of well-known stages of the creative idea generation process: that is the initial retrieval of common and old ideas, followed by the actual generation of novel and more creative ideas by overcoming typical responses through processes of mental simulation and imagination (Gilhooly et al., 2007; Fink et al., 2009a; Benedek et al., 2011, 2014b; Fink and Benedek, 2012, 2013; Jauk et al., 2012).

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The effects of a single night of sleep deprivation on fluency and prefrontal cortex function during divergent thinking

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The dorsal and ventral aspects of the prefrontal cortex (PFC) are the two regions most consistently recruited in divergent thinking tasks. Given that frontal tasks have been shown to be vulnerable to sleep loss, we explored the impact of a single night of sleep deprivation on fluency (i.e., number of generated responses) and PFC function during divergent thinking. Participants underwent functional magnetic resonance imaging scanning twice while engaged in the Alternate Uses Task (AUT) – once following a single night of sleep deprivation and once following a night of normal sleep. They also wore wrist activity monitors, which enabled us to quantify daily sleep and model cognitive effectiveness. The intervention was effective, producing greater levels of fatigue and sleepiness. Modeled cognitive effectiveness and fluency were impaired following sleep deprivation, and sleep deprivation was associated with greater activation in the left inferior frontal gyrus (IFG) during AUT. The results suggest that an intervention known to temporarily compromise frontal function can impair fluency, and that this effect is instantiated in the form of an increased hemodynamic response in the left IFG.

Keywords: sleep, fatigue, fluency, divergent thinking, executive function

INTRODUCTION

Divergent thinking includes the cluster of "abilities concerned with the ready flow of ideas and with readiness to change direction or to modify information" (Guilford, 1967, p. 139). Researchers have long been interested in how divergent thinking ability is impaired by short-term sleep deprivation, defined as sleep deprivation under 48 h. In a pioneering study on this topic, Horne (1988) found that going 32 h without sleep impaired most aspects of divergent thinking (i.e., fluency, originality, elaboration, and flexibility). Furthermore, this effect was driven not by the participants' loss of motivation or interest in the tasks, but rather "sleep loss made them fixate on previously successful strategies when attempting solutions to the next problem" (Horne, 1988, p. 535). In other words, sleep deprivation affected cognitive performance in the form of perseveration – defined as "difficulty in changing strategies" (Horne, 1988, p. 530). A subsequent study assessed divergent thinking performance following a single night of sleep deprivation and also demonstrated that it impaired flexibility in divergent thinking – a measure of the conceptual diversity of generated solutions (Wimmer et al., 1992). These early studies converged to demonstrate that short-term sleep deprivation is detrimental for divergent thinking performance.

However, what are the neuroanatomical underpinnings of the impact of short-term sleep deprivation on divergent thinking performance? Much evidence suggests that tasks loading on the prefrontal cortex (PFC) are particularly vulnerable to the impact of sleep loss (Harrison and Horne, 2000; Jones and Harrison, 2001). In this sense, sleep deprivation can be viewed as producing "a reversible functional lesion in the PFC" (Lim and Dinges, 2010, p. 376). Although engagement in divergent thinking activates a distributed network in the brain, functional magnetic resonance imaging (fMRI) studies of divergent thinking have most consistently activated the ventral and dorsal aspects of PFC (Goel and Vartanian, 2005; Fink et al., 2009; Kröger et al., 2012). Activation in these regions has been frequently linked to two processes. First, dorsal and ventral PFC form key regions in the working memory (WM) and executive function systems – necessary for the maintenance and manipulation of information in the focus of attention as well as minimizing distraction during divergent thinking (Gilhooly et al., 2007; Vartanian, 2011; Beaty and Silvia, 2012; De Dreu et al., 2012). This suggests that functional impairment in ventral and/or dorsal PFC due to short-term sleep deprivation could impair divergent thinking by negatively impacting WM and executive function.

Second, consistent with neuropsychological evidence from patient populations (Miller and Tippett, 1996; see also Goel et al., 2013), activation in ventral lateral PFC has been linked to the reduction of constraints that define concepts, thereby facilitating the ways in which they can be manipulated flexibly into new products (Vartanian and Goel, 2005; see also Abraham et al., 2012b). For example, Vartanian and Goel (2005) instructed participants to solve three types of anagrams in the fMRI scanner. On unconstrained trials, they rearranged letters to generate solutions (e.g., Can you make a "Word with ZJAZ"?). On semantically constrained trials, they rearranged letters to generate solutions within particular semantic categories (e.g., Can you make a type of "Music with ZJAZ"?). On baseline trials, they rearranged letters to make specific words (e.g., Can you make the word "JAZZ with ZJAZ"?). The critical comparison of unconstrained vs. semantically constrained trials revealed significant activation in a network including right ventral lateral PFC. Furthermore, a parametric analysis revealed that activation in this region increased as the constraints placed on the anagram search space were reduced across the three trial types. Because optimal performance on divergent thinking tasks necessitates reducing the constraints that define concepts so that they can be manipulated flexibly, functional impairment of ventral lateral PFC because of short-term sleep deprivation could impair divergent thinking by negatively impacting cognitive flexibility.

Consistent with this picture, the results of Gonen-Yaacovi et al.'s (2013) recent large-scale meta-analysis of functional imaging studies of creativity revealed that PFC regions were involved across all task types. The core creativity network was shown to consist of left lateral PFC, associated with various executive processes related to creativity (e.g., fluency, flexibility, inhibition, cognitive control, etc.). Gonen-Yaacovi et al. (2013) noted that these executive processes likely represent components of creative cognition. In addition, the core network included regions involved in the retrieval or formation of remote semantic associations, including the inferior frontal gyrus (IFG), as well as the left angular gyrus and the superior temporal gyrus. These activations were attributed to mechanisms that contribute to both the combination and generation of ideas during creative cognition.

