CREATIVITY AND MENTAL IMAGERY

EDITED BY: Massimiliano Palmiero, Laura Piccardi, Raffaella Nori, Liana Palermo, Carola Salvi and Cecilia Guariglia

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CREATIVITY AND MENTAL IMAGERY

Topic Editors:
Massimiliano Palmiero, Fondazione Santa Lucia, IRCCS & University of L'Aquila, Italy
Laura Piccardi, Fondazione Santa Lucia, IRCCS & University of L'Aquila, Italy
Raffaella Nori, University of Bologna, Italy
Liana Palermo, Magna Græcia University of Catanzaro, Italy
Carola Salvi, Northwestern University & Rehabilitation Institute of Chicago, USA
Cecilia Guariglia, IRCCS & Sapienza University of Rome, Italy

Creativity is increasingly attracting attention of scientific community given its role in different aspects of human life. So far we have only began to understand its complexity and how it correlates with other cognitive processes. A further understanding of its key processes is essential to better implement applications of creativity tools to daily life. Therefore, it is the aim of this Research Topics to further elucidate how creativity can be measured, and its components, such as mental imagery, are determined.

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Section 4 - Creativity: New measures

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EDITORIAL
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Editorial: Creativity and Mental Imagery

Massimiliano Palmiero[1,2]*, *Laura Piccardi*[1,2], *Raffaella Nori*[3], *Liana Palermo*[4], *Carola Salvi*[5,6] and *Cecilia Guariglia*[7]

[1] Neuropsychology Unit, Fondazione Santa Lucia, I.R.C.C.S, Rome, Italy, [2] Department of Life, Health and Environmental Sciences, University of L'Aquila, L'Aquila, Italy, [3] Department of Psychology, University of Bologna, Bologna, Italy, [4] Department of Medical and Surgical Sciences, Magna Græcia University of Catanzaro, Catanzaro, Italy, [5] Department of Psychology, Northwestern University, Evaston, IL, USA, [6] Rehabilitation Institute of Chicago, Chicago, IL, USA, [7] Department of Psychology, Sapienza University of Rome, Rome, Italy

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The Editorial on the Research Topic

Creativity and Mental Imagery

Considering the pivotal role that creative ideas play in human societies, and creativity's contribution to multiple aspects of human life, understanding the cognitive components underlying creativity has become increasingly fundamental. Since the Five-Stages Model of the creative process proposed by Wallas (1926), creativity has become associated with topics as wide-ranging as from problem-solving (Plucker et al., 2004) to art (van Leeuwen et al., 1999; Batt et al., 2010). Furthermore, creativity has been identified as a predictor for educational success and wellbeing (Plucker et al., 2004), and has been proposed as a way to improve the quality of life in healthy and pathological aging (Cohen, 2006; Palmiero et al., 2012, 2014, 2016a,b; Palmiero, 2015).

In the present Frontiers in Cognition Research Topic 11 novel publications were collected: 8 Original Research Articles, 1 Review, and 2 Perspective Articles. From the beginning, the Research Topic was planned as a collection of studies exploring the relationships between creativity and mental imagery. Mental imagery is a representational medium for providing researchers access to thoughts, symbolization, and combination of elements, possibly facilitating the emergence of new ideas and creativity. In this direction, different aspects of mental imagery were considered which could increase or explain the emergence of creativity: daydreaming styles (common forms of imagination that involve spontaneous thoughts unrelated to the context, Zedelius and Schooler); imagination of activities over a long period of time, relevant especially for actual creative achievements in science and writing (Jung et al.); as well as 'looking at nothing' and blinking behaviors, that do not necessarily involve visual imagery (Salvi and Bowden). In addition, we explored the relationships between different creative objects' production and artistic drawings with different mental imaging processes (i.e., generation, inspection and transformation, Palmiero et al.).

We also collected studies that investigated distinct and peculiar aspects of creativity and its cognitive components, such as: the equal-odds rule of divergent thinking, also known as the relationships between fluency (the number of responses) and creativity as assessed by independent judges (Jung et al.); or the relationships between flexibility of divergent thinking (the number of categories encompassing the relevant responses) and attentive processing (Zmigrod et al.). Interestingly, the relationships between convergent thinking involving insight and intelligence (Zmigrod et al.), and working memory updating (that is maintenance of items in working memory and binding of the incoming information, Necka et al.). In addition, neural correlates of creativity were investigated. Chavez highlighted the key role of brain areas involved in motor imagery on highly creative individuals, whereas Boccia et al. showed that general creativity relies on

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Edited and reviewed by:
Bernhard Hommel,
Leiden University, Netherlands

****Correspondence:***
Massimiliano Palmiero
massimiliano.palmiero@univaq.it

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multi-componential neural networks supporting executive functions, whereas domain-specific creativity (verbal, musical and visuo-spatial) roughly depends on different functional specialized brain regions.

Finally, two different tests recently developed have been reported: the Test of Creative Imagery Abilities (Jankowska and Karwowski), aimed at assessing three components of creative imagination: vividness of imagery, originality of responses, and transformative imagery ability; and the Artistic Creativity Domains Compendium (Lunke and Meier), aimed at measuring artistic creativity in visual arts, performing arts, literature and music.

Taken together, the articles included in this Research Topic bring up novel perspectives for better understanding creativity as a cognitive process and its relation with mental imagery. Despite, the role of mental imagery in creativity has been robustly supported, several issues remains to be addressed to clarify the extent to which different forms, abilities and strategies of imagery affect creative idea generation, for example, the subcomponents of the relationships between imagery and creativity in specific domains of knowledge. Apart from imagery, the Research Topic also highlights the key role of attention in creativity, opening up the question of how attention might increase creativity in different ways. Finally, the neural bases of creativity need to be further investigated since there is no agreement about the brain areas specialized for creativity.

In conclusion, the variety of approaches and methods to measure creativity and its components makes difficult to draw clear conclusion about this topic. In future studies, comparing special groups of subjects in normal and pathological conditions (e.g., artists, designers, mathematicians, patients with dementia, brain-damaged patients and so forth) might help to better understand the cognitive and neural correlates of creativity and the relationships among creativity and other cognitive domains, such as mental imagery, attention, and problem solving. We hope that the papers included in this Research Topic can help to stimulate more studies on these topics and in increasing research in the field of creativity.

AUTHOR CONTRIBUTIONS

MP: Planned the topic and edited the most of papers included in the topic. LaP: Edited some papers included in the topic. RN: Edited some papers included in the topic. LiP: Edited some papers included in the topic. CS: Edited some papers included in the topic. CG: Edited some papers included in the topic.

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The Richness of Inner Experience: Relating Styles of Daydreaming to Creative Processes

Claire M. Zedelius* **and Jonathan W. Schooler**

Department of Psychological and Brain Sciences, University of California, Santa Barbara, Santa Barbara, CA, USA

Psychologists have long hypothesized that daydreaming (i.e., engaging in stimulus-independent, task-unrelated thoughts and images) may facilitate creativity, but evidence for this hypothesis has been mixed. We propose that, to fully understand the relationship between daydreaming and creativity, it is essential to distinguish between different creative processes as well as between alternative styles of daydreaming. A prominent distinction in creativity research is that between analytic problem solving, which involves incremental and largely conscious processes, and insight, which is characterized by the spontaneity with which an idea springs to mind. In this aspect, insight resembles daydreaming. Indeed, recent evidence has linked daydreaming to creative performance. But like creativity, daydreaming is a multifaceted concept. Daydreams vary in style and content, a fact that is receiving little attention in contemporary research. Not all kinds of daydreaming are likely to have the same effects on creativity. We discuss different factors prevalent in people's daydreaming, such as mood, attentional focus, and intentionality, and consider how these factors may be related to creative processes. We further discuss implications for ways to enhance creativity through deliberate daydreaming practice.

Keywords: daydreaming, mind wandering, imagination, creativity, insight

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Carola Salvi,
Northwestern University, USA

Reviewed by:
Kalina Christoff,
University of British Columbia, Canada
Gregoire Borst,
Université Paris Descartes, France

Correspondence:
Claire M. Zedelius
claire.zedelius@psych.ucsb.edu

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Creativity and mental imagery are closely entwined. Creative ideas and individuals are often described as "imaginative," perhaps based on the popular notion that coming up with novel ideas relies on the ability to mentally simulate things that are not (yet) present—we imagine potential futures and explore "what if" questions (Moulton and Kosslyn, 2009; Dietrich and Haider, 2014). Common forms of imagination are daydreaming and mind wandering. Daydreaming entails engaging in spontaneous thoughts unrelated to one's current context (i.e., stimulus-independent), and mind wandering has been defined as daydreaming occuring while performing another task (Singer and Schonbar, 1961; Smallwood and Schooler, 2006). It is compelling that daydreaming may facilitate creativity, and there are countless anecdotes of ideas having emerged from daydreams. However, one can easily come up with many examples of creative ideas that resulted from task-focused thought. In the present article, we explore the relationship between daydreaming and creativity, and formulate hypotheses about the mechanisms through which different types of daydreaming facilitate creative processes.

Psychologists have long speculated about the role of daydreaming in creativity. Singer and Schonbar (1961; also Singer and Antrobus, 1963) proposed that daydreaming is associated with creative exploration and expression. Shepard (1978) and Flowers and Garbin (1989) postulated that daydreaming facilitates the formation of novel associations and the recombination of mental images, which can be a source of creative ideas. They attributed this to the fact that during daydreaming one's imagination is relatively undisturbed by stimulation from the environment. Other perspectives suggest a different way in which daydreaming may benefit creativity. Daydreams typically revolve around current goals (Klinger and Cox, 1987; Klinger, 2009, 2013; Smallwood et al., 2009; Baird et al., 2011; Poerio et al., 2015). When confronted with a problem or obstacle to a goal, daydreaming might help generate creative solutions.

Research has supported the theorized benefit of stimulus-independent thought for creativity. It was found that taking a break from consciously working on a creative problem and engaging in an unrelated task improves subsequent creativity, a phenomenon termed incubation (see Sio and Ormerod, 2009). Moreover, Baird et al. (2012) found that incubation is enhanced by engaging in undemanding tasks that leave room for mind wandering. Baird et al. (2012) had participants generate unusual uses for common objects. Participants assigned to perform an undemanding (vs. demanding) task during a break subsequently generated more, and more unique uses. (They also reported greater mind wandering). Importantly, the effect was specific to objects encountered before the break, suggesting, in line with Flowers and Garbin (1989), that mind wandering had a transformative impact on participants' representations of task-relevant information.

Additional findings suggested that frequent mind wandering is associated with increased creativity (Baird et al., 2012) and greater engagement in creative activities (Baas, 2015). Other research suggested that individuals higher in fantasy proneness, a tendency toward long and intense involvement in fantasies (Singer and Antrobus, 1972; Singer, 1975; Lynn and Rhue, 1986), are also more creative (Lynn and Rhue, 1986). While the processes underlying these trait-level correlations are somewhat unclear, they lend support to the idea that imagination and creativity are related.

In contrast, other research suggests an advantage of controlled and focused thought. For instance, Ostafin and Kassman (2012) found a positive relationship between creativity and mindful awareness, which they operationalized in opposition to mind wandering (Mrazek et al., 2012). According to Ostafin and Kassman (2012), a mindful focus on present moment experience enables individuals to suppress habitual associations, which often are not particularly creative (Ostafin and Kassman, 2012). Even Flowers and Garbin (1989) reserved a role for controlled, externally focused thought for creativity, arguing that it could aid in the strategic transformation of unconsciously generated ideas.

DIFFERENT CREATIVE PROCESSES

In trying to reconcile these seemingly contradicting perspectives, we (Zedelius and Schooler, 2015) have argued that creativity should be understood as encompassing several distinct processes. A prominent division between creative processes is that between insight and analytic problem solving. In the literature, various aspects of insight have been highlighted, including a state of understanding (Smith, 1995), as well as cognitive processes such as the selective encoding, combination, or restructuring of information, which typically precede insights (Sternberg and Davidson, 1983; Metcalfe and Wiebe, 1987; Davidson, 1995). Another important aspect is the *experience* of having an insight. Insights are characterized by the spontaneity with which an idea or solution comes to mind, seemingly out of nowhere, and accompanied by an "Aha!" or "Eureka!" moment (Mednick, 1962; Beeman et al., 1994; Schooler and Melcher, 1995; Kounios et al., 2008). Research suggests that insight experiences are the result of unconscious associative processing (e.g., Fiore and Schooler, 2001; Bolte and Goschke, 2005; Bowden et al., 2005).

In contrast, analytic thought involves consciously and systematically searching for an idea or solution and rejecting inadequate ideas (Ericsson and Simon, 1993; Kounios et al., 2008). This process progresses incrementally, with continuous awareness of the steps in the search process that lead to a solution (Metcalfe, 1986; Schooler and Melcher, 1995; Weisberg, 1995). Insight and non-insight processes also differ in their verbalizability, the former being less readily communicated in words (Schooler and Melcher, 1995) and consequently more vulnerable to verbal overshadowing by thinking out loud (Schooler et al., 1993).

Researchers have sometimes studied insight and analytic thought by comparing the processes involved in solving so-called "insight problems" to those involved in non-creative tasks (e.g., Ansburg and Hill, 2003; Ostafin and Kassman, 2012). This conveys the implicit assumption that only processes that lead to insights are creative. However, while analytic thought *can* be useful for non-creative tasks, it is also often used to solve insight problems, to generate novel and useful ideas or find uncommon solutions to creative problems (e.g., Weisberg, 1986; MacGregor et al., 2001; Bowden et al., 2005). The same could be argued for insight. While insight is typically studied in creative tasks, the experience of a solution suddenly bursting into consciousness may also occur in non-creative tasks, such as searching for a specific target in the environment (see Snodgrass et al., 1995; Smilek et al., 2006a,b). Thus, while analytic thought, and perhaps also insight, can be used for non-creative problem solving, they both can be used for attaining creative ideas or solutions. For this reason, we think that insight and analytic thought can be compared and contrasted as alternative creative processes.

To examine how insight and analytic thought relate to mind wandering (or its opposing construct mindful awareness), we performed two studies (Zedelius and Schooler, 2015) in which participants solved remote associate problems (verbal puzzles which require combining words to form compound words or phrases; Mednick, 1962; Bowden and Jung-Beeman, 2003; Kounios and Beeman, 2009). To differentiate between creative processes, participants were asked to report if they had solved each problem through insight or analytically (Study 1), or were instructed to approach problems with an insightful or analytic strategy (Study 2). To assess differences in mind wandering or mindful awareness (treated as opposite ends of a continuum), we used the Mindful Attention Awareness Scale (Brown and Ryan, 2003), which measures the tendency for attentional lapses. The results showed that a greater disposition toward mind wandering was associated with increased insight solving, while a greater tendency toward mindful awareness was associated with increased analytic solving.

We speculated that individuals high in mindful awareness may not rely as much on unconscious associative processes when attempting to solve creative problems, but more on conscious, controlled thought (see also Remmers et al., 2014). This account is consistent with Flowers and Garbin's (1989) notion that daydreaming benefits creativity through associative thought. Another possibility is that the very process of directing attention inwardly and blending out external information, a process characteristic of mind wandering (Smallwood et al., 2008, 2011), is itself facilitative of creative insights. Research has found that, just prior to attaining a solution through insight, individuals show increased brain activity in the midfrontal and anterior cingulate cortex, areas associated with the ability to block out task-irrelevant information. In contrast, analytic solutions are preceded by heightened activity in the visual cortex (Kounios et al., 2006; see also Jung-Beeman et al., 2004). These findings may suggest that blocking out input from the environment facilitates insight. Corroborating evidence for this comes from a recent study by Salvi et al. (2015) showing that frequent eye-blinking, which had previously been linked to creative idea generation (Chermahini and Hommel, 2010; Ueda et al., 2015) as well as mind wandering (Smilek et al., 2010) was associated with solving creative problems with insight. Specifically, it was found that more frequent blinking while problems were visually displayed to participants predicted insight solutions as compared to analytic solutions. Participants also looked away from the problems more before insight compared to analytic solusions. Thus, there is evidence that shifting to an internal focus of attention, such as during daydreaming, increases the likelihood of insights.

Admittedly, insight and analytic thought are only two among many creative thought processes, and future research needs to relate daydreaming to other processes that play a role in creative performance and artistic creativity.

DIFFERENT STYLES OF DAYDREAMING

As with creativity, daydreaming, too, is not a unitary concept. Daydreams can differ in thought content, affective tone, and style of thinking. Therefore, to understand the relationship between daydreaming and creativity, it is essential to differentiate between styles of daydreaming. Pioneering work by Singer and Schonbar (1961), Singer and Antrobus (1963, 1970), Huba et al. (1981) and later Giambra (1980, 1989, 1995) laid the groundwork for discerning different daydreaming styles. They identified three broad styles: (1) *positive-constructive daydreaming*, which is characterized by pleasant thoughts, vivid imagery, planning, and interpersonal curiosity, (2) *guilty-dysphoric daydreaming*, which is characterized by unpleasant emotions such as guilt, fear of failure, and aggressive inclinations, and finally (3) *poor attentional control,* which is characterized by fleeting daydreams and general difficulty focusing attention on internal or external events (Singer and Antrobus, 1963; Singer, 1975).