An important recent contribution to this literature was made by Kleibeuker et al. (2013), who examined neural activity in relation to generating alternative uses or ordinary characteristics for common objects. Their results demonstrated that generating alternative uses vs. ordinary characteristics was associated with greater activity in the left angular gyrus, left supramarginal gyrus, and bilateral middle temporal gyrus. However, when they directly compared alternative uses trials in which subjects had generated two or more solutions with trials with zero or one solution, activation was observed in left middle and IFG (pars triangularis). This dissociation suggests that whereas creative idea generation is linked to a primarily left-lateralized parietal and temporal network, the generation of multiple (vs. fewer) creative ideas is associated with activation in left lateral PFC. In other words, engagement in creative cognition *per se* activates a different set of structures than those that are activated when subjects generate multiple ideas. This dissociation is particularly germane to the present study, the focus of which is not creative idea generation but rather *fluency* – defined as the number of generated responses.

Although the aforementioned evidence highlights PFC as key target region where the impact of short-term sleep deprivation on divergent thinking performance might be localized, it is unclear how this effect would manifest itself. In part, this is because the neural effects of sleep loss have been shown to be varied and context-dependent. On the one hand, researchers have observed an elevated hemodynamic response profile [based on the blood-oxygenation level-dependent (BOLD) signal] in relation to verbal learning and logical reasoning following sleep deprivation (Drummond et al., 2000, 2004, 2005; Jonelis et al., 2012). This effect has been interpreted as demonstrating the brain's compensatory ability to counteract the impairment of normal brain function in the form of increased activity. Furthermore, this compensatory response has been observed most consistently throughout PFC. On the other hand, there is evidence from WM tasks demonstrating that sleep deprivation can in fact lead to a reduction in the BOLD response in PFC (for reviews, see Dang-Vu et al., 2007; Chee and Chuah, 2008). The variability observed in the direction of the effect (i.e., increase or decrease) may be a function of task difficulty. Specifically, the cerebral compensatory response is more likely to be observed in relation to more difficult tasks (Drummond et al., 2004). For the present purposes, we hypothesized that impairment in fluency following short-term sleep deprivation would be accompanied by variation in brain activity in ventral or dorsal PFC, although we did not have an *a priori* prediction regarding the *direction* of the effect.

Furthermore, research on the neuroscience of sleep loss has demonstrated that large individual differences exist in vulnerability to its effects (Caldwell et al., 2005; Chee and Chuah, 2008). For a number of reasons, an individual-differences measure of particular interest to us was fluid intelligence. First, individual differences in fluid intelligence have been shown to predict performance on divergent thinking (and creativity) tasks (Sligh et al., 2005; Nusbaum and Silvia, 2011; Silvia and Beaty, 2012). Second, individual differences in fluid intelligence have been shown to be related to variation in brain activation in ventral and dorsal PFC (Neubauer et al., 2002, 2005; Gray et al., 2003; Lee et al., 2006; Jung and Haier, 2007; Luders et al., 2009; Neubauer and Fink, 2009; Van der Heuvel et al., 2009; Deary et al., 2010). Therefore, we explored the possibility that individual differences in fluid intelligence might influence the impact of sleep deprivation on brain activation in ventral and dorsal PFC during divergent thinking.

Complementing this individual-differences approach, we also explored the possible effects of two self-report measures on brain activation during divergent thinking. The first self-report measure was the Big Five personality factor of openness to experience (John et al., 1991), and the second was the Creative Achievement Questionnaire (CAQ), which measures recognized creative achievements across 10 domains (Carson et al., 2005). They were included because scores on both measures have been shown to be related to performance on divergent thinking tasks (McCrae, 1987; Carson et al., 2005), and could influence the extent to which a participant might be vulnerable to sleep deprivation effects on divergent thinking.

Finally, we were also interested in modeling cognitive effectiveness as a function of daily sleep. To model cognitive effectiveness, each participant in our experiment wore a wrist activity monitor for 7 days (i.e., six nights) prior to each of the fMRI scan sessions. Based on a reduction algorithm, a wrist activity monitor can discriminate a sleeping state from a waking state and thus quantify daily sleep to the nearest minute around the clock, demonstrating significant correlation with polysomnography based on electroencephalography (Dawson and Reid, 1997; Lamond and Dawson, 1999; Arnedt et al., 2001). Actigraphic data were fed into the Fatigue Avoidance Scheduling Tool (FAST^{TM}), enabling us to model cognitive effectiveness when scanning for the divergent thinking task was initiated in the scanner. Note that the modeled data do not represent a direct measure of cognitive effectiveness, but rather a derived metric. They are meant to complement our self-report measures of fatigue and sleepiness.

HYPOTHESES

We conducted an fMRI study to test the following four hypotheses: First, we predicted impairment in fluency following a single night of sleep deprivation compared to a night of normal sleep. Second, we predicted a reduction in modeled cognitive effectiveness following sleep deprivation compared to a night of normal sleep. Third, we predicted that sleep deprivation would impact PFC function in the ventral and/or dorsal regions during divergent thinking, although we had no *a priori* prediction regarding the *direction* of this effect. Fourth, we predicted that the impact of sleep deprivation on PFC function during divergent thinking would be influenced by individual differences in fluid intelligence, openness to experience, and scores on CAQ.

MATERIALS AND METHODS

PARTICIPANTS

This study was approved by Defence Research and Development Canada's Human Research Ethics Committee (DRDC HREC) and Sunnybrook Health Sciences Centre's Research Ethics Board. The participants were 13 neurologically healthy right-handed volunteers (3 females, 10 males) with normal or corrected-to-normal vision (all determined by medical questionnaire). Average age was 32.23 years (SD = 8.45). The participants received stress remuneration in accordance with DRDC HREC guidelines.

MATERIALS AND PROCEDURE

After volunteering to participate in this experiment, participants were asked to report to our laboratory 1 week prior to the first fMRI session to be equipped with a wrist activity monitor (www.ambulatory-monitoring.com/motionlogger.html). They were instructed to wear the wrist activity monitor continuously thereafter until arrival at the fMRI facility for the first scan session. Additionally, during this initial session, participants completed paper-and-pencil measures. Our measure of fluid intelligence was *Raven's Advanced Progressive Matrices* (*RAPM*; Raven et al., 1998). All participants were tested individually. We used a shortened form of the RAPM with 12 problems (Bors and Stokes, 1998). Each participant was given 10 min to complete as many problems as possible (see Vartanian et al., 2013). They also completed the Big Five Inventory (BFI) and the CAQ.