Singer and Schonbar (1961) and Singer (1975) speculated that these daydreaming styles might be differentially related creativity, and indeed a study by Zhiyan and Singer (1996) showed that positive-constructive daydreaming was related to openness to experience, a trait associated with creativity. However, this finding is indirect at best. Moreover, the research classified daydreaming styles purely based on thought *content*. We think that it is fruitful to examine other aspects that may define styles of daydreaming and are known or speculated to be related to creative processes.

An aspect extensively studied in relation to creativity is mood (see Baas et al., 2008). There is evidence that positive mood enhances cognitive flexibility, and thereby benefits creativity (e.g., Isen et al., 1987; Isen, 1990; Murray et al., 1990; Ashby et al., 1999; Dreisbach and Goschke, 2004; De Dreu et al., 2008). Based on this literature, daydreaming styles associated with positive mood should benefit creativity. However, a more nuanced picture emerges when differentiating between creative processes. Studies have shown that positive mood specifically benefits insight, but not necessarily analytic problem solving (Subramaniam et al., 2009). Moreover, there is evidence that negative mood can *increase* creativity through a different route. Negative mood is often interpreted as a signal that one's current state is discrepant from one's desired state. This promotes an analytic information processing style and increased effort recruitment (Schwarz and Bless, 1991; Bolte et al., 2003). Persistent systematic effort, in turn, can yield highly creative output (De Dreu et al., 2008). Thus, while positive mood facilitates creativity by increasing insight, negative mood can enhance creativity through analytic thought and persistence.

Findings from experience sampling studies suggest that daydreaming, compared to being focused on the present, is often associated with negative mood (Killingsworth and Gilbert, 2010). This was true when participants reported negative or neutral thoughts, and even when they reported positive thoughts their mood was no better than when they were on-task. There are, however, exceptions to this finding. Daydreams experienced as highly interesting (Franklin et al., 2013), and positive mind wandering during unpleasant activities (Spronken et al., 2015) have been associated with positive mood. Moreover, daydreams with social content and involving close others are associated with increased happiness (Poerio et al., 2015). Thus, we expect that interesting or positive daydreams (especially when they take the mind off unpleasant activities) and daydreams about social relationships should facilitating creative insights.

Next to thought content and valence, daydreaming is defined by styles of thinking. One well-studied style of thinking that tends to occupy some people's daydreams is rumination, or repetitive, self-referential thought. A consequence of rumination is a narrowed focus of attention (Whitmer and Gotlib, 2013; Grol et al., 2015). Research has associated a narrow focus of attention with reduced creativity (e.g., Kasof, 1997). More recent studies suggest that this applies particularly when creative problems are approached insightfully, not when approached analytically. For instance, Wegbreit et al. (2014) manipulated participants' attentional focus by having them perform a task that either required attending to a broad space, or to focus attention narrowly. The broad focus task led to increased insight solutions in a subsequent creativity task, while the narrow focus task led to more analytic solutions. Based on this research, we predict that a ruminative daydreaming style with a narrow focus of attention impedes creative insights, but may improve creativity through analytic thought.

Another factor that may moderate the relationship between daydreaming and creativity is intentionality (see also Forster and Lavie, 2009; McMillan et al., 2013; Dorsch, 2014; Seli et al., 2014). Spontaneous stimulus-independent thoughts often arise unintentionally and without awareness (e.g., Schooler, 2002; Schooler and Schreiber, 2004; Schooler et al., 2011; Baird et al., 2013). However, creative individuals sometimes deliberately engage in daydreaming, because they believe their daydreams to be a source of inspiration. Few studies directly speak to this hypothesis, but it is reasonable to expect that unintentional and deliberate daydreaming are dominated by different types of thought. For instance, deliberate daydreaming may be more structured than unintentional daydreaming and more narrowly focused on personal goals (including creative goals), which should associate it with an analytic thinking style. In contrast, unintentional daydreaming may be characterized more by the kind of associative processing thought to facilitate insight.

Other differences between deliberate and unintentional daydreaming may lead to different predictions. It seems probable that unintentional daydreaming is more likely to involve negative, ruminative thought, while deliberate daydreaming involves more positive thoughts. If this were the case, we would predict deliberate daydreaming to spark creative insights more than unintentional daydreaming, a prediction that runs counter to the one discussed before. More research is needed to examine this possibility. This research should take into account people's motives, which may moderate the effects of deliberate daydreaming. For instance, chronic ruminators often report that they deliberately engage in ruminative thought, because they believe it to be helpful for gaining self-knowledge (Lyubomirsky and Nolen-Hoeksema, 1993; Papageorgiou and Wells, 2003; Smallwood et al., 2003; Simpson and Papageorgiou, 2004). For them, deliberate daydreaming may be structured, goal-directed, and negative, and hence associated with analytic thinking. Individuals with a stronger motive for mood-repair, on the other hand, may deliberately wander off to pleasant daydreams that put them in a good mood, and facilitate creative insight.

BENEFITS OF DELIBERATE DAYDREAMING PRACTICE FOR CREATIVITY

The issue of intentional daydreaming raises an interesting question: if some styles of daydreaming are more conducive to creativity than others, can we improve creative performance by *deliberately* engaging in those styles of imagination? A few studies have used instructed imagination in interventions for increasing creativity, specifically creative writing. Long and Hiebert (1985) developed visualization exercises encouraging students to vividly imagine memories and current experiences and let these images "trigger" further images. After three weekly sessions of such training (compared to a control training in which students listened to and wrote stories), students' creative writing improved. Jampole et al. (1994; see also Jampole et al., 1991) developed a similar intervention, which included specific instructions such as mentally manipulating the appearance of objects and imagining traveling to different locations. Again, compared to students in a control condition who only engaged in reading and writing exercises, students who participated in the imagination intervention wrote more original stories.

Following a similar approach, future studies could compare creativity-related effects of instructions encouraging different types of daydreaming. Do instructions that promote positive or interesting daydreams lead to greater creativity? How about instructions that invoke a broad versus narrow focus of attention? Can people learn to invoke different types of daydreaming dependent on the creative task? Perhaps broad positive daydreams are more helpful for tasks that require reconceptualization, whereas narrowly defined critical reflection facilitates fleshing out details of ideas. To date, little attention has been paid to distinguishing daydreaming styles at the state level. Given that creativity can be achieved through distinct routes, flexibly invoking the daydreaming style that fits the situation seems a fruitful approach for enhancing creative potential.

To summarize, our goal was to illuminate the relationship between daydreaming and creativity by considering the different creative processes that benefit from daydreaming and the daydreaming styles that may be conducive to creativity. The first part of the article provided a foundation for understanding how daydreaming can facilitate creativity. We distinguished two distinct creative processes: insight, which appears to benefit from daydreaming, and analytic thought, which is hampered by daydreaming. In the second part, we offered a similarly nuanced approach for understanding the heterogeneous phenomenon of daydreaming itself. Although the empirical work on the effects of different daydream styles is underdeveloped, we speculated about a number of factors prevalent in people's daydreaming that may contribute to creativity. We closed by considering how future research might lead to practical interventions for improving creativity and theoretical advancements in understanding the ways in which people daydream and generate new ideas. Although much remains to be done, we hope that these speculations will provide some fodder for researchers to daydream about, and ultimately pursue.

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A New Measure of Imagination Ability: Anatomical Brain Imaging Correlates

Rex E. Jung[1,2]*, Ranee A. Flores[2] and Dan Hunter[3]

[1] Department of Psychology, University of New Mexico, Albuquerque, NM, USA, [2] Department of Neurosurgery, University of New Mexico, Albuquerque, NM, USA, [3] Hunter Higgs, LLC, Boston, MA, USA

Imagination involves episodic memory retrieval, visualization, mental simulation, spatial navigation, and future thinking, making it a complex cognitive construct. Prior studies of imagination have attempted to study various elements of imagination (e.g., visualization), but none have attempted to capture the entirety of imagination ability in a single instrument. Here we describe the Hunter Imagination Questionnaire (HIQ), an instrument designed to assess imagination over an extended period of time, in a naturalistic manner. We hypothesized that the HIQ would be related to measures of creative achievement and to a network of brain regions previously identified to be important to imagination/creative abilities. Eighty subjects were administered the HIQ in an online format; all subjects were administered a broad battery of tests including measures of intelligence, personality, and aptitude, as well as structural Magnetic Resonance Imaging (sMRI). Responses of the HIQ were found to be normally distributed, and exploratory factor analysis yielded four factors. Internal consistency of the HIQ ranged from 0.76 to 0.79, and two factors ("Implementation" and "Learning") were significantly related to measures of Creative Achievement (Scientific—$r = 0.26$ and Writing—$r = 0.31$, respectively), suggesting concurrent validity. We found that the HIQ and its factors were related to a broad network of brain volumes including increased bilateral hippocampi, lingual gyrus, and caudal/rostral middle frontal lobe, and decreased volumes within the nucleus accumbens and regions within the default mode network (e.g., precuneus, posterior cingulate, transverse temporal lobe). The HIQ was found to be a reliable and valid measure of imagination in a cohort of normal human subjects, and was related to brain volumes previously identified as central to imagination including episodic memory retrieval (e.g., hippocampus). We also identified compelling evidence suggesting imagination ability linked to decreased volumes involving the nucleus accumbens and regions within the default mode network. Future research will be important to assess the stability of this instrument in different populations, as well as the complex interaction between imagination and creativity in the human brain.

Keywords: imagination, creativity, brain volume measurements, neuroimaging (anatomic and functional), nucleus accumbens (NAcc), lingual gyrus

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***Correspondence:**
Rex E. Jung
rex.jung@runbox.com

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INTRODUCTION

The ability to imagine oneself carrying out activities in the future is an important aspect of both creative cognition and creative achievement. There is a fairly long history of linking imagination to creativity, with early researchers seeing imagination as a subset of the broader construct of creative cognition, especially in developmental disorders (Craig and Baron-Cohen, 1999). More recently, imagination has been conceptualized as a critical mediating linkage between acquired knowledge and creative insight, constraining the possible solutions through mental simulations or "incubation" (Duch, 2007; Helie and Sun, 2009). This "imaginative" aspect of creativity is not assessed by current measures of imagination (proper), most of which focus on visualization, or imagery (Zhang et al., 2012), or are quite similar to standard measures of divergent thinking (Jankowska and Karwowski, 2015).

An operational definition of imagination likely involves aspects of episodic memory retrieval, visualization, simulation, spatial navigation, and future thinking, but these are pieces of a bigger puzzle, comprising various stages of the creative process, from preparation, through incubation, illumination, and verification (Poincare, 1913). At what level of resolution should we parse this important human attribute? While imagination is certainly dependent upon fundamental cognitive processes including attention, semantic memory retrieval, working memory (the list goes on and on), we aim to define and measure this construct *in toto* in spite of the temptation to fragment it into less interesting (albeit scientifically submissive) parts. Thus, the understanding of imagination, as a critical component of creative cognition, is the aim of this study. As part of this understanding, we endeavor to describe, for the first time, anatomical correlates of imagination ability in normal human participants.

Classic studies of imagery, a component of "imagination" in patients suffering hippocampal damage, ask questions such as "Imagine you are lying on a white sandy beach in a beautiful tropical bay," and ask them to describe what they see (Hassabis et al., 2007). While these studies get at imagination through visualization, they do not ask participants to generate ideas related to their own lives or work (i.e., episodic memory retrieval), nor do they ask them to think about themselves in the future (i.e., future thinking), cognitive processes hypothesized to be important to creativity (Jung et al., 2015; Beaty et al., 2016a; Crespi et al., 2016). Second, these studies of imagery do not allow ideas to incubate over time, but are often "snapshot" representations of impressions captured in the moment. While comprehensive imagination capacity is anticipated to be difficult to capture with either brain or behavioral measures, we adopt Simonton's "test" of a "most desirable" measure: applicable to different domains and ability levels, and not suffering from excessive granularity (Simonton, 2012).

Imagination is a large cognitive construct. However, if imagination involves fundamentally interwoven cognitive processes including memory, visualization, spatial navigation, and episodic future thinking, these processes should involve concomitant neural structures associated with their behavioral manifestation. For example, the hippocampus has been well associated with episodic memory formation, extending from the unfortunate case of HM, who underwent bilateral resection of his hippocampi as a cure for intractable epilepsy, rendering him unable to form new memories (Scoville and Milner, 1957). Studies with rats have also demonstrated location-specific firing within the hippocampus, with damage to this structure resulting in disrupted spatial navigation ability (O'keefe and Nadel, 1978). When participants with acquired hippocampal damage are asked to imagine themselves in various scenes, they do so with great effort, and with lower spatial contiguity and coherence (Hassabis et al., 2007). Outside of the medial temporal lobe *per se*, a broader network of regions has been implicated in imagination. This network includes a "core" within the hippocampus, parahippocampus, posterior cingulate and posterior parietal cortices, and "secondary" and "infrequent" involvement of medial/lateral prefrontal and lateral temporal cortices, associated with concepts of self/other and mental time travel (Nyberg et al., 2010).

Based on our review above, we define imagination as drawing upon previous experiences to engage in mental simulation, in order to achieve future goals. We describe a measure of imagination, the Hunter Imagination Questionnaire (HIQ), designed to (1) capture aspects of memory retrieval, visualization, simulation, spatial navigation, and episodic future thinking, (2) capture imagination activities over an extended period of time, and (3) ask participants to envision future goals and achievements. We hypothesized that, if participants engaged in such imagination activities, then associated brain networks, identified previously within the neuroscientific literature, would be involved in their responses, particularly those at the core of imagination (e.g., medial temporal) as well as those involved in thinking about oneself vs. others, and mental time travel (e.g., medial frontal, lateral temporal).

METHODS

This study was conducted according to the principles expressed in the Declaration of Helsinki, and was approved by the Institutional Review Board of the University of New Mexico (IRB#11-531). All participants provided written informed consent prior to collection of any experimental samples and subsequent data analysis. Eighty participants (29 males; 51 females) between the ages of 16 and 35 (Mean = 22.5; SD = 4.3) were recruited from the University of New Mexico and surrounding community. Participants were screened by questionnaire to exclude major neurological injury or disease (e.g., traumatic brain injury, epilepsy) and psychiatric disorder (e.g., major depression, attention deficit disorder). All participants underwent a magnetic resonance imaging (MRI) session, including measures of brain structure, diffusion tensor imaging, and functional measures of the default mode network (DMN).

Behavioral Measures

Participants were administered behavioral measures including the HIQ. All participants had previously completed a battery of measures including tests of intelligence (Wechsler Abbreviated Scale of Intelligence—WASI), personality (Big 5 Aspect Scale—BFAS), and aptitude (Paper Folding, Vocabulary, Foresight), and received $100 compensation for their time. The WASI is a standardized measure of intelligence, used in both clinical and educational testing to derive an intelligence quotient (IQ) from ages 6 to 90 (Wechsler, 1999). It is comprised of subtests including Vocabulary, Similarities (e.g., how are green and red alike), Block Design, and Matrix Reasoning; we administered all subtests but Vocabulary, which was obtained from an aptitude measure described below. The BFAS is self-report measure, consisting of 100 items, of non-clinical personality domains including Neuroticism, Extroversion, Openness, Agreeableness, and Conscientiousness (DeYoung et al., 2007). The facet of Openness has been well associated with creative cognition (McCrae and Ingraham, 1987; Miller and Tal, 2007; Kaufman et al., 2014) and linked to brain measures within the default mode network (Sampaio et al., 2014; Beaty et al., 2016b). Paper Folding, Vocabulary, and Foresight are measures of aptitude from the Johnson O'Connor battery of tests. Paper Folding measures the ability to mentally manipulate paper forms having holes punched out of them in different patterns; Vocabulary measures single word knowledge, in a multiple choice format, with a range of words presented from easy (e.g., plump) to quite difficult (e.g., mephitic); Foresight measures the ability to generate as many ideas about visual designs as possible in 45 s. These measures, and their anatomical correlates, have been reported by our group previously (Jung et al., 2014, 2015). We were particularly interested in the relationship between the HIQ and the Creative Achievement Questionnaire (CAQ). The CAQ is a reliable and valid measure of creative achievement across 10 domains including visual arts, music, creative writing, dance, drama, architecture, humor, scientific discovery, invention, and culinary arts (Carson et al., 2005).