The two fMRI assessments occurred 1 week apart – once following one night of sleep deprivation and once following a night of normal sleep. The order of scans was counterbalanced across participants such that for six participants sleep deprivation occurred prior to the first fMRI scan, whereas for seven participants sleep deprivation occurred prior to the second fMRI scan[1]. Each participant reported to our laboratory for the sleep deprivation session, instructed to arrive at 8 p.m. on the evening prior to the scan. They were instructed not to consume any caffeine, nicotine, or alcohol for 24 h prior to the scan session, were not allowed to leave the laboratory during the sleep deprivation session, and were monitored by staff at all times to ensure that they did not fall asleep[2]. Participants were allowed to read, watch TV, use the telephone, and engage in conversation with research staff. They were provided with two items of food and two beverages during their stay in the laboratory, and could also bring their own snacks and drinks as long as they contained no caffeine, nicotine, or alcohol. They completed the Stanford Sleepiness Scale (SSS) and the Psychomotor Vigilance Task (PVT) hourly between 8 p.m. and 6 a.m. (Hoddes et al., 1973; Dinges and Powell, 1985). On each trial of PVT, participants were instructed to press the spacebar as quickly as possible following the detection of a single target appearing at the center of the computer screen. Participants were brought to the cafeteria for a light breakfast (excluding coffee) prior to departure to the scanning facility (Sunnybrook Health Sciences Centre, Toronto, ON, Canada). In contrast, for scanning following a normal night of sleep, participants were instructed to arrive at our laboratory at 7 a.m. on the day of the scan. They were also instructed not to consume any caffeine, nicotine, or alcohol for 24 h prior to the scan session. All participants were transported by a designated driver, and accompanied by research staff to the scanning facility in order to arrive onsite at 7:30 a.m. All fMRI scans were collected between 8 and 10 a.m.

Upon arrival at the scanning facility, the participants completed the Multidimensional Fatigue Inventory (MFI; Smets et al., 1995) and a brief questionnaire about caffeine, nicotine, and alcohol consumption during the previous 24 h. They were then given instructions about, and examples from, the Alternate Uses Task (AUT). The AUT is a classic and perhaps the most commonly used measure of divergent thinking ability (Guilford, 1967). It instructs participants to generate as many uses as possible for common objects (e.g., brick). In the present study, we only measured fluency, operationalized as the number of generated uses to each prompt. The scanner version of the AUT was modeled after Fink et al. (2009), an identical version of which was administered by our group in a recent fMRI study on divergent thinking (Vartanian et al., 2013). The task was presented in two blocks (i.e., uses and characteristics), the order of which was counterbalanced across participants. Each of the 20 trials in the *uses* block had the same structure. During the *generation* phase, participants were presented with the name of a common object (e.g., knife) and instructed to think of as many uses for it as possible for 12 s. In this phase, the name of the object appeared in black ink. The *response* phase followed immediately afterward during which participants were given 3 s to enter the

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[1] Previous neuroscientific protocols involving data collection following nights of sleep deprivation and normal sleep have shown that when administered in counterbalanced order, a gap of 4–7 days is sufficient between sessions (e.g., Mograss et al., 2009).

[2] Although dietary caffeine consumption *and* withdrawal are potential confounding variables in fMRI (Field et al., 2003), we opted to restrict consumption to minimize its potential mitigation of the effects of sleep deprivation on fatigue and sleepiness.

number of generated uses (using an MRI-compatible response pad). In this phase the name of the object appeared in green. Note that in the response phase participants were not instructed to enter the actual uses they had generated, but rather the digit on the keypad corresponding to the number of uses generated in response to the prompt. This color change acted as a prompt to enter the response as quickly as possible[3]. This was followed by an ITI (inter-trial interval) which consisted of three adjacent plus signs (+ + +) varying randomly between 4 and 6 s. Each trial in the *characteristics* block had an identical structure, except that participants were instructed to recall, from long-term memory, physical features characteristic of the object. For example, possible physical features for "knife" could be solid, sharp, metallic, etc.[4] Note that in the response phase participants were not instructed to enter the actual physical features they had recalled from long-term memory, but rather the digit on the keypad corresponding to the total number of features recalled in response to the prompt.

fMRI ACQUISITION AND ANALYSIS

A 3-Tesla MR scanner with an eight-channel head coil (Discovery MR750, 22.0 software, GE Healthcare, Waukesha, WI, USA) was used to acquire T1 anatomical volume images (0.86 mm × 0.86 mm × 1.0 mm voxels). For functional imaging, T2*-weighted gradient echo spiral-in/out acquisitions were used to produce 26 contiguous 5 mm thick axial slices [repetition time (TR) = 2 s; echo time (TE) = 30 ms; flip angle (FA) = 70°; field of view (FOV) = 200 mm; 64 × 64 matrix; voxel dimensions = 3.1 mm × 3.1 mm × 5.0 mm], positioned to cover the whole brain. The first five volumes were discarded to allow for T1 equilibration effects. The number of volumes acquired was 418 (per session).

Data were analyzed using Statistical Parametric Mapping (SPM8). Head movement was less than 2 mm in all cases. We implemented five preprocessing steps in the following order. We began by slice timing, used to correct for temporal differences between slices within the same volume, using the first slice within each volume as the reference slice. This was followed by realignment and coregistration to ensure that all volumes from the two sessions were realigned to the first volume from the first session. A mean image created from realigned volumes was spatially normalized to the Montreal Neurological Institute echo planar imaging (MNI EPI) brain template using non-linear basis functions. Voxel size after normalization was the SPM8 default, namely 2 mm × 2 mm × 2 mm. The derived spatial transformation was applied to the realigned T2* volumes, and spatially smoothed with an 8 mm full-width at half-maximum (FWHM) isotropic Gaussian kernel. Time series across each voxel were high-pass filtered with a cut-off of 128 s, using cosine functions to remove section-specific low frequency drifts in the BOLD signal. Condition effects at each voxel were estimated according to the general linear model (GLM) and regionally specific effects compared using linear contrasts. The BOLD signal was modeled as a box-car, convolved with a canonical hemodynamic response function. Each contrast produced a statistical parametric map consisting of voxels where the z-statistic was significant at $p < 0.001$. Using a random-effects analysis, reported activations survived a voxel-level intensity threshold of $p < 0.001$ (uncorrected for multiple comparisons), and a minimum cluster size of 40 contiguous voxels (Lieberman and Cunningham, 2009; see also Forman et al., 1995).