Procedure

Participants were drawn from a larger pool of participants who were being studied to determine individual differences in creative cognition and aptitude reported on previously (Jung et al., 2014, 2015). As part of this larger study, all participants underwent a 4-h battery of measures including tests of intelligence, personality, and aptitude. All of these measures were administered in a laboratory setting, with research assistants utilized to administer tests requiring individual administration (e.g., WASI, Vocabulary, Paper Folding, Foresight, CAQ). Participants underwent a separate neuroimaging session, usually within 1 month of individual testing, where they underwent anatomical Magnetic Resonance Imaging (aMRI), Diffusion Tensor Imaging (DTI), and an echoplanar session designed to elicit the Default Mode Network of brain functioning. This imaging session took no longer than ½ h to complete.

For the current study, all participants from the larger sample were asked to participate in an online questionnaire where they were asked several questions about their imagination activity. Eighty of 246 participants agreed to participate in this subsequent questionnaire, and were sent instructions regarding how to access an online portal where their responses were recorded (REDCap). Participants were paid $50 for their time.

Participants were given instructions to complete Session 1 of the HIQ, and to submit their responses to the cue (below) in the REDCap system. Participants were instructed that they should take no longer than 8 min to complete Session 1.

Session 1 Cue

What would you like to do, make, create, or achieve in the next few months? You may include both feasible and fantastical ideas. Write as much as you need to be able to remember your ideas. Begin each new idea on a new line. Try to generate 3–5 (or more) ideas in 8 min. When you are done hit the "submit" button at the end of the page.

Following 3 days, participants were sent an email with a link to complete Session 2 of the HIQ. Participants were given instructions to complete Session 2 of the HIQ, and to submit their responses to the REDCap system. If they did not respond within 1 week, they were sent one email reminder to complete Session 2.

Session 2 Cue

Visualize a scene in your mind invoking your senses. The scene may be realistic or fantastical; landscape, or interior. Write as much detail as you need to remember the scene. Try to visualize 3–5 (or more) scenes in 8 min. When you are done hit the "submit" button at the end of the page.

Following 3 days, participants were sent an email with a link to complete Session 3 of the HIQ. Participants were given instructions to complete Session 3 of the HIQ, and to submit their responses to the REDCap system. If they did not respond within 1 week, they were sent one email reminder to complete Session 3.

Session 3 Cue

Imagine something you would like to discover or invent or change. It could be real or imaginary. Begin each new idea on a new line. Try to generate 3–5 (or more) scenes in 8 min. When you are done hit the "submit" button at the end of the page.

Following 3 days, participants were sent an email with a link to complete Session 4 of the HIQ. Participants were given instructions to complete Session 4 of the HIQ, and to submit their responses to the REDCap system. If they did not respond within 1 week, they were sent one email reminder to complete Session 4.

Session 4 Cue

What would you like to do, make, create, or achieve in the next few months? You may include both feasible and fantastical ideas. Write as much as you need to be able to remember your ideas. Begin each new idea on a new line. Try to generate 3–5 (or more) ideas in 8 min. When you are done hit the "submit" button at the end of the page.

Following 3 days, participants were sent an email with a link to complete the Review of Ideas of the HIQ. They were instructed to review all of their ideas and notes from the last four sessions and to consider which appealed to them the most, which ideas they will implement, and which they are most likely to forget or not implement. They were instructed to select (type) three of their best ideas. This was followed by a set of questions ranked on a scale from 1 (low) to 10 (high).

1. How passionate or engaged are you with the ideas you generated? (1 = Disengaged/Bored; 10 = Passionate/Engaged).
2. Have you taken steps to implement any of your ideas? (1 = No Steps Taken; 10 = Idea Completed).
3. How likely are you to implement or continue implementing your ideas in the days and weeks to come? (1 = Unlikely; 10 = Very Likely).
4. How difficult was the first session? (1 = Not Difficult at All; 10 = Very Difficult).
5. Did the process become easier or more difficult as you repeated the assessment? (1 = Easier; 10 = More Difficult).
6. Please estimate how much time you devoted to thinking about your ideas between sessions. (1 = No Time; 10 = A Lot of Time).
7. Are you satisfied with the number of ideas you generated? (1 = Not Satisfied; 10 = Completely Satisfied).
8. Did the assessment process help you learn about your own thinking? (1 = Not At All; 10 = Quite A Bit).
9. How would you rate your experience of the assessment? (1 = Very Bad; 10 = Very Good).
10. Please provide an overall assessment of your ideas on a scale of 1–10 (1 = Very Bad; 10 = Very Good).

Questions from Session 1 and 4 were never presented sequentially, and questions were presented to participants in pseudorandom order to control for order effects. All questions were answered on a Likert scale ranging from 1 (not at all, unlikely, etc.) to 10 (high, quite a bit, likely, etc.). The HIQ Total Score was obtained by summing scores obtained on items 1 through 10, and dividing by 10 (**Figure 1**).

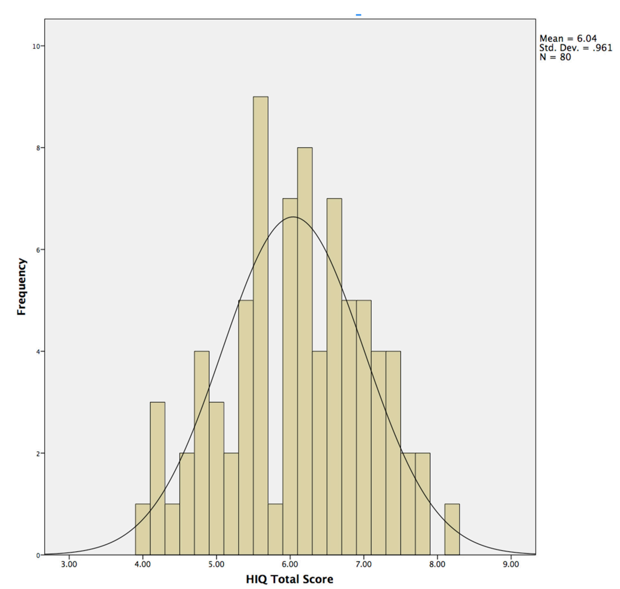

FIGURE 1 | Histogram demonstrating normal distribution of Hunter Imagination Questionnaire (HIQ) total scores across the entire sample (*N* = 80).

Neuroimaging

Anatomical imaging was obtained using a 3 Tesla Siemens scanner using a 32-channel head coil. We obtained a T1 5 echo sagittal MPRAGE sequence (TE = 16.4; 3.5; 5.36; 7.22; 9.08 ms; TR = 2530 ms; voxel size = 1.0 × 1.0 × 1.0 mm3; slices = 192; acquisition time = 6:03). Methods for cortical reconstruction and volumetric segmentation were performed with the FreeSurfer image analysis suite (http://surfer.nmr.mgh.harvard.edu/) and are described in detail elsewhere (Fischl et al., 2002, 2004; Han and Fischl, 2007). Thickness measurements were obtained by reconstructing representations of the Gray Matter/White Matter boundary and the pial surface and then calculating the distance between those surfaces at each point across the cortical mantle (Dale et al., 1999). The results of the automatic segmentations were quality controlled and any errors were manually corrected. Volume measures are a combination of thickness (a one-dimensional measure) and area (a two dimensional measure) across 33 measures per hemisphere (i.e., 66 across the surface of the brain) as well as seven subcortical volumes per hemisphere (i.e., 14 across the brain) including bilateral caudate, putamen, globus pallidus, nucleus accumbens, thalamus, amygdala, and hippocampus (Fischl et al., 2002).

Analysis

We used Shapiro–Wilk to test normality of the distribution of the HIQ. Student's t was used to test for differences between males and females on major variables of interest, including all scores on the HIQ. Exploratory factor analysis, with Principal Axis Factoring, Varimax rotation, and Kaiser Normalization was used to characterize the structure of items on the HIQ. Cronbach's alpha was used to determine internal consistency of items within each factor. Partial correlation, controlling for sex, was used to determine the relationship between total scores and factor scores of the HIQ and total scores and item scores on the CAQ. Finally, linear regression, controlling for age, sex, Full Scale Intelligence Quotient, and Total Supratentorial Volume was used to determine the relationship between the HIQ factor scores and brain volume measures. There are 80 (66 cortical and 14 subcortical) volumes obtained across the brain for each participant. Given that five in 100 Type I errors are considered to be generally acceptable in research designs, we would expect roughly four regions of 80 to be related to our measures by chance. We have adjusted our significance levels to $P < 0.005$ to account for such possible chance relationships as in our previous research (Jung et al., 2015). While this does not fully account for Type I error, we believe that it reasonably balances the risk of both Type I and Type II error in this exploratory experiment.

RESULTS

Normality

Responses on the HIQ were normally distributed (Shapiro–Wilk = 0.987), with a mean of 6.0 and standard deviation of 1.0 (**Table 1**; **Figure 1**). Males ($N = 29$) did not differ significantly from females ($N = 51$) in overall scores, although males tended to score slightly higher overall (Male Mean = 54.8; Female Mean = 52.8), largely driven by significant differences in satisfaction

TABLE 1 | Descriptive statistics for participants on behavioral measures.

Measure	Minimum	Maximum	Mean	s.d.
Wechsler intelligence scale—FSIQ	90.0	153.0	113.3	11.8
Johnson O'Connor vocabulary	3.0	23.0	12.8	4.5
Johnson O'Connor paper folding	4.0	54.0	27.9	13.9
Johnson O'Connor foresight	26.0	95.0	50.5	14.4
BFAS neuroticism	11.5	39.5	25.5	5.8
BFAS extraversion	22.5	49.0	35.0	4.8
BFAS openness	31.0	46.0	39.2	3.8
BFAS agreeableness	19.0	48.0	38.8	5.4
BFAS conscientiousness	23.5	45.0	34.8	5.5
Creative achievement questionnaire	1.0	96.0	18.6	19.2
HIQ engagement	3.0	10.0	8.0	1.8
HIQ implement	1.0	10.0	5.5	2.5
HIQ implement idea	1.0	10.0	7.3	2.7
HIQ difficulty	1.0	9.0	3.4	2.5
HIQ process	1.0	10.0	4.7	2.3
HIQ time spent	1.0	10.0	4.7	2.4
HIQ satisfaction	1.0	10.0	6.0	2.6
HIQ learning	1.0	10.0	5.9	2.5
HIQ experience	3.0	10.0	7.9	1.9
HIQ overall	2.0	10.0	7.0	1.7
HIQ total	4.0	8.1	6.0	1.0

FSIQ, Full Scale Intelligence Quotient; BFAS, Big Five Aspect Scale; HIQ, Hunter Imagination Questionnaire; s.d., Standard Deviation.

(Male Mean = 6.7; Female Mean = 5.5; $t = 2.0$, $p = 0.05$). Means and standard deviations for all behavioral measures are presented in **Table 1**.

Factor Structure

We next sought to determine the underlying structure of the HIQ by conducting an exploratory factor analysis of the 10 questions answered at the end of the survey. Four factors were extracted, corresponding to broad domains, which are defined as "Satisfaction" (comprised of items 1, 7, 9, and 10), "Implementation" (comprised of items 2 and 3), "Learning" (comprised of item 8), and "Process" (comprised of items 4 and 5). The rotated factor matrix is presented in **Table 2**.

Reliability and Validity

We next sought to determine the reliability of the HIQ by means of internal consistency of questions across factors consisting of multiple, positively related, measures. Cronbach's alpha for Satisfaction was 0.76, and for Implementation was 0.79, suggesting acceptable internal consistency of the measure, particularly across measures of Satisfaction and Implementation. Seventy-one of the original 80 participants were administered the HIQ on a second occasion, with at least 1 month of time between administrations (range 4–8 weeks). Cronbach's Alpha was 0.75 for the HIQ Total Score, suggesting good test-retest reliability for this measure. Finally, we sought to determine the correlation between the HIQ and established measures of creative achievement via the CAQ across all participants. While we found low, non-significant, correlations between the total

TABLE 2 | Rotated factor matrix of the Hunter Imagination Questionnaire.

	Factor			
	Satisfaction	Implementation	Learning	Process
Overall	0.822			
Experience	0.703			
Engagement	0.625			
Satisfaction	0.621			
Implement 1		0.815		
Implement 2		0.811		
Learning			0.754	
Process				0.641
Difficulty				−0.450

HIQ and total CAQ, controlling for sex, (HIQ-CAQ $r = 0.13$, ns) we found significant correlations between the Implementation factor and Scientific Achievements ($r = 0.26$, $p = 0.02$), and between the Learning factor and Writing Achievements ($r = 0.31$, $p = 0.006$), suggesting concurrent validity of measures. It should be noted that these participants were over-selected for representation within the Science, Technology, Engineering, and Math disciplines; therefore, correlates between their imagination ability and Scientific Achievements might be expected to be higher than for normally selected samples.

Brain Correlates

Finally, we sought to determine anatomical brain correlates of the HIQ, including Factor Scores of Satisfaction, Implementation, and Learning. We regressed all volume measures, as well as subcortical volumes, against each factor controlling for Total Supratentorial volume, sex, and Full Scale Intelligence Score. The total score on the HIQ was predicted by a model that included decreased left nucleus accumbens and increased right lingual volumes ($F = 3.3$, $p = 0.01$; $r2 = 0.18$; **Figure 2**). A model including *decreased* volumes in the left posterior cingulate, left superior temporal gyrus, and right precuneus, and *increased* volume of left caudal middle frontal, right putamen, right rostral middle frontal, right superior frontal gyri predicted Satisfaction scores on the HIQ ($F = 5.34$, $p < 0.001$; $r2 = 0.44$). Scores on the Implementation factor were predicted by a model including *decreased* volumes of the right medial-orbital frontal gyrus, and right isthmus of the cingulate gyrus, and *increased* volumes of the left hippocampus, left lingual gyrus, and left isthmus cingulate gyrus ($F = 4.46$, $p < 0.001$; $r2 = 0.34$). Finally, the Learning score was predicted by a model that included *decreased* volumes of the left nucleus accumbens and left transverse temporal gyrus, and *increased* volumes of the right lingual gyrus and right hippocampus ($F = 5.06$, $p < 0.001$; $r2 = 0.33$) (**Figure 3**).

DISCUSSION

We found that this complex, naturalistic, measure of imagination was related to a network of brain regions previously identified to be associated with various components of this complex cognitive capacity, including the bilateral hippocampi, posterior

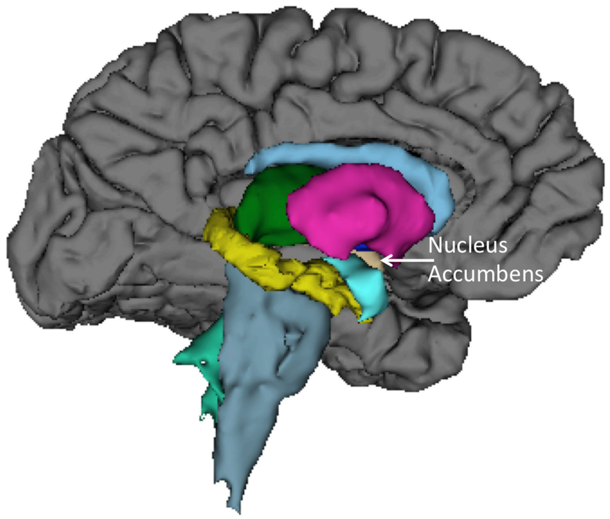

FIGURE 2 | Left medial view of average brain surface volumes (gray), and subcortical structures including the Nucleus Accumbens (light brown).

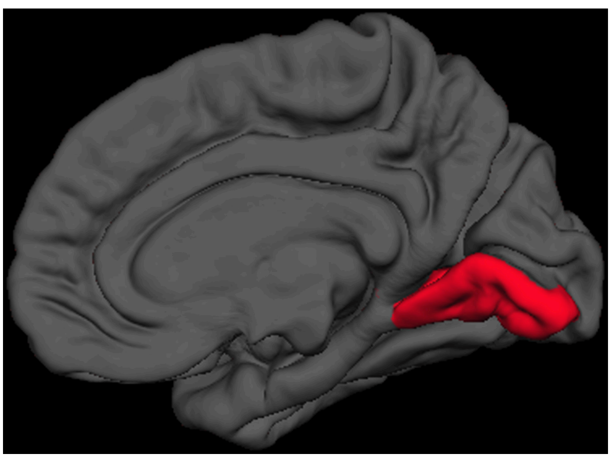

FIGURE 3 | Right medial view of average brain surface volumes (gray), showing lingual gyrus region (red).

regions of the cingulate gyrus, both medial and lateral prefrontal cortical regions, and the lingual gyrus. It is both compelling and gratifying that participants could be asked to engage in a complex task of imagination, over a period of weeks, and that their self-reported measures of satisfaction, implementation, learning, and overall experience in performing the task would be correlated with key brain regions identified as being critical to key aspects of imagination ability. The HIQ was found to be a psychometrically sound instrument, with a normal distribution of scores, good internal reliability, good test-retest reliability, and good concurrent validity with measures of creative achievement (particularly Scientific Creativity and Writing from the CAQ). As would be expected given such a complex behavioral task, the relationship between imagination and brain regions was also complex, although increased left hippocampal volume was associated with higher likelihood of implementing the imagined ideas, and increased right hippocampal volume was associated with participants' perception of increased learning about their own imagination process. This is the first study to demonstrate such brain-behavior relationships in a naturalistic setting (i.e., an online questionnaire), undertaken over a period of weeks, in normal human subjects.