Using an event-related design, for each session we specified the following regressors corresponding to (1) the generation phase (i.e., uses), (2) the number of uses varying parametrically with the generation phase (first-order polynomial expansion exploring their linear relationship), and (3) the recollection phase (i.e., characteristics), (4) the number of characteristics varying parametrically with the recollection phase (first-order polynomial expansion exploring their linear relationship). Although incorporated into the design, (5) response phase, (6) motor response, and (7) ITI were modeled out of the analyses by assigning null weights to their respective regressors.

RESULTS

MANIPULATION CHECKS

We first ascertained the effectiveness of our sleep deprivation procedure by analyzing hourly reaction time (RT) data from PVT (for fatigue) and SSS scores (for sleepiness). For PVT, there was a linear increase in RT throughout the night, $F(1,11) = 23.07$, $p = 0.001$, $\eta_p^2 = 0.68$. Similarly, for SSS, there was a linear increase in ratings throughout the night, $F(1,10) = 20.20$, $p = 0.001$, $\eta_p^2 = 0.67$.[5] Next, we compared MFI data collected immediately prior to entry into the fMRI scanner on both days. The results demonstrated that self-rated fatigue was higher following a night of sleep deprivation than following a night of normal sleep on all subscales of MFI: general [$t(12) = 4.90$, $p = 0.001$, $d = 1.81$], physical [$t(12) = 2.46$, $p = 0.030$, $d = 0.81$], activity [$t(12) = 3.15$, $p = 0.008$, $d = 0.62$], motivation [$t(12) = 2.58$, $p = 0.024$, $d = 0.73$], and mental [$t(12) = 2.38$, $p = 0.035$, $d = 0.81$][6]. There was no difference in self-reported consumption of caffeine [$t(8) = -1.98$, $p = 0.083$, $d = -0.79$], nicotine [$t(8) = -1.00$, $p = 0.347$], or alcohol [$t(8) = -1.00$, $p = 0.347$] in the 24 h prior to two scan sessions[7].

BEHAVIORAL DATA

As predicted, the results demonstrated that participants generated fewer uses for objects (averaged across the uses generated for each of the 20 prompts) following a night of sleep

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[3] The dissociation between the generation phase and the response phase is implemented so that brain activation due to fluency is not confounded with brain activation due to the motor movement of pressing a button.

[4] The characteristics block was included to mimic Fink et al.'s (2009) design as closely as possible. It is used as a control condition for recall from long-term memory. We did not test any hypotheses involving the effect of sleep deprivation on recall from long-term memory.

[5] We were not able to collect complete SSS data from one subject.

[6] Throughout the manuscript Cohen's d is used as a measure of effect size for t tests. We used the following online calculator for calculating d: www.cognitiveflexibility.org/effectsize/

[7] Self-reported data on the consumption of caffeine, nicotine, and alcohol were only available from nine participants. Cohen's d for nicotine and alcohol could not be calculated because in both cases the average consumption following sleep deprivation was 0 (SD = 0).

deprivation ($M = 4.59$, SD = 1.70) than following a night of normal sleep ($M = 5.53$, SD = 1.35), $t(12) = 3.09$, $p = 0.009$, $d = 0.61$. Similarly, they recalled fewer characteristics (averaged across the characteristics recalled for each of the 20 prompts) following a night of sleep deprivation ($M = 4.98$, SD = 1.32) than following a night of normal sleep ($M = 5.86$, SD = 1.42), $t(12) = 2.46$, $p = 0.030$, $d = 0.64$. RT was calculated from the beginning of the response phase when the name of the object appeared in green. There was no difference in RT for generating uses for objects after sleep deprivation ($M = 978$ ms, SD = 312) and a night of normal sleep ($M = 892$ ms, SD = 311), $t(12) = -0.735$, $p = 0.989$, $d = 0.28$. Similarly, there were no difference in RT for recalling characteristics following a night of sleep deprivation ($M = 918$ ms, SD = 283) and a night of normal sleep ($M = 904$ ms, SD = 310), $t(12) = -0.26$, $p = 0.802$, $d = 0.07$.

MODELED COGNITIVE EFFECTIVENESS

Modeled cognitive effectiveness (at time of initiating fMRI scanning) was derived by analyzing the FAST$^{\text{TM}}$ models which are based on the actigraphically measured sleep data[8]. The FAST$^{\text{TM}}$ algorithm is based on variations in time of day, biological rhythms, time spent awake, and amount of sleep. Fitted and transformed FAST$^{\text{TM}}$ graphs from a representative participant are illustrated in **Figure 1**. Three participants failed to provide complete actigraph data. Therefore, modeled cognitive effectiveness was computed for the remaining 10 participants. As predicted, modeled cognitive effectiveness was lower at time of fMRI data acquisition following a night of sleep deprivation ($M = 68.98\%$, SD = 3.38) than following a night of normal sleep ($M = 91.36\%$, SD = 4.72), $t(9) = 11.58$, $p = 0.000001$, $d = 3.70$.

COVARIATES

Average RAPM score was 8.46 (SD = 1.45). For BFI, the average score for openness to experience was 3.50 (SD = 0.40)[9]. For CAQ, average score was 8.77 (SD = 10.80). There was no correlation between RAPM and openness to experience [$r(11) = 0.38$, $p = 0.195$], RAPM and CAQ [$r(11) = 0.42$, $p = 0.151$], and CAQ and openness to experience [$r(11) = 0.11$, $p = 0.719$]. There were no differences between males and females in RAPM [$t(11) = 1.09$, $p = 0.299$, $d = 0.87$], openness to experience [$t(11) = 0$, $p = 1$, $d = 0$], or CAQ [$t(11) = 0.10$, $p = 0.923$, $d = 0.08$] scores, although our small sample size limits an exploration of sex differences. Although there is evidence to suggest that openness to experience is correlated positively with general intelligence (Ackerman and Heggestad, 1997; Gignac et al., 2004), as well as CAQ (Silvia et al., 2009), the absence of significant correlations among the three variables in the present sample meant that we opted to explore the role of each variable independently on the effect of sleep deprivation on brain function.

fMRI DATA

We began our target analyses of interest by first examining the uses–rest (ITI) and recalling characteristics–rest (ITI) contrasts following a night of normal sleep. As can be seen in **Table 1** and **Figure 2**, the uses–rest and recalling characteristics–rest contrasts activated two dissociable networks. Most noticeably, whereas the recalling characteristics–rest contrast activated a bilateral network centered largely in the parietal and temporal lobes, the uses–rest contrast activated a network including the left IFG. We then examined the uses–recalling characteristics contrast following a night of normal sleep. This contrast revealed activations in the right middle temporal gyrus, cingulate gyrus, and left precuneus (**Table 1**).

Next, we examined the uses–rest (ITI) and recalling characteristics–rest (ITI) contrasts, following sleep deprivation. Again, these contrasts demonstrated dissociable patterns of activation for generating uses vs. recalling characteristics (**Table 1**; **Figure 2**). Specifically, generating uses was associated with a primarily left-lateralized pattern of activation, with the largest cluster centered within the left IFG. In contrast, recalling characteristics was associated with a distributed bilateral pattern of activation involving the frontal, parietal, and temporal lobes. Then, we examined the uses–recalling characteristics contrast following sleep deprivation. This contrast revealed exclusive activation in the left IFG (**Table 1**; **Figure 3**).

To further isolate specific task-related activations underlying fluency and recalling characteristics under sleep deprivation vs. a night of normal sleep, we carried out three additional contrasts (of contrasts). The first involved uses–rest (sleep deprivation)–uses–rest (normal sleep), revealing activations in left superior temporal gyrus and IFG (**Table 1**). The second contrast involved recalling characteristics–rest (sleep deprivation)–recalling characteristics–rest (normal sleep), revealing no suprathreshold activation. Similarly, the third contrast involving uses–recalling characteristics (sleep deprivation)–uses–recalling characteristics (normal sleep) did not reveal any suprathreshold activation.

Finally, we examined whether RAPM, openness to experience, or CAQ had a significant effect on the activation patterns (when entered as covariates into the analysis). In each case, the results remained largely identical.

DISCUSSION

The results demonstrated that our sleep deprivation intervention was effective in producing greater levels of fatigue and sleepiness in our participants compared to a night of normal sleep. Specifically, RT on PVT and ratings on SSS were progressively higher between 8 p.m. and 6 a.m. on the night of sleep deprivation, as were fatigue ratings on all five dimensions of MFI immediately prior to entry into the fMRI scanner in the morning following sleep deprivation. Furthermore, modeled cognitive effectiveness also exhibited significant reduction following sleep deprivation, suggesting that the participants' capacity for engagement in cognitive tasks was diminished compared to a night of normal sleep. These results are necessary manipulation checks for interpreting our measures of interest.

Following a night of normal sleep, the uses–rest contrast revealed activation in a small network of regions shown previously to be activated in divergent thinking tasks

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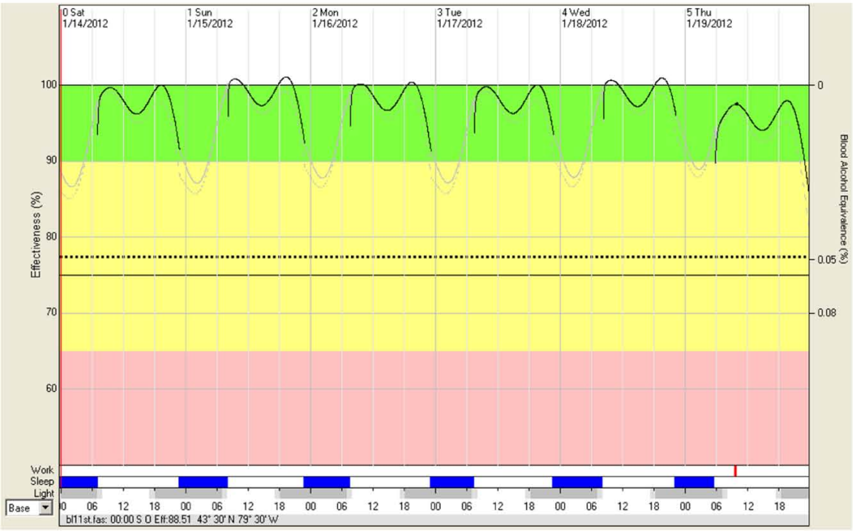
[8] The model underlying FAST$^{\text{TM}}$ is SAFTE$^{\text{TM}}$ (Sleep, Activity, Fatigue, and Task Effectiveness; Hursh et al., 2004). Specifically, FAST$^{\text{TM}}$ is the interface for generating graphical representations of effectiveness scores, which are predictions derived from SAFTE$^{\text{TM}}$.

[9] Although unrelated to our *a priori* hypotheses, for interested readers we also calculated BFI scores for extraversion ($M = 3.12$, SD = 0.68), agreeableness ($M = 3.91$, SD = 0.69), conscientiousness ($M = 3.91$, SD = 0.37), and neuroticism ($M = 2.42$, SD = 0.59).

Actigraph data for 6 nights prior to fMRI scanning following a night of normal sleep



Actigraph data for 6 nights prior to fMRI scanning following a night of sleep deprivation