Some of the complexity of the brain-behavior relationships might be explained by our previous work in creative cognition research. In our recent overview of the anatomical neuroimaging studies of creativity (Jung et al., 2013), we noted two major patterns: first, we noted a significant overlap with regions within the so-called default mode network (DMN), a brain network associated with "remembering the past, envisioning future events, and considering the thoughts and perspectives of other people" (Buckner et al., 2008); second, many of the relationships were inverse—that is lower measures of brain "integrity," including decreased cortical volume (Jung et al., 2010b), white matter fidelity (Jung et al., 2010a), brain biochemistry (Jung et al., 2009), and even overt brain lesions (Shamay-Tsoory et al., 2011; Abraham et al., 2012), were associated with higher creative ability. Our results also conform to this general pattern; indeed, we found that nearly all *decreased* volumes that related to HIQ rankings were within DMN regions, including the posterior cingulate, precuneus, medial-orbital frontal gyrus, transverse temporal gyrus, and isthmus of the cingulate gyrus. This correspondence between decreased volumes and HIQ performance within DMN regions further supports this instrument as a measure of key aspects of imagination, including (1) remembering the past, (2) envisioning the future, and (3) considering the thoughts and perspectives of other people (Crespi et al., 2016).

We also found rather consistent associations between decreased nucleus accumbens volume and higher scores across the HIQ (i.e., Total Score and Learning factor). The nucleus accumbens is a structure linked to anticipation of incentives (i.e., reward) in humans, with lesions to this structure associated with increased impulsivity (Cardinal et al., 2001), addictive behaviors (Dalley et al., 2007), and abnormalities of appetitive and aversive behaviors (Salamone, 1994). In humans, functioning of the nucleus accumbens has been critically linked to sensation seeking and novelty seeking behaviors in non-clinical populations (Abler et al., 2006). While these results are intriguing, we anticipate that future research will help to identify the specific relationship between nucleus accumbens structure and function and imagination activity and ability. Brief mention should be made of associations between the HIQ (Total score, Implementation, and Learning factors) and increased volume of the lingual gyrus. These relationships likely reflect this structures importance to encoding and recalling complex visual material (Machielsen et al., 2000), modulating and naming visual stimuli (Howard et al., 1992; Price et al., 1994), and the analysis of the logical sequence of events (Brunet et al., 2000), all likely to be important to imagination activity and ability.

There are several limitations to the current research. The main limitation for neuroimaging studies almost always includes a note of caution given the relatively small sample, and given the complexity of brain-behavioral research questions entertained. This limitation is further highlighted by the fact that our sample included roughly twice the number of females as compared to males. We do not know why females were more likely to respond to the invitation to participate in the HIQ; however, this could have created biases in our sampling that could have affected our results. We controlled for sex throughout the analyses and there was no indication that the results did not reflect relationships across both sexes. However, future studies, with larger samples comprised of equal numbers of males and females would tend to increase the inferences that could be made. Relatedly, our sample was comprised of a young, healthy, cohort and we do not know whether our results would apply to individuals older than 35 years of age. We chose a young sample to ensure that volumetric brain changes associated with normal aging, which tend to stabilize in early adulthood (Tamnes et al., 2010), and then resume in mid adulthood would not affect our results (Ardekani et al., 2007). With regard to HIQ administration, we asked participants to limit their idea generation time to 8 min, but did not create a mechanism to check whether they took longer (or significantly shorter) to complete each session. Future studies should attempt to explicitly control and/or measure this potentially important variable. Finally, because the participants acted as their own raters, it is possible that other factors (e.g., self image, mood, etc.) could have influenced the ratings. Future studies should attempt to measure and control for such factors to determine their potential influence upon HIQ ratings.

We believe this to be the first study to relate a complex, naturalistic, measure of imagination to a network of brain regions previously associated with various facets of imagination ability. The participants' responses to the HIQ were associated with volumes across a broad network of brain regions previously associated with imagination including:

(1) Bilateral hippocampi—associated with episodic memory retrieval.
(2) Precuneus, medial-orbital frontal gyrus, posterior cingulate, and transverse temporal gyrus—overlapping significantly with the DMN—associated with "remembering the past, envisioning future events, and considering the thoughts and perspectives of other people".
(3) Nucleus Accumbens—associated with sensation and novelty seeking behavior.
(4) Lingual gyrus—associated with recall, modulation, and analysis of complex visual material.

In conclusion, the HIQ showed good psychometric qualities, and was well tolerated by all participants. It represents a broad survey of imagination ability, obtained over days/weeks, which is more naturalistic than is customarily found in either the neurosciences or the psychological sciences. It provides a reliable, valid, method by which to assess brain-behavior relationships related to this complex cognitive construct.

AUTHOR CONTRIBUTIONS

RJ, RF, and DH each contributed to the design of the experiment. RJ, RF each contributed to the analysis of the data. RJ and DH wrote the manuscript.

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REVIEW
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Looking for Creativity: Where Do We Look When We Look for New Ideas?

Carola Salvi[1,2]† and Edward M. Bowden[3]*†*

[1] Department of Psychology, Northwestern University, Evanston, IL, USA, [2] Rehabilitation Institute of Chicago, Chicago, IL, USA, [3] Department of Psychology, University of Wisconsin–Parkside, Kenosha, WI, USA

Recent work using the eye movement monitoring technique has demonstrated that when people are engaged in thought they tend to disengage from the external world by blinking or fixating on an empty portion of the visual field, such as a blank wall, or out the window at the sky. This 'looking at nothing' behavior has been observed during thinking that does not explicitly involve visual imagery (mind wandering, insight in problem solving, memory encoding and search) and it is associated with reduced analysis of the external visual environment. Thus, it appears to indicate (and likely facilitate) a shift of attention from external to internal stimuli that benefits creativity and problem solving by reducing the cognitive load and enhancing attention to internally evolving activation. We briefly mention some possible reasons to collect eye movement data in future studies of creativity.

Keywords: creativity, imagination, eye movements, blink rate, attention, insight problem solving

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****Correspondence:***
Carola Salvi
carola.salvi@northwestern.edu;
Edward M. Bowden
bowden@uwp.edu

†These authors have contributed equally to this work.

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It has been said that the eyes are the windows on the soul. In this paper we will examine whether the eyes are the windows to the mind. We will concentrate on eye movements and blinking, and how they both reveal and influence creative thinking.

Anecdotally, when people are engaged in retrieving information from memory, imagining, problem solving or thinking creatively, they often shift their gaze from the problem or from other people toward an empty space or a blank wall. This was popularly understood to be a way to disengage from distracting information so that one can concentrate on inner thoughts. The artist Paul Gauguin described his necessity of disengaging from outside reality to enhance his imagination and creativity in his famous quote 'I shut my eyes in order to see.'

The connection between thinking and visual processes has a long history in psychology, predating the development of eye tracking equipment and neuroimaging techniques. One of the founders of psychology as a science, William James (1890), remarked on the connection between eye movements and cognitive processes in his 'Principles of Psychology':

> When I try to remember or reflect, the (eye) movements in question, instead of being directed toward the periphery, seem to come from the periphery inward and feel like a sort of *withdrawal* from the outer world. As far as I can detect, these feelings are due to an actual rolling outward and upward of the eyeballs, such as I believe occurs in me in sleep, and is the exact opposite of their action in fixating a physical thing. (http://psychclassics.yorku.ca/James/Principles/prin10.htm)

Clearly as early as 1890, when 'Principles of Psychology' was first published, psychologists had noticed a possible relation between eye movements and cognition. During the first half of the 20th Century, Gestalt Psychologists suggested that there are many processes that are shared by visual perception and problem solving. For example, perceptual organization that determinates various aspects of vision, such as object recognition and depth perception have analogs (if not the same processes) in problem solving that lead to both difficulties and to sudden insights. One of the key points of the Gestalt principles of visual perception is that object recognition can come suddenly and holistically, following a reorganization of the visual elements into a new integrated whole. Analogously, while engaged in a creative activity, or in problem solving, a new idea or a new solution can arise suddenly and holistically from a reinterpretation or reorganization of the problem elements. Gestalt psychology faded with the cognitive revolution in the 1950s, largely due to its theories being more descriptive than explanatory (Bruce et al., 1996), yet the similarities, at least at a surface level, between visual and problem solving processes had been established. In the second half of the 20th Century non-Gestalt perception psychologists, most notably Rock (1983), suggested that much of visual perception is, in fact, a form of intelligent problem solving rather than merely the result of automatic processes.

More recently, the Embodied Cognition movement has led to increased interest in how cognitive processes and seemingly non-cognitive body processes are linked. Embodied cognition is the belief that cognitive processes and the body are not separate but are linked at the most basic level. The connection between thought and the body is bidirectional with thought influencing and directing the states and actions of the body (e.g., Lakoff and Johnson, 1980, 1999), and states and actions of the body influencing and directing thought (e.g., Eerland et al., 2011).

Two fundamentals assumptions underlie the position we take in this paper: The first is the evolutionary position that existing structures and systems are not replaced by new ones, rather that new ones are built on top of the existing ones (Jonides et al., 2005), the second is that the connection between thought and the body is bidirectional.

EYE MOVEMENTS AND MEMORY

Existing neural systems that enable search for information in the visual environment may have given rise to neural systems able to search for non-visual information stored in long-term memory (Ehrlichman and Micic, 2012). The connection is supported by the finding that when people search for (non-visual) information in long-term memory they make multiple eye movements analogous to those made when searching the environment visually, and when they focus on information in long-term memory they make very few eye movements just as happens when people focus on an object in the visual environment. Thus, mechanisms for internal attention may have evolved from those already in place for attending to the external world. In this theory Ehrlichman and Micic (2012) speculate that internal thought processes are systematically related to (non-visual) eye movements. More frequent movements of the eyes are found when people are engaged in tasks that require search of long-term memory than when they are engaged in tasks that do not require long-term memory search, even when the tasks do not seem to have any visual component. In fact, Ehrlichman and Weinberger (1978) found that participants were less likely to make eye movements (were more likely to stare) when answering visuospatial questions than when answering verbal questions. Bergstrom and Hiscock (1988) found that differences in eye movements are related to the memory demands of questions, and Glenberg et al. (1998), found that when people try to respond to difficult questions they avert their gaze from engaging visual inputs.

LOOKING AT NOTHING OR AT OBJECTS THAT AREN'T THERE

Hebb (1968) introduced the idea that imagining an object is associated with the same eye-movement scan paths that would be associated with actually viewing that object. He suggested that eye movement during imagery has a functional role, to, as in perception, put together and organize the 'part images' to construct a complete visualized image. More recent empirical evidence demonstrated that eye movements during imagery are not random, but reflect the content of the imagined scene (Brandt and Stark, 1997) therefore imagining any visual stimulus triggers corresponding oculomotor responses as if thinking of an object involves pretending to look at it. In a series of studies, Spivey and Geng (2001) demonstrated how eye movements mirror mental images. In two experiments (Spivey and Geng, 2001) participants were instructed to look at a white projection screen while (1) imagining (by listening to pre-recorded instructions of specific directionality, i.e., rightward, leftward, upward, and downward) or (2) recalling objects that were not physically present on the display in what was called the Hollywood squares paradigm; (Richardson and Spivey, 2000), they were asked to recall a characteristic of one of the four objects that was previously presented on the screen). Results of the first experiment showed that participant's eye movements were biased toward the direction of the spatiotemporal imagery in the scene description. Results of the second experiment showed that participants were more likely to look at the blank region of the screen where the missing object had been presented, despite the fact that looking at the blank region was not informative because there was no visual information there to address the recall. The results have been replicated even when participants were asked to relax and to close their eyes while listening to the ten short stories (i.e., there were no instructions to specifically imagine anything) (Spivey et al., 2000).

Several cognitive-neuroscience models suggest memory retrieval is based on the recreation of cortical processes that were active at the time of the original experience (e.g., Marr, 1971; Norman and O'Reilly, 2003). Indeed, it has been shown that common neural systems are activated during initial perception and later retrieval (e.g., Nyberg et al., 2000; Wheeler et al., 2000). Brandt and Stark (1997) demonstrated that during recall of picture or scenes participants' eyes moved spontaneously and the movements closely reflected the spatial relations and the overall content of the imagined picture or scene. Johansson et al. (2006) further investigated this phenomenon by comparing eye movements in four conditions: (1) while participants listened to a spoken scene description and (2) when participants were later retelling it from memory; (3) while studying a complex picture visually, and (4) when they were later describing it from memory. When participants were instructed to recall a visual scene, previously presented either via a verbal description or visual scene, the eye movements made during initial listening or viewing spontaneously reappeared with recall of the scene. This repetition of the eye movements made at encoding occurred for participants both when they looked at a blank white board and in conditions of complete darkness (see also Ehrlichman and Barrett, 1983). Thus, remembering a visual scene seems to involve the reinstatement of the visual processes that were active during encoding. Johansson and Johansson (2014) hypothesized that the probability of remembering should improve when the visual processes engaged at retrieval overlap with those engaged at encoding. Their results demonstrated that spontaneously looking at a blank area and positioning the eyes on a location congruent with the location of stimuli during encoding facilitates retrieval. In fact, when participants made different eye movements at the time of recall than they had made at encoding they showed a decrease in their ability to recall the visual scene (Laeng and Teodorescu, 2002).

It is important to note that participants in the verbal description condition (Johansson et al., 2006) never saw a visual stimulus, yet the overlap between eye movements at the time of recall with those made at the time of encoding still predicted recall performance. Why would this be so? Ferreira et al. (2008) examined this ‘looking at nothing’ behavior, and suggested that it reflects an integrated memory representation based on visual and linguistic input. They proposed that reactivation of one part of the representation results in the other parts being retrieved as well. Thus, there is a feedback loop in which, for example, the reactivation of a linguistic component of the memory can cause the eyes to move to the location in which the item originally appeared, and that returning the eyes to this location can improve memory for other information associated with that item, including any visual and conceptual information. Looking at the location where a stimulus was presented, even after it is no longer present, is a result of the integrated representation, and facilitates retrieval of further information from it.

It seems reasonable that if looking at a location that was previously occupied by a visual stimulus can aid in the recall of both visual and conceptual information, then looking *away* from a still present stimulus, or from the place the stimulus previously occupied, could serve the opposite purpose. That is, looking at nothing could reduce the tendency to perseverate on an idea, or reduce that information’s level of activation and its ability to capture and maintain attention. According to Ferreira et al. (2008) this would apply to both the visual elements of the stimulus and any associated conceptual information. This also suggests that longer fixations away from a stimulus would predict better inhibition of retrieval and less interference, whereas shorter fixations away and frequent returns to the stimulus would predict poorer inhibition and greater interference.

EYE MOVEMENTS AND ATTENTION

Some of the clearest evidence for the bidirectional connection between eye movements and cognition comes from studies of attention; the direction of a person’s gaze is generally a clear (though not perfect) indication of where attention is directed. When a person wants to attend to an object or spatial location she/he moves her/his eyes so that she can fixate on the object or location, and when a person’s eyes moves to an object or location attention usually moves too.

Attention is central to perceptual and higher level cognitive processes, and it plays a central role in creativity (Kounios and Beeman, 2009, 2014). Though attention and eye movement are not one and the same, they are tightly linked (Golberg and Wurtz, 1972; Posner, 1980; Rizzolatti et al., 1987; Klein et al., 1992; Hoffman and Subramaniam, 1995; Kowler et al., 1995; Deubel and Schneider, 1996). The pre-motor theory of attention (Rizzolatti et al., 1987) suggests a strict link between both overt and covert orienting of attention and programming explicit ocular movements. Given a limited capacity to process competing external stimuli, attention selects, regulates, and maintains focus on the information relevant for behavior while simultaneously inhibiting processing of information that is also available, but that is irrelevant. It seems likely that control of attention has evolved out of the necessity to efficiently manage limited cognitive processing capacity and focus it on the information most relevant to ongoing goals and behaviors (Pashler et al., 2001). Attention guides and controls how we move our eyes, allowing us to handle the wealth of visual information provided by the surrounding environment (Rayner, 2009; Schall and Thompson, 1999). Multiple stimuli compete for selection, and the goal of attention is to bias the competition to favor a target object (Desimone and Duncan, 1995). Processing of a target object would be facilitated by both enhancing activation of the target and inhibiting distractors and noise. A very straightforward way to inhibit processing of an irrelevant stimulus would be to look away from it, close one’s eyes, or engage in increased blinking.