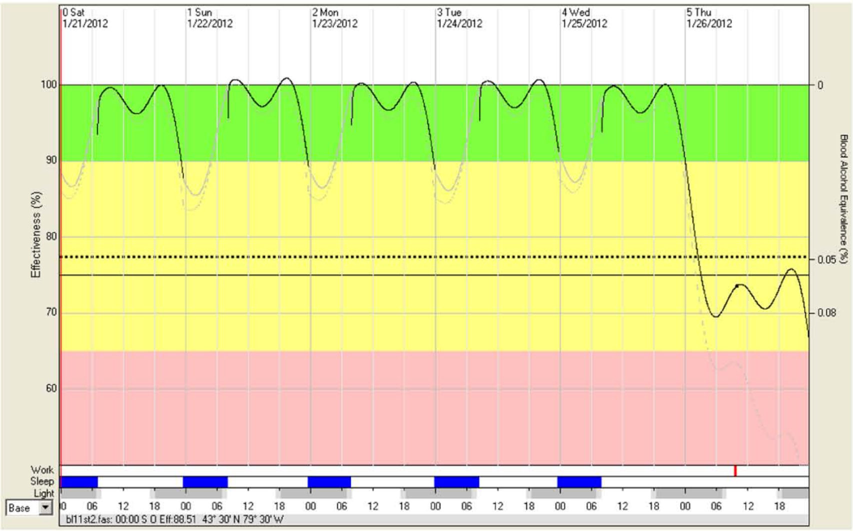


FIGURE 1 | Impairment in modeled cognitive effectiveness as a function of sleep deprivation. The vertical axis on the *left* side of the FAST^{TM} graphs represents fitted and transformed modeled cognitive effectiveness as a percentage of optimal performance (100%). The oscillating line in the diagram represents average modeled cognitive effectiveness as determined by time of day, biological rhythms, time spent awake, and amount of sleep. The vertical axis on the *right* side of FAST^{TM} graphs represents the Blood Alcohol Content (BAC) equivalency throughout the spectrum of modeled cognitive effectiveness. A value of 77% modeled cognitive effectiveness corresponds to a blood alcohol content of 0.05% (legally impaired in some jurisdictions). A value of 70% modeled cognitive effectiveness corresponds to a blood alcohol content of 0.08% (legally impaired in most jurisdictions). The dotted line represents the lower 10th percentile of modeled cognitive effectiveness. The green band (from 90 to 100%) represents acceptable modeled cognitive performance effectiveness for workers conducting safety sensitive jobs (e.g., flying, driving, weapons operation, command and control, etc.). The yellow band (from 65 to 90% modeled cognitive effectiveness) indicates caution. Personnel engaged in skilled performance activities such as aviation are recommended not to operate in this bandwidth. The area from the dotted line to the pink area represents the modeled cognitive effectiveness equivalent to the circadian nadir and a second day without sleep. The pink band (below 65%) represents performance effectiveness after two days and one night of sleep deprivation. The abscissa (*x*-axis) illustrates a single 15-min period (red bar) during the fMRI scans for each of the baseline and sleep deprivation conditions as well as sleep timing/duration (blue bars), darkness (gray bars), and time of day in hours. The red bar shows a thickening of the modeled cognitive effectiveness line (immediately above the red bar), reflecting cognitive effectiveness during the fMRI scans.

Table 1 | Coordinates for the activations reported in the text.

Analysis	Structure	*x*	*y*	*z*	*z-Score*	*k*
Uses–rest (normal sleep)	Medial frontal gyrus	−10	6	64	4.18	144
	Inferior frontal gyrus	−44	32	12	3.71	139
	Caudate	6	8	−12	3.68	59
	Lingual gyrus	14	−90	−8	3.63	44
Recalling characteristics–rest (normal sleep)		−20	−64	−10	5.09	254
	Parahippocampus	28	−54	−6	4.54	509
	Inferior parietal lobule	−56	−26	50	4.28	71
	Paracentral lobule	−10	−8	56	4.24	204
	Inferior parietal lobule	−58	−20	38	4.23	134
	Hippocampus	−28	−14	−22	4.08	392
	Precentral gyrus	−28	−16	64	4.01	68
	Fusiform gyrus	−28	−62	−20	3.92	212
	Middle temporal gyrus	−58	−22	−8	3.92	99
	Insula	36	−2	12	3.90	340
	Insula	−46	−12	16	3.80	61
	Superior temporal gyrus	28	4	−16	3.50	75
Uses–recalling characteristics (normal sleep)	Middle temporal gyrus	54	−10	−22	3.79	66
	Cingulate gyrus	0	−18	34	3.55	41
	Precuneus	−8	−62	32	3.49	47
Uses–rest (sleep deprivation)	Middle frontal gyrus	60	10	40	4.82	243
	Inferior frontal gyrus	−50	14	14	4.47	2476
	Middle temporal gyrus	48	−38	2	4.17	111
	Middle temporal gyrus	−58	−44	−14	4.06	617
	Middle frontal gyrus	−30	12	58	3.99	66
	Postcentral gyrus	62	−16	34	3.92	145
	Medial frontal gyrus	−8	10	56	3.91	399
	Middle frontal gyrus	−24	−6	56	3.82	102
	Medial frontal gyrus	−24	52	8	3.74	64
	Putamen	−18	12	2	3.57	239
	Cerebellum	34	−62	−30	3.47	55

(Continued)

Table 1 | Continued

Analysis	**Structure**	***x***	***y***	***z***	***z-Score***	***k***
Recalling characteristics–rest (sleep deprivation)	Medial frontal gyrus	−14	56	22	5.17	1435
	Insula	−48	−8	−6	4.73	832
	Middle temporal gyrus	−60	−52	−2	4.05	105
	Superior temporal gyrus	−46	−36	16	3.96	215
	Middle temporal gyrus	62	−52	−6	3.85	184
	Superior temporal gyrus	52	−50	18	3.77	642
	Culmen	14	−38	−28	3.76	95
	Superior occipital gyrus	38	−84	34	3.74	45
	Middle frontal gyrus	32	42	20	3.74	173
	Middle frontal gyrus	30	50	8	3.55	225
	Inferior parietal lobule	54	−54	46	3.30	73
Uses–recalling characteristics (sleep deprivation)	Inferior frontal gyrus	−52	24	10	3.51	73
Uses–rest (sleep deprivation)–uses–rest (normal sleep)	Superior temporal gyrus	−58	−58	20	5.00	56
	Inferior frontal gyrus	−46	40	2	3.41	50
Recalling characteristics–rest (sleep deprivation)–recalling characteristics–rest (normal sleep)	No suprathreshold activation					
Uses–recalling characteristics (sleep deprivation)–uses–recalling characteristics (normal sleep)	No suprathreshold activation					

k – cluster size (number of contiguous voxels), The coordinates are reported in MNI space.

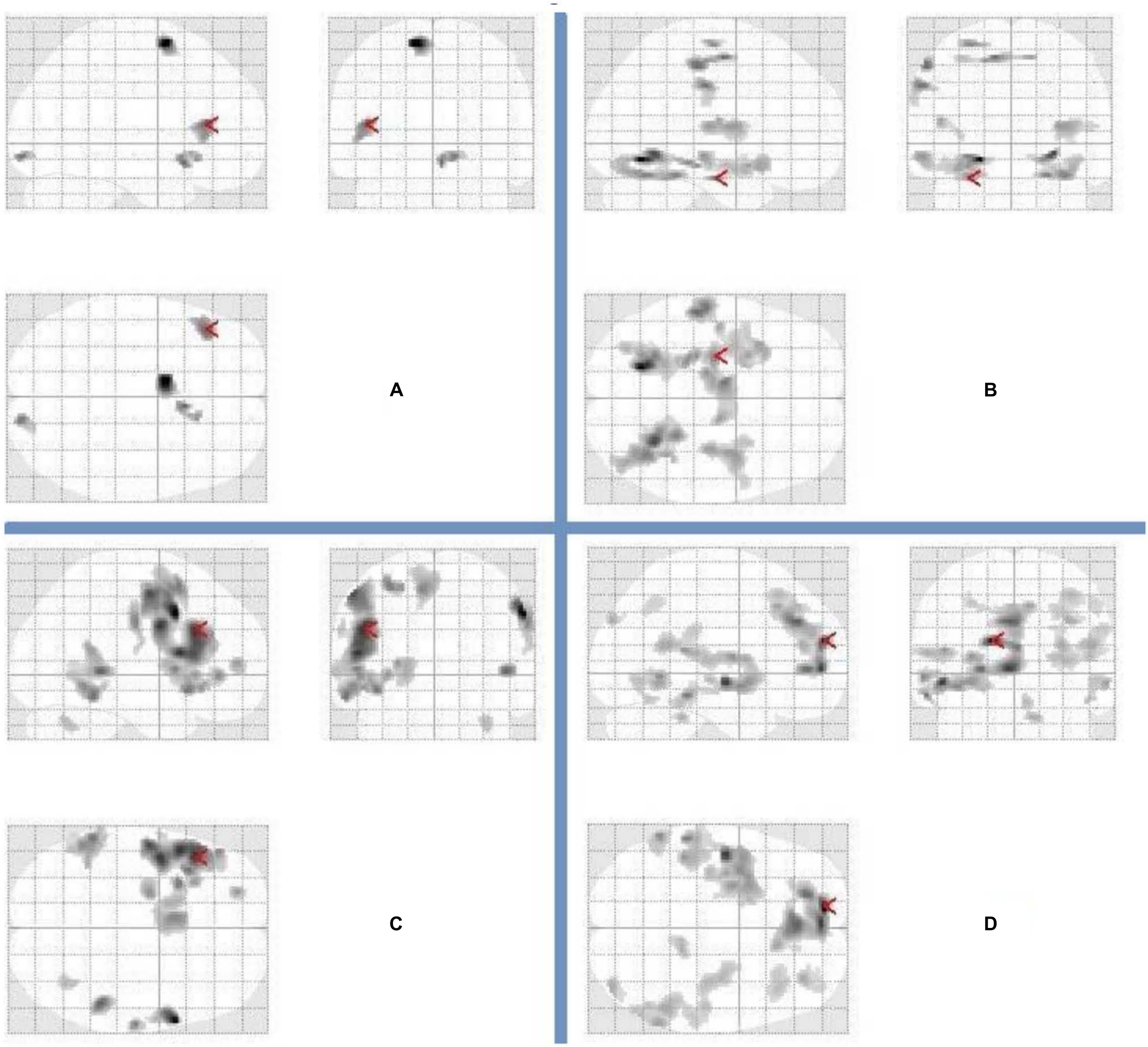


FIGURE 2 | Patterns of brain activation for divergent thinking (fluency) and recalling characteristics following a night of normal sleep and sleep deprivation. Glass brains representing activations in relation to **(A)** uses–rest following a night of normal sleep (arrow points to the left inferior frontal gyrus), **(B)** recalling characteristics–rest following a night of normal sleep (arrow points to the left hippocampus), **(C)** uses–rest following sleep deprivation (arrow points to the left inferior frontal gyrus), **(D)** recalling characteristics–rest following sleep deprivation (arrow points to the left medial frontal gyrus). The complete list of activations appears in **Table 1**.

(Chávez-Eakle et al., 2007; Fink et al., 2009; Abraham et al., 2012a; Kröger et al., 2012). Notable among the activated regions is left IFG, which was also shown to be activated in Fink et al.'s (2009) uses–fixation contrast using a similar paradigm. In turn, the recalling characteristics–rest contrast activated a bilateral network centered largely in the parietal and temporal lobes. Many of the activated regions in the temporal lobes – specifically those located in the medial temporal lobe (e.g., hippocampus and parahippocampus) – have been historically implicated in long-term memory (e.g., Squire and Zola-Morgan, 1991). Furthermore, the fusiform gyrus has been shown to contribute to the representation of object concepts in the brain (Martin, 2007). As such, their activation here is consistent with the requirements of the task (i.e., recollection of object characteristics). The uses–recalling characteristics contrast revealed activations in the right middle temporal gyrus, cingulate cortex, and left precuneus. Gonen-Yaacovi et al.'s (2013) recent large-scale meta-analysis demonstrated the reliable contributions of the middle temporal gyrus, the precuneus, and the cingulate gyrus across creativity tasks (see also Kleibeuker et al., 2013).

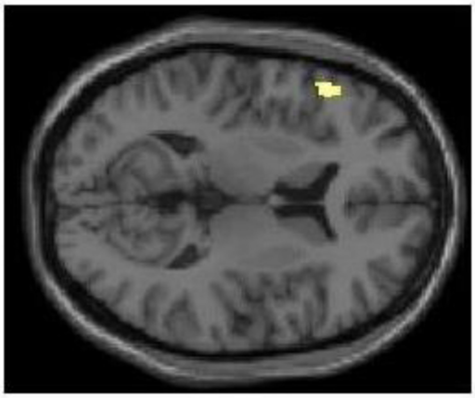


FIGURE 3 | Following sleep deprivation the left inferior frontal gyrus was activated more when generating uses (fluency) in the divergent thinking task. Following sleep deprivation, there was greater activation in left inferior frontal gyrus when generating uses (compared to recalling characteristics) in the Alternate Uses Task. SPM rendered into standard stereotactic space and superimposed on to transverse MRI in standard space.