The pre-motor theory of attention (Rizzolatti et al., 1987) suggests that eye movements and attentional shifts are driven by the same internal mechanisms, and they are both managed mostly by the superior colliculus (Golberg and Wurtz, 1972).

Chun et al. (2011), propose a taxonomy based on the types of information that attention operates over (i.e., the target of attention): Information coming in from the outside, through the senses (external or bottom-up attention), and information that already has an internal representation (internal or top–down attention). External attention is driven by properties of the outside world and involves the selection and modulation of sensory information, in a modality-specific representation, and often with tags for spatial locations and time (Chun et al., 2011). These two types of attention share the same capacity limitations and they are mutually exclusive. In other words, if attention to internal thoughts is increased, attention to the external world will decrease, and vice versa.

Several studies, using different behavioral and neurophysiological measures and across different fields, e.g., problem solving (Jung-Beeman et al., 2004; Kounios et al., 2006;

Kounios and Beeman, 2009; Salvi et al., 2015), mind wandering (Smallwood et al., 2007; Schooler et al., 2011; Smallwood et al., 2011, 2013), have produced converging evidence demonstrating that, when attention is focused internally processing of external stimuli is suppressed. This mechanism would allow the enhancement of internal concentration by reducing distractions.

As mentioned above, studies of gaze aversion have shown that the frequency of 'looking away' increases with the difficulty of cognitive processing, that it has a functional consequence on memorization, and that closing the eyes improves accuracy for questions of moderate difficulty (Glenberg et al., 1998). Analysis of eye blink rates has shown a similar pattern. Blinking physically blocks incoming information by the closing the eyelid, and generates a suppression of vision associated with an inhibitory signal sent out by the brain (Volkmann et al., 1980) both before and after the time of actual lid closure (Stevenson et al., 1986; Volkmann, 1986; Bristow et al., 2005a,b). But, blinking is something more than a mere interruption of visual input, it has been suggested that blinking is a sensory ending of a top-down processes that allows or facilitates an internal and more complex cognitive mechanism of attention (Salvi, 2013). Specifically, directing attention internally has been found to produce higher eye blink rates (Wood and Hassett, 1983). According to Holland and Tarlow (1975), blinking occurs at the moment of cognitive change as an indicant of transitions between different gazes, sets, or ideas. Conversely, both blink rate and blink duration decline as a function of more intense mental workload (Brookings et al., 1996; Hankins and Wilson, 1998; Veltman and Gaillard, 1998), task concentration, mental activity, and when information in memory is being operated on (Telford and Thompson, 1933)–such as solving arithmetic problems (Holland and Tarlow, 1975). Blinking has been consistently found to be associated with internal thought processes like insight problem solving (Salvi et al., 2015), creativity and divergent thinking (Akbari Chermahini and Hommel, 2010; Ueda et al., 2015), mind wandering (Smilek et al., 2010), errors in vigilance related to external stimuli (Van Orden et al., 2000; Papadelis et al., 2007), and conflicts between internal and external workloads (Recarte et al., 2008).

EYE MOVEMENTS, BLINKING, AND MIND WANDERING

Our attention fluctuates over time between being internally and externally focused (Smallwood et al., 2008a,b). Mind wandering is a state of focus on internal information, where our attention switches from the primary task to our private thoughts that become the focus of awareness (Smallwood and Schooler, 2006). This entails a state of processing decoupled from perception, and a temporary failure in meta-awareness, i.e., the ability to self-reflect upon the content a mental state (Schooler, 2002).

When looking for a creative idea, or the possible solution to a problem, people often mind wander. Of course, mind wandering does not necessarily imply that one is working on a problem or having a creative idea, for example one could be thinking of a past vacation. However, several lines of evidence converge to show that mind wandering is related to both creativity (e.g., Baird et al., 2012; Ritter and Dijksterhuis, 2014) and the 'looking at nothing' behavior mentioned before (Smilek et al., 2010).

Mind wandering has been associated with both internally focused attention and with reduced cortical analysis of the external environment (Smallwood et al., 2008a). Specifically, when people try to engage attention in a sustained manner the depth of cognitive analysis applied to the external environment fluctuates. Reichle et al. (2010) established that a person's fixation pattern while reading is a reliable indicant of attentive or mindless reading. Their results demonstrated that right before episodes of mind wandering subjects were more likely to avoid the text, looking somewhere else, and to elongate their fixations. This study, demonstrates that mind wandering competes with the processing of task-relevant information and reduces the cognitive analysis of external events (e.g., Dehaene and Changeux, 2005; Smallwood and Schooler, 2006). Smilek et al. (2010) showed that an increased blinking rate is associated with mindless reading. Their study demonstrated that mind wandering is coupled with physical blocking of sensory information provided by closing the eyes, suggesting that eye blinks can serve as an index of the degree to which a person is attending to internal thoughts. Thus, the evidence from the variety of studies discussed above supports the position that eye movements and blinking can be used to infer cognitive processes such as memory search and focus of attention.

EYE MOVEMENTS, BLINKING, AND CREATIVITY

Problem solving often implies the construction of mental models (Johnson-Laird, 1983). Mental models serve to both depict the abstract relations between objects and events, and orient attention toward information relevant for the mental model (Smallwood et al., 2008b). Demarais and Cohen (1998) showed that when reasoning, specifically during syllogisms containing the words 'left' and 'right', participants make more horizontal eye movements, and during syllogisms containing 'above' and 'below' participants make more vertical eye movements. Similarly, when attempting to solve problems we often imagine the abstract representation of the problem space and the elements that make up the problem scenario. The creation of models can be triggered in an automatic bottom–up manner (Gerrig, 2005) or constructed in a more purposeful analytic, top–down manner (Graesser et al., 1994), with most problem solving efforts involving an interaction between the two.

Another way to conceptualize problem solving is to suggest that people solve problems via heuristic search through a problem space (Newell and Simon, 1972). In this space the various pieces of information given in a problem and other previous knowledge, which may have initially seemed unrelated, can become linked together to reach a solution. One way to reach a solution is to search the problem space by analysis, following the most likely paths in a gradual approach toward solution with awareness of the intervening steps (Metcalfe and Wiebe, 1987). Alternatively, a novel solution to a problem can suddenly emerge into consciousness in what is called *Insight* or an 'Aha!'

moment. Insight is a form of creative problem solving that appears to be distinct from analytic solutions because it relies on the sudden reorganization of a mental representation of a problem (Sternberg and Davidson, 1995), and it often seems surprising to the solvers, who are typically unaware of how the reorganization occurred, yet remain confident that the solution fits the whole problem.

Cognitive neuroscience has begun to shed light on specific components that underlie problem solving in general, and the differences between creative and more analytic problem solving styles. Neuroimaging reveals that, within a network of neural substrates engaged during problem solving, distinct areas are recruited or emphasized when people solve with sudden insight compared to when they solve analytically (for review: Kounios and Beeman, 2014). Much of this evidence at least circumstantially suggests that distinct patterns of attention (broad or narrow focus) differentiate the two types of solutions. We suggest that evidence from eye movement recordings adds significantly to this understanding.

The association between eye movements and thinking has been demonstrated for some time. Early studies suggested that the direction of eye movements indicates increased activation of the contralateral cerebral hemisphere. Bakan (1969) found that leftward eye movements in response to questions were associated with clearer mental imagery and relatively poorer mathematical performance on the Scholastic Aptitude Test (SAT). Harnad (1972) found that among twenty participants the ten who predominantly moved their eyes in a leftward direction had higher RAT (Mednick and Mednick, 1967) scores and made more extreme esthetic ratings than the right-movers. Kocel et al. (1972) found that the direction of lateral eye movements was strongly modified by the type of question, with verbal and arithmetical questions eliciting more rightward eye movements than did spatial and musical questions. Each of these studies suggests at least a weak relationship between the tendency to look in one direction and the level of performance on certain tasks that would appear to require either more analytic or more creative thinking. Hines and Martindale (1974) went a step further and examined whether artificially induced right or left eye movements facilitated intellectual and creative tasks, respectively. In two experiments male left-lookers scored significantly higher than male right-lookers on the RAT and Alternate Uses Test (AUT; Guilford, 1967). However, in a third experiment female right-lookers scored non-significantly higher than female left-lookers on the RAT and AUT. Hines and Martindale concluded that the effect of induced lateral eye movements was real but relatively weak.

Recent research by Shobe et al. (2009) and Fleck and Braun (2015) has continued to support the effect of lateral eye movements on creativity. Shobe et al. (2009) investigated the effects of increased inter-hemispheric interaction on five dimensions of creativity (appropriateness, detail, flexibility, fluency, and originality) of the AUT. They used a bilateral eye movement task to directly manipulated inter-hemispheric interaction. They found that bilateral eye movements increased originality and flexibility of participants with a strongly dominant hand, but had no effect on mixed-handers. Fleck and Braun (2015) combined the visual-hemifield presentation technique with eye movement tasks to investigate whether the bilateral eye movement effect could be extended to a creativity task similar to the RAT [the Compound Remote Associates (CRA) Task; Bowden and Jung-Beeman, 2003]. They found that eye movement conditions resulted in improved performance on a solution-recognition task, with the bilateral eye movement condition demonstrating the best performance for solution targets.

Studies using the visual-hemifield presentation technique have provided more specific data on how the hemispheres contribute differentially to creativity. Two studies showed that participants were faster to read, and recognize as solutions, solution words presented to the left visual field, and thus initially the Right Hemisphere (Bowden and Beeman, 1998; Jung-Beeman and Bowden, 2000). This indicated that there was greater activation of solution-relevant information in the right hemisphere than in the left hemisphere. A further visual-hemifield study showed that following unsolved problems participants showed greater priming for solutions that they rated as evoking an insight experience on the subsequent solution decision than for solutions that did not evoke an insight experience. This association was stronger for solutions presented to the left visual field-RH than for those presented to the right visual field-LH. These results tied the subjective experience of insight to an objective measure—semantic priming—and suggested that people have an *Aha!* experience in part because they already had semantic activation that could lead them to recognize the solution quickly (Bowden and Jung-Beeman, 2003). The evidence suggests that semantic activation in both hemispheres cooperatively contributes to problem solving, whereas weak solution activation that contributes to the *Aha!* experience is more likely to occur in the RH than in the LH. These studies were followed up by a neuroimaging study combining fMRI and EEG, which revealed increased activity in the right hemisphere anterior superior temporal gyrus for insight solutions relative to non-insight solutions (Jung-Beeman et al., 2004). This area is associated with making connections across distantly related information during comprehension (Beeman et al., 2000). Thus, what was hinted at by early studies of the relation between lateral eye movements and activation of the hemispheres was ultimately fine tuned to show that specific areas within each hemisphere play important and distinct roles in problem solving.

Eye movements have also been used to test theories of problem solving. For example, Knoblich et al. (2001) used recording of eye movements to test the representational change theory of insight. They predicted that when a person is at an impasse that person should have fewer eye movements (longer fixations) and that fixation patterns would reveal what parts of the problem people consider relevant, so that the elements of the problem that people fixated on would change following constraint relaxation. They found that for successful problem solvers, the percentage of fixation time spent on the element that must be changed to reach a solution increased over time and that the percentage of fixation time increased dramatically in the time period immediately prior to solution. Their study demonstrates the power of eye movement recordings to reveal facets of problem solving that would have remained hidden when using more traditional performance measures like solution time and solution rate.

Bilalić et al. (2008) were able use eye movement data to reveal the mechanisms of Einstellung (cognitive set). They demonstrated that once chess experts had found one solution they continued to look at the squares related to their first idea, even while reporting that they were looking for a better idea. In other words, the fixations showed that chess experts were continuing to allocate most of their attention to their first idea even when they thought they were searching for other possible moves. Ellis et al. (2011) and Ellis and Reingold (2014), further investigated Einstellung by monitoring participants' eye movements while they attempted to solve anagrams. The anagrams were presented as six letters: a central three-letter string whose letters were always part of the solution word, and three additional individual letters one of which was a distractor letter (not part of the solution word). Participants were asked to find a five-letter solution word. The central letter string was presented as either a nonword or as a three-letter word. The typical Einstellung effect was found with better overall performance for nonword than word trials, however, participants' eye movements revealed both interference and facilitation as a function of the familiarity of the central letter string. Participants spent less time looking at the central letters when they were presented as a word, suggesting that a word was easier to encode and maintain in memory a word than three individual letters. Participants also spent more time viewing the individual letters when the central letters were presented as a word, suggesting that they found it more difficult to incorporate the individual letters into an existing central word.

Not only can eye movements reveal underlying processes and strategies, they can influence these processes and strategies. Based on Grant and Spivey's (2003) suggestion that there is an implicit link between eye movements and cognition, Thomas and Lleras (2009a) subtly guided the eye movements of some participants as they attempted to solve Duncker's (1945) radiation problem (Duncker, 1945)–*Given a human being with an inoperable stomach tumor, and lasers which destroy organic tissue at sufficient intensity, how can one cure the person with these lasers and, at the same time, avoid harming the healthy tissue that surrounds the tumor?*[1] Thomas and Lleras (2009a) found that using an eye-tracking task to induce eye movements that embodied the solution led to an increase in solution rates compared to participants who were allowed to move their eyes freely. In another study Thomas and Lleras (2009b), required participants to either move their eyes, move their attention while holding their eyes still, or keep both their eyes and attention fixated in the center of the display. The results show that shifting attention in a pattern that expressed the problem's solution increased the probability of solving the problem even in the absence eye movements. Therefore, it is not the eye movements themselves that lead to the solution; rather it is the effect the eye movements have on attention that is important.

[1]The correct solution to this problem involves firing multiple low-intensity lasers from different locations around the tumor so that they converge at the tumor.

Thomas (2013) also manipulated eye movements while participants attempted to solve a problem, and simultaneously performed a verbal or spatial working memory task. Participants who moved their eyes in a pattern that embodied the solution were more likely to solve the problem than participants who maintained fixation, however, this was only true for participants who performed the verbal working memory task. Since the solution to the radiation problem relies largely on spatial information, loading spatial working memory prevented the eye movement manipulation from improving problem solving. In contrast, when paired with the verbal memory task the eye movement manipulation improved solving performance just as in the earlier studies.

Of course, to influence solution rates by directing eye movements it would seem that one has to know what the solution is. However, Werner and Raab (2014, p. 1572) advance the argument that 'it is not the movement *per se* but the goal of the movement that is causal for the effect of sensorimotor information on cognitive processes' (Raab and Green, 2005; Engel et al., 2013). Therefore, influencing eye movements, and blink rates, might also work at a level more general or abstract than the specific solution by influencing attention and memory retrieval. Eye movements to, and fixations on, a stimulus can serve to focus attention on that external stimuli and facilitate the retrieval of further information from it, whereas eye movements away from the stimulus, and fixations on empty space, can serve to shift attention away from external stimuli, inhibiting further processing, and allowing weaker (more distantly related) internal information to come to the fore.

In a study using CRA problems Jung-Beeman et al. (2004) strongly discouraged (so as not to get eye movement artifacts in EEG data) this tendency to look away or blink. They found that EEG revealed a sudden increase in alpha-frequency activity over the right occipital-parietal cortex 1.5 s prior to insight solutions, but not prior to analytic solutions. Alpha activity over sensory cortex is thought to indicate active suppression of input (Haegens et al., 2011; Händel et al., 2011; Ben-Simon et al., 2013) so this increase in alpha under the condition of restriction in eye movements and blinking was interpreted as a covert effort to reduce the amount of visual information passed from visual areas to higher areas that perform more abstract computation (Kounios and Beeman, 2009; Payne and Kounios, 2009). In other words, this alpha burst was interpreted as attention shifting away from the visual representation of the problem, toward internal processing (Benedek et al., 2014) just prior to insight but not solutions by analysis.