However, our focal interest in the present study consisted of examining patterns of activation in relation to fluency following sleep deprivation. The results demonstrated that following sleep deprivation, generating uses (compared to rest) was associated with a primarily left-lateralized pattern of activation, with the largest cluster centered within the left IFG. Much like the picture that emerged following a night of normal sleep, the pattern of brain activation in relation to generating uses was clearly dissociable from the pattern of brain activation in relation to recalling characteristics. Critically for testing our focal hypothesis, the uses–recalling characteristics contrast following sleep deprivation revealed exclusive activation in the left IFG. Our results suggest that the greater recruitment of PFC following short-term sleep deprivation – consistently observed in studies of verbal learning and logical reasoning – can be extended to fluency in divergent thinking. In other words, the elevated BOLD response in the left IFG might signal compensation due to sleep deprivation (Drummond et al., 2000, 2004, 2005; Jonelis et al., 2012).

The notable commonality across verbal learning, logical reasoning and divergent thinking tasks is that they all draw on WM and executive function, well known to engage lateral and inferior PFC. Perhaps not surprisingly, several recent studies have shown that divergent thinking ability (and creativity more broadly) draws heavily on executive function and WM (Sligh et al., 2005; Gilhooly et al., 2007; Nusbaum and Silvia, 2011; Beaty and Silvia, 2012; Benedek et al., 2012; De Dreu et al., 2012). Greater executive function and WM capacity have been shown to aid creative production in at least two ways. First, mechanistically, they increase one's capacity to maintain and manipulate information in the focus of attention in the service of product generation. Second, motivationally, executive function and WM capacity enhance persistence, thereby minimizing undesirable mind wandering that would otherwise lead to premature cessation of problem solving (De Dreu et al., 2012). Evidence showing that impairment in fluency following sleep deprivation is accompanied by greater activation in left IFG is consistent with the account that executive function and WM likely play a role in response generation.

Our interpretation is also consistent with evidence regarding the role of IFG in controlled selection and retrieval of semantic information (e.g., Fink et al., 2009; Abraham et al., 2012a; Kröger et al., 2012). Strong evidence for this link was provided by Gonen-Yaacovi et al.'s (2013) meta-analysis which revealed that activation in a set of areas consisting of the left inferior frontal junction (BA 44/46) extending to dorsolateral PFC, left IFG (BA 45/47), and left angular gyrus (BA 39) was associated with generation *as well as* combination of remote ideas – both of which require the controlled selection and retrieval of semantic information. Those processes likely also draw on WM and executive function, such that the activation of IFG in the present study may reflect WM and executive function involvement in the service of selection and retrieval of semantic information.

Notably, the joint results of the three contrasts (of contrasts) conducted to isolate specific task-related activations support the conclusion that the activations observed in left IFG and superior temporal gyrus in relation to fluency under sleep deprivation are more likely due to general WM and executive function processes – including controlled selection and retrieval of semantic information – rather than more specific processes that distinguish fluency from recalling characteristics. Specifically, whereas the contrast of uses–rest (sleep deprivation)–uses–rest (normal sleep) revealed activations in left superior temporal gyrus and IFG, the contrast of uses–recalling characteristics (sleep deprivation)–uses–recalling characteristics (normal sleep) revealed no suprathreshold activation.

It is important to note that divergent thinking ability is not defined exclusively by executive function and WM capacity, despite the fact that they are necessary for establishing attentional control. In fact, evidence suggests that divergent thinking thrives as a function of flexible switching between focused and defocused modes of cognition as a function of task demands (Vartanian, 2009; Zabelina and Robinson, 2010; Wiley and Jarosz, 2012). The data presented here suggest that by disrupting sleep, one impairs fluency likely by disrupting the neural networks necessary for establishing attentional control. It will require additional experimentation to determine whether disrupting the neural networks that underlie defocused modes of cognition (e.g., the default network) will result in similar impairments in divergent thinking.

Interestingly, accounting for individual differences in fluid intelligence, openness to experience, and creative achievement did not change the magnitude of the response in PFC in fluency following short-term sleep deprivation. This result must be viewed with caution because our small sample size was not optimal for fully exploring the impact of individual differences on brain activation.

Related to this issue, the small sample size used in the present study represents a methodological limitation of our design. Although we used a liberal voxel-level criterion for reporting our results, all reported activations also survived a cluster-level correction of 40 contiguous voxels – four times the recommended minimum cluster size (i.e., 10) for selecting reliable activations (Lieberman and Cunningham, 2009; see also Forman et al., 1995).

Because of our small sample size, the robustness of our findings must be determined in future replications.

Furthermore, we assessed performance on AUT only using *fluency*, represented by the total number of generated responses to a prompt. Although fluency accounts for a significant portion of the variance in divergent thinking tasks (Plucker and Renzulli, 1999), it is not itself a measure of creative cognition. In this sense, the results of the recent study by Kleibeuker et al. (2013) are particularly germane for interpreting our data. Their results demonstrated that the act of divergent thinking – when measured as a function of the production of multiple responses – recruits left PFC. In contrast, creative cognition in the context of a divergent thinking task recruits a more distributed network, including bilateral PFC. Because our participants were instructed to generate as many solutions as possible to prompts and we focused fully on fluency, the involvement of the left PFC exclusively in the contrast of interest (**Figure 3**) should be attributed to the demand to generate multiple responses rather than the demand to generate creative responses.

The results of the present study should be interpreted within the context of Lim and Dinges' (2010) recent meta-analysis, which demonstrated that short-term sleep deprivation impairs a wide host of cognitive outcome variables including simple attention, complex attention, processing speed, WM, and short-term memory. Given that divergent thinking draws on many of these component processes – notably complex attention (i.e., executive function) and WM (Gilhooly et al., 2007; Beaty and Silvia, 2012; De Dreu et al., 2012) – its behavioral profile under short-term sleep deprivation demonstrates that divergent thinking performance will be affected by targeting its component processes. In addition, our results demonstrate that impairment in fluency following short-term sleep deprivation is likely to be instantiated in brain structures that underlie its component processes, in this case the left IFG.

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