Results from an fMRI study of problem solving indicate that during the rest period prior to presentation of visual problems stronger activity in dorsal Anterior Cingulate Cortex (dACC) is associated with subsequently solving by insight, whereas stronger activity in visual cortex is associated with subsequently solving by analysis (Kounios et al., 2006). The ACC is a critical hub in the network subserving cognitive control (Posner and DiGirolamo, 1998; Kerns et al., 2004), the process by which the brain guides and controls processing, and plays a pivotal role in attention shifting (Kondo et al., 2004). The greater neural activity found over the visual cortex–prior to problems solved analytically-suggested that participants are pre-oriented to elaborate visual information thus more prone to direct their attention outwardly (Kounios et al., 2006; Kounios and Beeman, 2009). This perspective is consistent with the more general idea that creative thinkers have the ability to change cognitive states between defocused and focused attention (Martindale, 1995), strategically inhibit peripheral information when necessary (Stavridou and Furnham, 1996), and allocate attention in a diffuse manner (Dykes and McGhie, 1976). Wood and Hassett (1983) have shown that internally directed attention yields higher blink rates during problem solving and Tsubota et al. (1999) demonstrated that the visual cortex activation is greater with voluntary blink inhibition. Thus, solving by insight is associated with directing attention toward cognitive control – perhaps enhancing the ability to shift processing from one idea to another – whereas solving by analysis is associated with a readiness to process visual information. This latter conclusion has been demonstrated by measuring eye movements when people have insights. In a study paralleling the neuroimaging and EEG work, Salvi et al. (2015) monitored overt attention, before and while people solved word problems, through three different measures: blinking, fixation frequency, and fixation location. The results suggest that solutions via insight are facilitated by actively reducing potentially interfering visual inputs, by blinking more before and during problem solving, and avoiding visual distractors by looking in the white space outside of the problem area just prior to solving. These results directly demonstrate that people overtly direct their attention differently when solving a set of CRA problems by insight versus solving by analysis. Decreased blinking and increased number of fixations show that externally focused attention, on the problem itself or the space where the problem will appear, is more conducive to solving problems with analysis. Increased blinking and decreased eye movements, as well as increased fixations on empty space, indicate that internally focused attention on associations generated by the problem, is more conducive to solving with sudden insight. This pattern of blinking, fixations, and eye movements–which indicate disengaging from the visual stimuli–appear to enhance imagination and creativity by diminishing processing of inputs and their strong associations, and switching attention inwardly to allow detection of weaker associations.

Ueda et al. (2015) also found that blinking could have an effect on creativity. Analyses of eye blinks during creative performance indicated that increased eye blink rates corresponded with the production of more alternative uses on the AUT and slower solutions on the RAT. They suggest that the slower RAT solutions reflect a more divergent search for solution candidates, an interpretation that would be consistent with increased eye blinks being related to using an insight approach to solve RAT problems. The results are compatible with the suggestion that spontaneous eye blinks are actively involved in attentional disengagement from the external world allowing more divergent thinking to occur.

A THIRD VARIABLE INTERPRETATION OF EYE-MOVEMENTS, BLINKING, AND CREATIVITY

As we have discussed above, there is a fair amount of evidence that eye movements and blinking reflect basic cognitive processes such as memory search (e.g., Ehrlichman and Weinberger, 1978; Ehrlichman and Barrett, 1983; Bergstrom and Hiscock, 1988; Glenberg et al., 1998; Laeng and Teodorescu, 2002; Ferreira et al., 2008; Ehrlichman and Micic, 2012; Johansson and Johansson, 2014) and attention (e.g., Golberg and Wurtz, 1972; Posner, 1980; Rizzolatti et al., 1987; Klein et al., 1992; Hoffman and Subramaniam, 1995; Kowler et al., 1995; Deubel and Schneider, 1996; Salvi et al., 2015), and can be used to infer these cognitive processes with a reasonable degree of accuracy (Henderson et al., 2013). There is also evidence (though less) that eye movements and blinking can affect, as well as reveal, cognitive processes (e.g., Shobe et al., 2009; Thomas and Lleras, 2009a,b; Thomas, 2013; Fleck and Braun, 2015). However, a third possibility that we have not discussed is that eye movements and blinking, and cognitive processes such as divergent thinking and ability to focus attention are all affected by a third variable. One possible candidate for the third variable is a person's level of dopamine.

Spontaneous blink rates have been linked to dopamine function (DA; Karson, 1983; Blin et al., 1990; Kleven and Koek, 1996; Taylor et al., 1999; Colzato et al., 2007, 2009) and spontaneous eye blink rate is used as an index of striatal dopamine production (Karson, 1983; Shukla, 1985; Taylor et al., 1999). DA, in turn, is highly associated with executive function, and anatomically with the dACC that contributes to these processes. Increasing dopamine levels or activity via lesions or pharmacology, increases blink rates; conversely, decreasing dopamine decreases blink rates (Karson, 1983; Akbari Chermahini and Hommel, 2010).

Dopamine functioning is associated with attention/cognitive control and with the degree to which people maintain ongoing processes or switch to new processes (Müller et al., 2007). This kind of cognitive flexibility, important for generating new ideas, depends on dopamine D2 receptor signaling (Van Holstein et al., 2011).

Specifically, there are a number of reasons to believe that dopamine plays an important role in creativity. Eysenck (1993) has related aspects of creativity to schizophrenia, and pointed out that schizophrenics and healthy creative individuals share a certain lack of constraints and inhibition in their thinking. Ashby et al. (1999) attempting to explain the beneficial effect of mood on creative behavior assume that higher DA levels are associated with less inhibition of alternative thoughts and greater cognitive flexibility (cf., Cohen and Servan-Schreiber, 1992).

Akbari Chermahini and Hommel (2010) measured EBR in the resting periods before and after participants performed both a divergent thinking task (the Alternative Uses Task – of Guilford, 1967) and convergent thinking one (the Remote Associate Task – RAT, Mednick, 1962). For the AUT, participants who produce moderate levels of spontaneous eye blinks perform better than those with higher or lower levels. Conversely, the researchers found a weak, negative relationship between EBR and RAT accuracy. Akbari Chermahini and Hommel (2010) provided evidence regarding the relationship between creativity and spontaneous eye blinks at rest and their results strengthen the claim that creativity and the dopamine system are related. Thus, both EBRs and convergent and divergent thinking might be the result of different levels of dopamine.

One difficulty with reaching conclusions regarding the relation between dopamine and creativity by using the AUT and RAT (or CRAs) is that the AUT is a relatively pure measure of divergent thinking (with four components originality, fluency, flexibly, and elaboration) while the RAT requires a combination of divergent and convergent thinking. Both the RAT and CRA require that solvers generate many possible words that are related (or form compounds with) the words in the triads, which is a divergent component of the task. Solvers must then be sensitive to the overlap between the many words generated, which is a convergent component of the task, to be able to select the one correct answer. Studies have often focused only on solution rates, used few problems, and given relatively long solution periods, possibly obscuring some subtle changes in EBR or eye movement and fixation patterns.

As mentioned above, Ueda et al. (2015) also found that blinking could have an effect on creativity. They found essentially the same relation between ERB and AUT as reported by Akbari Chermahini and Hommel (2010), however, they examined solution speed as well as solution rate for RAT problems and found that participants with higher resting EBRs took longer to solve RAT problems. They suggest that the slower RAT solutions reflect a more divergent search for solution candidates. They also found no correlation between number solved and EBR during the task suggesting at least the possibility that solution rate is too coarse a measure to be used in studies of the components of creative problem solving.

Salvi et al. (2015) divided solutions to the CRAs into those produced via insight or via analysis (as self-reported by participants) and found that the number of blinks was greater for problems solved with insight than for problems solved with analysis. These results demonstrate that people overtly direct their attention differently when solving a set of CRA problems by insight versus solving by analysis.

Dopamine level has also been found to correlate with creativity in a neuroimaging study (de Manzano et al., 2010). de Manzano et al. (2010) found that scores on divergent thinking tests (Inventiveness battery, Berliner Intelligenz Struktur Test) were correlated with regional D2 receptor densities, as measured by Positron Emission Tomography. The results showed a negative correlation between D2 density in the thalamus and divergent thinking scores, demonstrating that the D2 receptor system is important for creative performance.

Several researchers have examined the emergence of artistic or creative behaviors in people with Parkinson's Disease (PD) who are undergoing treatment with levodopa or dopamine agonists (Canesi et al., 2012; Inzelberg, 2013).

By examining creative and non-creative PD patients Lhommée et al. (2014) found that creativity decreased significantly following reduction in dopaminergic treatment leading to the conclusion that creativity is at least partly dependent on dopamine. High dopamine levels may disrupt latent inhibition (which is the capacity of the brain to filter seemingly irrelevant stimuli from conscious awareness; Chakravarty, 2010) via alterations in the mesolimbic and mesocortical dopaminergic pathways, which are involved in the modulation of reward, motivation, inhibitory control, and decision-making (Kulisevsky et al., 2009). Reduced latent inhibition is thought to be a biological basis of creativity, therefore, the general hypothesis is that dopaminergic drugs may reduce inhibitory control through the stimulation of these pathways (Antonini and Cilia, 2009), possibly leading to greater creativity.

It is worth mentioning that PD is associated with some problems in visual processing and ocular-motor control (Armstrong, 2011). Some of these symptoms, such as hypometria of saccades, which is related to poor visual memory (Hodgson et al., 1999; Shaunak et al., 1999), are related to dopamine deficiency, while others such as visual hallucinations and prolonged latency of saccades are related to treatment with dopamine agonists (Michell et al., 2006).

CONCLUSION

Where do we look when we look for a creative idea? The evidence suggests that we 'look nowhere' and we blink. That is, looking at nothing, or the 'blank wall behavior' and increased blinking, has been found to be associated with insight, but not analytic solutions on RAT and CRA problems, and increased creativity on various measures of creativity such as the AUT, and better performance on mental imagery tasks. This looking nowhere behavior, as well as increases in blink rate, has also been observed during memory encoding and search, changes in attentional focus, and mind wandering–all forms of cognition that do not explicitly involve visual imagery. The research has demonstrated that 'looking at nothing' and blinking are associated with reduced analysis of the external visual environment. Thus, looking nowhere appears to indicate (and likely facilitate) a shift of attention from external to internal stimuli, which benefits creativity and problem solving by reducing the cognitive load and enhancing attention to internally evolving activation.

In this paper we have made a case for using eye movement patterns, fixations, and blink rates to study creativity and problem solving. We suggest that these data can reveal strategies people employ, and how memory search and allocation of attention differ for different types of problem solving. We also suggest that manipulating eye movements might induce attentional states that are more conducive to either analytic or insight problem solving. Eye movements can also be used to reveal what stage a person is at in the problem solving process. For example, eye movements could reveal when a person has reached an impasse and would be most receptive to information that could lead to a change in the representation of the problem, or when a period of incubation might be most effective in the problem solving process.

Finally, we would argue that even if eye movements, blink rates, and fixations are epiphenomena of creativity, or driven by differences in dopamine levels, the fact that they are correlated with different types of cognitive processes suggests that monitoring them during problem solving activities would still provide very useful information.

AUTHOR CONTRIBUTIONS

All authors listed, have made substantial, direct, and intellectual contribution to the work, and approved it for publication.

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Domain-Specificity of Creativity: A Study on the Relationship Between Visual Creativity and Visual Mental Imagery

Massimiliano Palmiero [1]*, Raffaella Nori [2], Vincenzo Aloisi [1], Martina Ferrara [1] and Laura Piccardi [1,3]

[1] Department of Life, Health and Environmental Sciences, University of L'Aquila, L'Aquila, Italy, [2] Department of Psychology, University of Bologna, Bologna, Italy, [3] Neuropsychology Unit, IRCCS Fondazione Santa Lucia, Rome, Italy

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Spanish National Research Council,
Spain

***Correspondence:**
Massimiliano Palmiero
massimiliano.palmiero@univaq.it

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Creativity refers to the capability to catch original and valuable ideas and solutions. It involves different processes. In this study the extent to which visual creativity is related to cognitive processes underlying visual mental imagery was investigated. Fifty college students (25 women) carried out: the Creative Synthesis Task, which measures the ability to produce creative objects belonging to a given category (originality, synthesis and transformation scores of pre-inventive forms, and originality and practicality scores of inventions were computed); an adaptation of Clark's Drawing Ability Test, which measures the ability to produce actual creative artworks (graphic ability, esthetic, and creativity scores of drawings were assessed) and three mental imagery tasks that investigate the three main cognitive processes involved in visual mental imagery: generation, inspection and transformation. Vividness of imagery and verbalizer–visualizer cognitive style were also measured using questionnaires. Correlation analysis revealed that all measures of the creativity tasks positively correlated with the image transformation imagery ability; practicality of inventions negatively correlated with vividness of imagery; originality of inventions positively correlated with the visualization cognitive style. However, regression analysis confirmed the predictive role of the transformation imagery ability only for the originality score of inventions and for the graphic ability and esthetic scores of artistic drawings; on the other hand, the visualization cognitive style predicted the originality of inventions, whereas the vividness of imagery predicted practicality of inventions. These results are consistent with the notion that visual creativity is domain- and task-specific.

Keywords: creative cognition approach, imagery, transformation imagery, cognitive style, visualization strategy

INTRODUCTION

Creativity is a mysterious aspect of human thinking. The general characteristics shared by the creative products are hard to recognize. There is wide agreement on the notion that creativity involves the ability to produce a work that is both original and appropriate (Sternberg and Lubart, 1996; Mumford, 2003), leading to new inventions and solutions in any area (Vanderbos, 2006). Therefore, creativity plays a crucial role on human thought, being involved in different activities, such as problem-solving (Basadur et al., 2000), scientific progress (Klahr and Simon, 1999), verbal thought (Fink and Neubauer, 2006), visual art (van Leeuwen et al., 1999), dance (Fink et al., 2009), music (Olivetti Belardinelli, 2002), and so forth. This multi-componential aspect of creativity opens to the issue of domain-specificity. According to Hong and Milgram (2010) creativity can be distinguishable in both domain-general and domain-specific. A though creativity has been long considered only domain-general, different studies showed that creativity is also domain-specific at both the behavioral (Plucker and Beghetto, 2004; Kaufman and Baer, 2005; Palmiero et al., 2010) and neuroanatomical levels (Boccia et al., 2015). In general, following the psychometric approach of individual differences, various creativity-relevant skills, such as the tolerance for ambiguity (Amabile, 1996), and divergent thinking (Silvia, 2008), which involves the assessment of the creative potential rather than of the creative outcomes (Runco and Acar, 2012), play a key role on creativity across many different domains. On the contrary, following problem-solving theories creativity appears to be more domain-specific (Silvia et al., 2009). Interestingly, when the focus is on the creative product creativity is mostly domain-specific (Baer, 1993). Thus, besides the domain specificity, creativity production also depends on the features of the domain and approach used. For example, Palmiero et al. (2010) showed that visual creativity is more domain- and task-specific than verbal creativity.

In the present paper, the extent to which visual creativity is related to visual mental imagery was explored considering the product-oriented approach. Firstly, the creative cognition approach (Finke and Slayton, 1988; Finke, 1990, 1996; Finke et al., 1992) was used. It focuses on the mental operations supporting visual creativity rather than on individual differences (Abraham and Windmann, 2007). According to Finke, generative processes (e.g., association, mental synthesis) are used in the construction of pre-inventive forms, and exploratory processes (e.g., conceptual interpretation, functional inference) are used to examine and interpret the pre-inventive forms. Although this approach encompasses a strong visual imagery component, only a few studies revealed that specific dimensions of the creative objects production are related to specific visual imagery operations (e.g., Palmiero et al., 2011; Morrison and Wallace, 2001; Verstijnen et al., 1998), whereas other studies failed to find such a relationship (Anderson and Helstrup, 1993; Palmiero et al., 2010).

Secondly, the visual creative behavior approach was used. The actual creative behavior involving performance in visual arts and drawing is assumed to be related to vividness of imagery, which refers to the pictorial dimension of imagery, given that previous studies revealed that vividness of imagery (Pérez-Fabello and Campos, 2007) and the ability to generate mental images to identify letters with parts omitted (Zemore, 1995) are enhanced in the presence of artistic training. In this direction, Morrison and Wallace (2001) also found a positive relationship between vividness and creative behavior in art in psychology students with artistic background as assessed by the visual art sub-score of the Creative Behavior Inventory (Hocevar, 1979). In contrast, the extent to which the actual visual creative behavior is related to performances on tests that measure the ability to mentally manipulate spatial images in two- or three-dimensions is unclear, since different studies failed to find such a relationship (for a review, see Palmiero and Srinivasan, 2015). This is consistent with the idea that people with formal artistic training or with involvement in past visual art rely on object imagery, preferring to construct high-resolution images of objects of scenes, rather than represent spatial relations among visual elements (Blazhenkova and Kozhevnikov, 2009).

The relationship between visual creativity products and visual mental imagery was investigated within Kosslyn's (1980) theoretical framework, which sustains that three different cognitive processes underlie visual imagery: generation of mental images of visual stimuli previously learned; inspection of visual details within a mental image, and transformation of abstract representations before matching them with visual stimuli. To this end, the Creative Synthesis Task (Finke, 1990), aimed at constructing creative objects, and Clark's Drawing Ability Test (Clark, 1989), aimed at making artistic drawings, were used. In addition, besides the tasks of generation, inspection and transformation of images, vividness of imagery was also measured to investigate the ability to represent pictorially visual images, and the verbalizer–visualizer cognitive (VVQ) style to investigate a personal general attitude toward visual mental imagery. Given that the relationship between visual creativity and visual imagery has never been studied by such a combination of approaches, the present study is unique in this respect.

MATERIALS AND METHODS

Participants

The research involved 50 College students from the "Department of Life, Health and Environmental Sciences," University of L'Aquila, Italy: 25 women (mean age = 20.64 ± 1.32—age range = 19–24) and 25 men (mean age = 23.4 ± 4.20—age range = 19–31). All participants were healthy and without neurological and/or psychiatric disorders; no problem with alcohol or drug addiction was reported. None of the participants had a background in art or creative activities in general. In order to exclude those with significant visuo-spatial working memory problems, the Corsi Block-tapping Test (Corsi, 1972; for the test procedure, see Piccardi et al., 2013) was administered both forward and backward. None of the participants was found to be impaired in visuo-spatial working memory (Corsi forward: men mean = 6.12; SD = 1.20; cut-off < 4.68; women mean = 6.29, SD = 1.28; cut-off < 4.07 in Piccardi et al., 2013; Corsi backward: men mean = 5.84; SD = 1.11; cut-off < 3.44; women mean = 5.76, SD = 0.91; cut-off < 3.44 in Monaco et al., 2013). All participants had normal or corrected to normal (soft contact lenses or glasses) vision. Everyone signed the written informed consent after the procedures had been fully explained to them. The study was designed in accordance with the ethical principles of human experimentation stated in the Declaration of Helsinki and was approved by the Institutional Review Board of the Department of Life, Health and Environmental Science, University of L'Aquila.

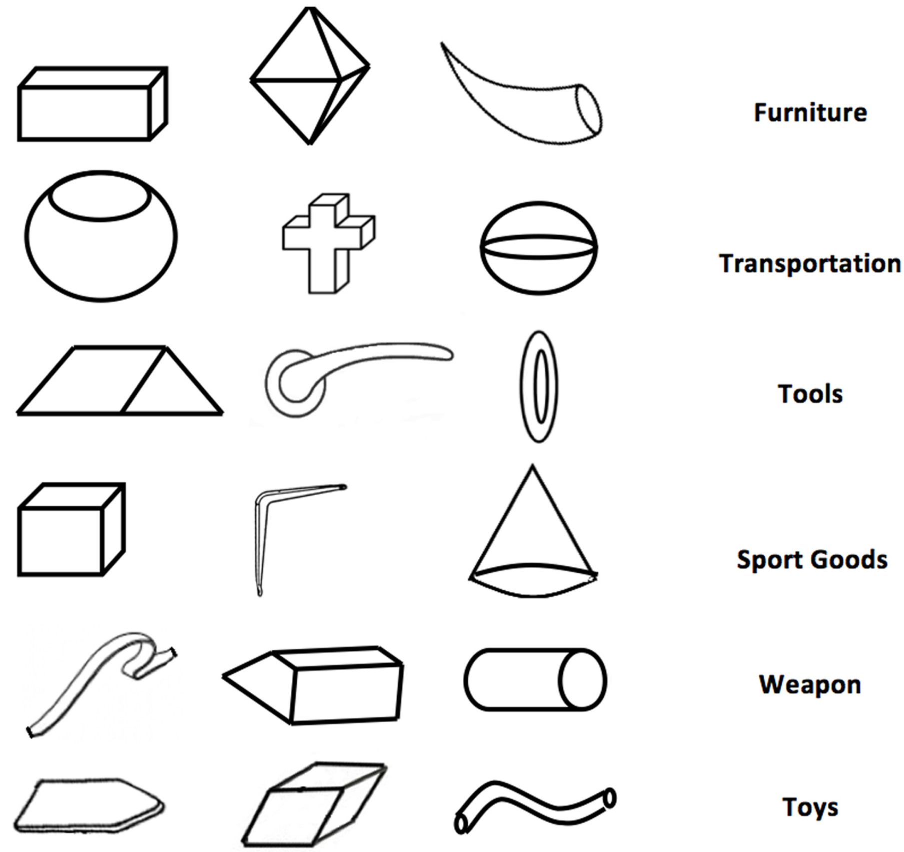

FIGURE 1 | Triads of Elements for the Figural Combination Task: (1) rectangular block, dipyramid, horn (furniture); (2) pot, cross, sphere (transportation); (3) rhombus, handle, ring (tools); (4) cube, bracket, cone (sport goods); (5) strip, trapezoid, cylinder (weapons); (6) board, rhomboid, tube (toys).

Materials and Procedure

Participants took part in the study individually. The experiment lasted approximately 2 h. The following tasks and questionnaires were administered in random order.

Creative Tasks:

The creative synthesis task

The Creative Synthesis Task (Finke, 1990) aimed to create objects belonging to specific categories, starting from visual components. Six triads of components and six categories were used (see **Figure 1**). The same combinations of stimuli and categories were presented across participants to increase the inter-rater reliability by reducing random error variation (Abraham and Windmann, 2007).

Participants were first introduced to the task with a practical example. Following Finke (1990), for each triad participants were given 2 min to mentally combine the components into a pre-inventive form (potential useful object). Components could be changed in position, rotation, and size, but not in their general structure. The instructions encouraged participants to assemble the visual components at their best and to sketch the pre-inventive form as they generated it. For each triad, names of stimuli were written in the upper part of a sheet of paper, and stimuli were drawn below. Participants were given 15 s to memorize the stimuli, and were then allowed to think of their pre-inventive form and subsequently sketch it on the sheet of paper. After creating the six pre-inventive forms, participants were presented with a category name for each of them and instructed to think of their objects as an invention within the category. Participants were given 1 min to describe the functioning of the invention and to write its name.

Clark's drawing ability test

Clark's Drawing Ability Test (Clark, 1989; Clark and Zimmerman, 2004) aimed to create in the visual arts. Participants were instructed to draw only two pictures out of four of the original version of this task: a front view of a house; a fantasy drawing from imagination. Participants were given 10 min per drawing. Colors were available. The instructions encouraged participants to be as creative as possible while making their artistic drawings.

Visual Imagery Testing

Vividness and cognitive style tasks

The vividness of visual imagery questionnaire. The Vividness of Visual Imagery Questionnaire (VVIQ; Marks, 1973) aimed to measure the vividness of visual imagery. Participants were

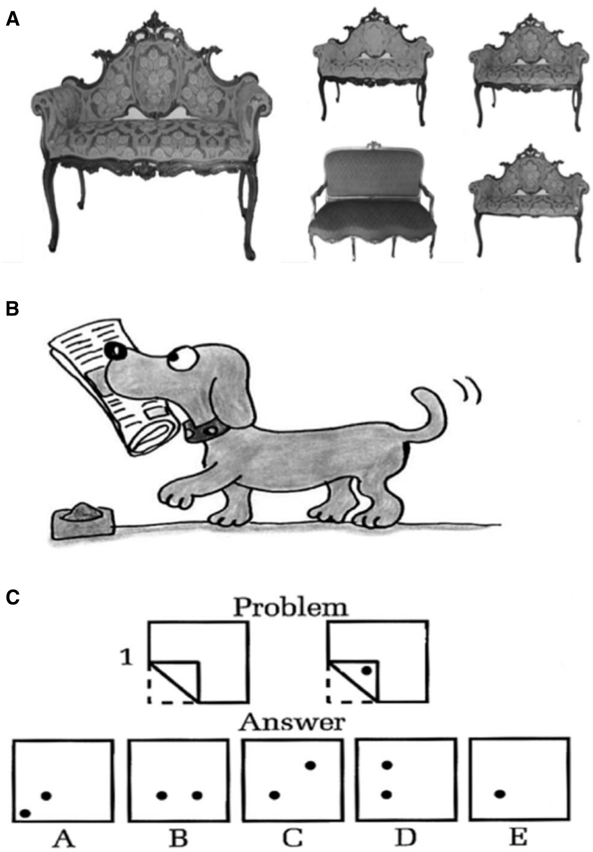

FIGURE 2 | (A) Generation Task: Example of item of the Object task: target (on the left), response option (on the right). **(B)** Inspection Task: Example of item of the Object Inspection Task. **(C)** Transformation Task: Example of item of the Paper Folding Task. The figures "Problem" represent a square piece of paper being folded, and the last of these figures has one or two small circles drawn on it to show where the paper has been punched. Each hole is punched through all the thicknesses of paper at that point. The five figures "Answer" show where the holes will be when the paper is completely unfolded.

instructed to rate 16 visual mental images cued by verbal descriptions along a 5 point-scale ranging from 1 (no image at all) to 5 (image clear and vivid as reality). The maximum score was 80.

The verbalizer–visualizer questionnaire. The Verbalizer–Visualizer Questionnaire (VVQ; Richardson, 1977) aimed to measure individual differences in the dimension of visualizer/verbalizer cognitive style, where visualizers were supposed to have high-imagery ability and verbalizers were supposed to have low imagery ability. Participants were instructed to choose a true/false response to 15 questions, such as "I like to learn new words" or "My dreams are extremely vivid." The maximum score was 15.

The tasks proceeded according to the three components of Kosslyn's Model (see **Figure 2**).

Generation Task

The object task

The Object task (Palermo et al., 2010) is a generation task including 20 items, each of which consisted of two stimuli. In each item, the first stimulus was a photo of an object (e.g., a boot, a spoon, etc.). The participants were asked to observe the photo target for 10 s. They then had to mentally generate the image of the previously seen photo with their eyes closed. When the participant was ready, the second stimulus was shown. In the second stimulus four pictures of objects were presented: the target and three distractors (see **Figure 2A**). The distractors included a mirror image of the target and two objects similar to the target, but with different basic visual characteristics (i.e., color) or with modification (or cancelation) of specific elements (such as the high heel of a boot or the decorative elements in the handle of a spoon). The score was either 1 (correct) or 0 (incorrect); the highest score was 20.

Inspection Task

The object inspection task

The Object Inspection Task (Nori et al., 2012) is an inspection task in which participants observed a picture for 20 s. The picture was then removed and the participants were asked to close their eyes, to imagine the picture previously seen and to answer questions about it (i.e., Was the dog's tail pointing up or down? see **Figure 2B**). The score was either 1 (correct) or 0 (incorrect), the highest score was 20.

Transformation Task

The paper folding test

The Paper Folding Test (PFT; Ekstrom et al., 1976) is normally used to measure spatial visualization ability, reflecting the ability to perceive, encode and mentally manipulate spatial forms (Lohman, 1988). It involves a strong imagery component, given that the performance on this task was found to be related to the ability to rotate and integrate imaged forms (Poltrock and Agnoli, 1986). Participants were presented with figures of papers being folded and holes being punched in the folded papers. They were instructed to imagine what the pattern of holes would look like if the paper were unfolded (see **Figure 2C**). Participants were given 6 min to complete the test, consisting of twenty items in total. The maximum score was 20.

Data Scoring

Before carrying out statistical analyses, data were scored according to different criteria. Visual creativity tasks were evaluated using Amabile's (1983) Consensual Assessment Technique, encompassing the idea that creativity products can be measured as the combined judgment of different people. Therefore, two independent and anonymous judges (as in other studies, e.g., Kavakli and Gero, 2001; Pearson et al., 2001; Abraham et al., 2006; Abraham and Windmann, 2008; Roskos-Ewoldsen et al., 2008; Palmiero, 2015), one female (23 years old) and one male (23 years old), were instructed with practical examples to evaluate both the pre-inventive forms and inventions created by participants by means of the Creative Synthesis Task (pre-inventive forms were rated independently of inventions) as well as the front view of a house and the fantasy drawing of Clark's Drawing Ability Test. Unrecognizable drawings were excluded from the analysis. For each criteria described below the average of the ratings given by the judges was taken as the final score.

The pre-inventive forms of the Creative Synthesis Task were evaluated in terms of: "originality," defined as a form being new and not derived from something else, from 1 (very poor originality) to 5 (very high originality); "synthesis," defined as the extent to which components were well assembled together, from 1 (very poor synthesis) to 5 (very high synthesis); "transformation," defined as the extent to which components were changed in position, orientation and size when assembled into the final form, from 1 (very poorly transformed) to 5 (very highly transformed). The inter-rater correlations (intra-class correlation coefficient—absolute agreement) were significant for both "originality" ($\alpha = 0.488$, $p < 0.05$), "synthesis" ($\alpha = 0.546$, $p < 0.005$), and "transformation" ($\alpha = 0.501$, $p < 0.01$).

Inventions were evaluated in terms of: "originality," defined as an invention being new and not derived from something else, from 1 (very poor originality) to 5 (very high originality); "practicality," defined as an invention involving an actual use in a specific context, rather than a hypothetical use, from 1 (very poor practicality) to 5 (very high practicality). The inter-rater correlations (intra-class correlation coefficient—absolute agreement) were significant for both "originality" ($\alpha = 0.583$, $p < 0.001$) and "practicality" ($\alpha = 0.481$, $p < 0.05$).

The creative drawings were evaluated in terms of: "graphic ability," defined as the extent to which drawings were performed accurately in terms of pictorial aspects, such as colors, shades, details provided, as well as in terms of spatial aspects, such as spatial relations among elements; "esthetic," defined as the extent to which drawings involved beauty, giving pleasure and satisfaction viewing them; "creativity," defined as drawings involving different new ideas, perspective, colourfulness. The inter-rater correlations (intra-class correlation coefficient—absolute agreement) were significant for "graphic ability" ($\alpha = 0.896$, $p < 0.001$), "esthetic" ($\alpha = 0.815$, $p < 0.001$), "creativity" ($\alpha = 0.746$, $p < 0.001$).

Regarding the Visual Imagery Tasks, the Building task, the Object Inspection Task and the PFT were scored by summing the number of correct responses (max 20 for each task), in order to obtain one independent variable for each cognitive process involved in visual mental imagery: generation, inspection and transformation, respectively.

The vividness score was computed by summing the scores of each item; the VVQ was scored according to Richardson' norms. The score was treated as a continuous independent variable, assuming that the higher the VVQ score was, the higher the degree of imagery ability.

RESULTS

In order to explore the relationship between visual creativity and visual mental imagery abilities Pearson correlations between different variables were performed (see **Table 1**). On the one hand, variables related to visual creativity were: "originality," "synthesis," "transformation" of pre-inventive forms; "originality" and "practicality" of inventions; "graphic ability," "esthetic," and "creativity" of Clark's Drawing Ability Test. On the other hand, variables related to visual mental imagery were: accuracy of the generation, inspection and transformation processes of visual imagery, the vividness score of visual imagery (VVIQ), the degree of style VVQ.

TABLE 1 | Correlation matrix.

	VVIQ	VVQ	Gen-ACC	Isp-ACC	Transf-ACC
Ori-Pre	−0,03	0,13	−0,05	0,14	0,37
Syn-Pre	−0,02	0,06	−0,05	0,04	0,38
Transf-Pre	−0,21	0,24	−0,04	0,08	0,32
Ori-Post	−0,06	0,32	0,02	0,07	0,41
Pract-Post	−0,33	0,24	0,22	0,09	0,30
GA-CDAT	0,02	0,26	0,05	0,09	0,48
Aesth-CDAT	−0,03	0,22	0,03	0,06	0,47
Creat-CDAT	0,09	0,17	−0,05	0,05	0,33

Correlations in Bold are significant. VVIQ, Vividness of Visual Imagery Questionnaire; VVQ, Verbalizer–Visualizer Questionnaire; Gen-ACC, Accuracy of Generation process; Insp-ACC, Accuracy of Inspection process; Transf-ACC, Accuracy of Transformation process; Ori-Pre, Originality of pre-inventive forms; Syn-Pre, Synthesis of pre-inventive forms; Transf-Pre, Transformation of pre-inventive forms; Ori-Inv, Originality of inventions; Pract-Inv, Practicality of inventions; GA-CDAT, Graphic Ability of the Clark's Drawing Ability Task; Aesth-CDAT, esthetic of the Clark's Drawing Ability Task; Creat-CDAT, Creativity of the Clark's Drawing Ability Task.

The VVIQ score was found to be negatively correlated with the "practicality" score of inventions ($r = -0.33$; $p < 0.05$), whereas the VVQ score was positively correlated with the "originality" score of inventions ($r = 0.32$; $p < 0.05$). The PFT score was found to be positively correlated with all measures of creativity tasks, as follows: "originality" ($r = -0.37$; $p < 0.01$), "synthesis" ($r = -0.38$; $p < 0.01$), and "transformation" ($r = -0.32$; $p < 0.05$) scores of pre-inventive forms; "originality" ($r = -0.41$; $p < 0.01$) and "practicality" ($r = -0.30$; $p < 0.05$) scores of inventions; "graphic ability" ($r = -0.48$; $p < 0.001$), "esthetic" ($r = -0.47$; $p < 0.005$), and "creativity" ($r = -0.33$; $p < 0.05$) scores of Clark's Drawing Ability Test.

In addition, Hierarchical Regression analyses aimed at investigating the extent to which visual creativity scores can be predicted by the vividness of imagery, the VVQ style and mental imagery abilities were performed. A Hierarchical Multiple Regression analysis was carried out for each of the following dependent variables: "originality," "synthesis," and "transformation" scores of pre-inventive forms; "originality" and "practicality" scores of inventions; "graphic ability," "esthetic," and "creativity" scores of Clark's Drawing Ability Test. For all analyses the predictor "gender" was first entered in order to check for any difference; then the VVIQ and VVQ scores were entered, followed by the accuracy of the generation, inspection and transformation processes. In total, three blocks of independent variables were used.

The analysis showed that the overall model of the "originality" [$F_{(6,43)} = 1.423$, $p > 0.05$], "synthesis" [$F_{(6,43)} = 1.35$, $p > 0.05$] and "transformation" scores [$F_{(6,43)} = 1.841$, $p > 0.05$] of pre-inventive forms were not significant.

Regarding the "originality" score of inventions, the analysis demonstrated that the first model was not significant [$F_{(1,48)} = 1.341$, $p > 0.05$]. After introducing the VVIQ and VVQ scores, the second model explained 17.7% of variance [$F_{(3,46)} = 3.287$, $p < 0.05$; $R^2 = 0.177$; R^2 Adjusted $= 0.123$], that is an additional 15% [R^2 change $= 0.149$; $F_{(2,46)} = 4.171$; $p < 0.05$]. After introducing the accuracy score of the generation, inspection and transformation processes of visual mental imagery, the third model explained 31.5% of variance [$F_{(6,43)} = 3.295$ $p < 0.01$; $R^2 = 0.315$; R^2 Adjusted = 0.219], that is an additional 13.8%, [R^2 change = 0.138; $F_{(3,43)} = 2.897$; $p < 0.05$]. In the model as a whole, the VVQ score ($\beta = 0.420$, $p < 0.01$, $t = 2.919$) and the PFT score ($\beta = 0.325$, $p < 0.05$, $t = 2.408$) were significant.

Regarding the "practicality" score of inventions, the analysis showed that the first model was not significant [$F_{(1,48)} = 0.0$, $p > 0.05$]. After introducing the VVIQ and VVQ scores, the second model explained 17.1% of variance [$F_{(3,46)} = 3.157$, $p < 0.05$; $R^2 = 0.238$; R^2 Adjusted = 0.170], that is an additional 17.1% [R^2 change = 0.171; $F_{(2,46)} = 4.736$, $p < 0.01$]. After introducing the accuracy score of the generation, inspection and transformation processes of visual mental imagery, the third model explained 29.2% of variance [$F_{(6,43)} = 2.962$, $p < 0.05$; $R^2 = 0.292$; R^2 Adjusted = 0.194], that is an additional 12.1% [R^2 change was not significant, $F_{(3,43)} = 2.466$, $p > 0.05$]. In the model as a whole, only the VVIQ score ($\beta = -0.307$, $p < 0.05$, $t = -2.311$) was significant.

Regarding the "graphic ability" score of Clark's Drawing Ability Test, the first [$F_{(1,48)} = 0.334$, $p > 0.05$] and the second [$F_{(3,46)} = 1.114$, $p > 0.05$] model were not significant. After introducing the accuracy score of the generation, inspection and transformation processes of visual mental imagery, the third model explained 30.5% of variance [$F_{(6,43)} = 3.146$, $p < 0.05$; $R^2 = 0.305$; R^2 Adjusted = 0.208], that is an additional 23.7%, [R^2 change = 0.237; $F_{(3,43)} = 4.895$, $p < 0.05$]. In the model as a whole, only the PFT score ($\beta = 0.479$, $p < 0.001$, $t = 3.515$) was significant.

Regarding the "esthetic" score of Clark's Drawing Ability Test, the first [$F_{(1,48)} = 0.975$, $p > 0.05$] and the second [$F_{(3,46)} = 0.950$, $p > 0.05$] model were not significant. After introducing the accuracy score of the generation, inspection and transformation processes of visual mental imagery, the third model explained 28.9% of variance [$F_{(6,43)} = 2.908$, $p < 0.05$; $R^2 = 0.305$; R^2 Adjusted = 0.208], that is an additional 23%, [R^2 change = 0.230; $F_{(3,43)} = 4.641$, $p < 0.05$]. In the model as a whole, only the PFT score ($\beta = 0.494$, $p < 0.001$, $t = 3.587$) was significant.

Regarding the "creativity" score of Clark's Drawing Ability Test, the analysis showed that the overall model [$F_{(6,43)} = 1.305$, $p > 0.05$] was not significant.

DISCUSSION

This study was aimed at investigating the extent to which dimensions of visual creativity, measured in terms of creative objects production and artistic drawings making, and imagery components, such as vividness of imagery, the strategy to use preferentially images and cognitive processes involved in imagery (generation, inspection and transformation of images) are related. The correlation analysis revealed that all dimensions of pre-inventive forms, inventions and artistic drawings positively correlated with the transformation imagery ability measured by means of the PFT, meaning that the higher the ability to construct pre-inventive forms, original and practical inventions and to make creative artistic drawings, the higher the ability to mentally manipulate spatial forms. According to our results only the high capability to mentally transform an image predicts dimensions of visual creativity products. Among the three cognitive components of visual mental imagery, transformation is the only one that requires a high cognitive load also involving working memory. All participants enrolled in the study showed a working memory capability above the cut-off reported by the two most recent Italian validation studies (Piccardi et al., 2013; Monaco et al., 2013) of the Corsi Test, and we can therefore exclude that this result could be a consequence of other cognitive processes underlying visual mental imagery transformation.

Focusing on the Creative Synthesis Task, the construction of pre-inventive forms, based on mental transformations and syntheses of visual elements, as well as the interpretation of pre-inventive forms were supported by the spatial imagery ability. These results confirm and extend Roskos-Ewoldsen et al. (2008), who found relationships between the originality score of pre-inventive forms and inventions and the PFT score in a sample of 70 people composed of young and old people. In addition, they are also in line with Morrison and Wallace (2001), who found significant correlations between different measures of rated creativity and recognisability of objects and the Surface Development Test (Ekstrom et al., 1976), which measures the ability to mentally assemble three-dimensional shapes in order to match lettered edges with numbered edges on an assembled shape. In other words, the creative object production involves mental transformations that comply with the way spatial forms are assembled, and pre-inventive forms are also explored, probably using analogical reasoning to determine the creative value of objects.

The regression analysis partially confirmed these results, given that the transformation imagery ability only predicted the originality score of inventions. Interestingly, the originality score of inventions positively correlated with the Visualizer-Verbalizer score: the higher the ability to use images, the more original were the inventions in the Creative Synthesis Task. This result was also confirmed by the regression analysis. Therefore, both the spatial imagery ability and the strategy to use images to process information play a key role when interpreting pre-inventive meaningless forms. In other words, while searching for a creative object in the category, participants probably mentally visualized possible objects of the same shape as the pre-inventive form and used spatial imagery to compare shapes.

In addition, the practicality score of inventions was found to be negatively correlated with the vividness of imagery, meaning that the more participants imagine vividly the less practical were their inventions. These results were also confirmed by the regression analysis. This apparently contradicts Palmiero et al. (2011), who found a positive correlation between the vividness score and the practicality score of inventions. However, this could be explained by taking into account the differences in the procedure between the two studies. In fact, Palmiero et al. (2011) used a one-step procedure, priming participants with object category names while performing on the Creative Synthesis Task, whereas in the present study a two-step procedure was used, that is participants were firstly instructed to construct pre-inventive forms and then interpret them within a specific conceptual category. One explanation might be that, if the category is not primed in advance, the ability to imagine pictorially is not useful while thinking of the practical use of objects, it likely being more important to classify objects in specific categories (Laws, 2002), regardless of the practical value. On the contrary, knowing the category in advance, as occurred in Palmiero et al. (2011), probably leads participants with high vividness to assemble objects thinking of the practical value, with positive effects on the relationships between the vividness and practicality dimension of objects.

Moving to Clark's Drawing Ability Test, the graphic ability, the esthetic and creativity scores of drawings correlated only with the transformation imagery ability. The regression analysis confirmed the predictive role of the PFT for the graphic ability and esthetic scores of the artistic drawing. No relationship was found between dimensions of the artistic drawing and processes supporting object imagery, such as vividness of imagery. Although these results partially confirm Morrison and Wallace (2001), who found a correlation between the visual art sub-score of the Creative Behavior Inventory (Hocevar, 1979) and performance on the Surface Development Task, they contradict previous studies showing that artists rely more on object imagery rather than on spatial imagery (e.g., Kozhevnikov et al., 2005; Blajenkova et al., 2006; Pérez-Fabello and Campos, 2007). Moreover, the present result also contradicts Kozhevnikov et al. (2013), who found that the spatial visualization ability measured by means of different tests, including the PFT, loaded on the factor of scientific creativity measures, whereas object imagery ability loaded on the factor of artistic creativity measures, such as Torrance's (1972) picture completion task and the Creative Behavior Inventory subscale of art achievement. However, it should be noted that in the present study novices and not experts were used. Thus, besides the expertise issue, the contrasting results are also consistent with the notion that the relationships between artistic creativity and imagery are also sensitive to the tasks used.

In conclusion, this study underlines that the relationship between visual creativity and visual mental imagery is rather problematic and hard to predict. Visual creativity is definitively supported by specific visual imagery processes, and this would led one to suppose that it is enabled by abilities that fall in the visual domain of knowledge, but the extent to which visual imagery processes play a key role seems to be task- and expertise-dependent. Results might change depending on the tasks used both to measure visual creativity and visual imagery proficiencies, as well as the individual differences in visual creativity and visual imagery processing. In the present study visual creativity was assessed in light of two different product-oriented tasks, and scores obtained were related to specific visual imagery abilities scores. Of course, given the complexity of the visual domain, the methodology used does not encompass the variety of possibilities that the relationships between visual creativity and visual imagery can take on. In this direction, it would be interesting to better consider the spatial domain. According to Gardner (1983, 1993), creativity in a specific domain relies on domain-specific intelligences. Thus, spatial intelligence would offer a unique opportunity to understand domain-specific creativity, as well as general creativity, given that this intelligence is not limited to visual domains (Gardner, 1983). Future studies should explore these relationships using different methodologies, including also variables relying on the creative person and divergent thinking, that are more domain-general aspects of creativity (Silvia et al., 2009). This would also help to clarify the extent to which domain-general abilities (e.g., divergent thinking, spatial abilities) affect visual creativity. Yet, it should be noted that the results discussed above were partially confirmed by the regression analysis. This may be due to several reasons, for example the statistical power of the analyses given the relatively limited number of subjects. Finally, only two independent judges were used to evaluate the Creative Synthesis Task (pre-inventive forms and inventions) and drawings of Clark's Drawing Ability Test. Therefore, although the correlations proved statistically significant, the magnitude of these effects was moderate, and caution should be taken before drawing any definitive conclusion.

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Quantity yields quality when it comes to creativity: a brain and behavioral test of the equal-odds rule

Rex E. Jung[1,2], Christopher J. Wertz[2], Christine A. Meadows[2], Sephira G. Ryman[1], Andrei A. Vakhtin[1] and Ranee A. Flores[2]*

[1] Department of Psychology, University of New Mexico, Albuquerque, NM, USA, [2] Department of Neurosurgery, University of New Mexico, Albuquerque, NM, USA

The creativity research community is in search of a viable cognitive measure providing support for behavioral observations that higher ideational output is often associated with higher creativity (known as the equal-odds rule). One such measure has included divergent thinking: the production of many examples or uses for a common or single object or image. We sought to test the equal-odds rule using a measure of divergent thinking, and applied the consensual assessment technique to determine creative responses as opposed to merely original responses. We also sought to determine structural brain correlates of both ideational fluency and ideational creativity. Two-hundred forty-six subjects were subjected to a broad battery of behavioral measures, including a core measure of divergent thinking (Foresight), and measures of intelligence, creative achievement, and personality (i.e., Openness to Experience). Cortical thickness and subcortical volumes (e.g., thalamus) were measured using automated techniques (FreeSurfer). We found that higher number of responses on the divergent thinking task was significantly associated with higher creativity ($r = 0.73$) as independently assessed by three judges. Moreover, we found that creativity was predicted by cortical thickness in regions including the left frontal pole and left parahippocampal gyrus. These results support the equal-odds rule, and provide neuronal evidence implicating brain regions involved with "thinking about the future" and "extracting future prospects."

Keywords: creativity, creative cognition, divergent thinking, imagination, cortical volume, neuroimaging (anatomic and functional), magnetic resonance imaging

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Cecilia Guariglia,
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Dean Keith Simonton,
University of California, Davis, USA

****Correspondence:***
Rex E. Jung,
Department of Neurosurgery,
University of New Mexico,
Two Woodward Center,
700 Lomas Boulevard NE, Suite 102,
Albuquerque, NM 87101, USA
rex.jung@gmail.com

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Introduction

There is a long history, within the creativity literature, noting an association between idea fluency (the number of ideas generated) and the associated quality, originality, and/or creativity of the ideas that are produced on divergent thinking tasks (Wallach and Kogan, 1965). This notion has since been conceptualized as the "equal-odds rule" by Simonton (1997), which states that "the relationship between the number of hits (i.e., creative successes) and the total number of works produced in a given time period is positive, linear, stochastic, and stable." This principle has great appeal in that it conforms broadly to evolutionary principles (i.e., there is a variation/selection process; Campbell, 1960), it is parsimonious (Simonton, 1984b), and it conforms to excitatory and inhibitory neuronal processes familiar to the neurosciences (Logothetis, 2008). However, this concept of productivity *leading to* originality is rarely exploited within either psychometric or neuroimaging studies of creative cognition, with most studies focused on rather convolved and/or abstruse psychometric aspects of creativity including (but not limited to) fluency, cognitive control, latent inhibition, improvisation, remote associates, divergent thinking, and the like (Arden et al., 2010).

As we have noted previously (Jung et al., 2013), the varieties of cognitive processes critical to creative cognition are likely to be relatively few when deconvolved from more general functions such as attention, memory, language, visual, spatial, and executive processes subserving most aspects of higher cognitive functioning. Variation/selection mechanisms facilitated by ideational fluency/quality presents a viable candidate for such a core cognitive and neuronal mechanism. Substantial support has been generated through historiometric analyses of Big C creative individuals, with the vast majority of individuals studied conforming to the equal-odds rule (Simonton, 1977, 1984a, 1985, 1988, 2010). The relationship is not universally observed, however, with one recent study of eminent composers finding a linear relationship between "hits" and age, which should be independent if conforming to "Darwinian" processes of variation/selection as opposed to accumulated experience (Kozbelt, 2008). Kozbelt and Ostrofsky (2013) further hypothesize an interaction of "domain specific knowledge, which is acquired through intensive training" with such variation/selection processes.

Poincare (1913) hypothesized five stages of his own creative process: preparation, incubation, intimation, illumination, and verification. The stages of preparation and verification are largely obscure to scientific research as they are carried out over periods of time that extend beyond the times allotted to most experimental protocols (e.g., hours). It is our contention that the cognitive processes between preparation and verification is populated by a blind-variation selective-retention (BVSR), characterized by ideational fluency and originality. This process is accessible to scientific examination, and has been recently examined in a large cohort of normal adult subjects, utilizing a scoring methodology that purports to disentangle fluency from creativity (Silvia et al., 2013). We have further noted the possible roles of excitatory and inhibitory neural processes in modulating this selection–retention process (Jung et al., 2013; Jung, 2014).

The interacting role of excitatory and inhibitory neural processes in creative cognition has been described previously (Heilman et al., 2003; Flaherty, 2005; Abraham and Windmann, 2007). Heilman et al. (2003) was the first to note the importance of frontal lobe interactions with "polymodal and supramodal regions of the temporal and parietal lobes" in divergent thinking, noting that "perhaps these connections are important for *inhibiting* the activated networks that store semantically similar information while *exciting* or activating the semantic conceptual networks that have been only weakly activated or not activated at all. Activation of these remote networks might be important in developing the alternative solutions so important in divergent thinking (page 373)." Flaherty (2005), in her seminal theoretical article regarding neural origins of innovation and creative drive, notes "the appropriate balance between frontal and temporal activity is mediated by mutually inhibitory corticocortical interactions." Finally, Abraham and Windmann (2007, p. 45) state "The mutual inhibition between frontal language production and temporal language reception has a parallel in the mutually inhibitory effects of idea generation and of assessing what one has produced." It appears that the field is converging around a bifurcated process involved in producing creative ideas: one involving variation (i.e., cognitive expansion, divergent thinking), and the other involving selection (i.e., constraint of example, usefulness; Abraham and Windmann, 2007; Benedek et al., 2011; Mok, 2014).

We sought to support the equal-odds principle of creative cognition as measured by the fluency–creativity association. Moreover, we sought to link such associations with relevant excitatory (i.e., fluency) and inhibitory (i.e., originality) brain networks as hypothesized previously (Heilman et al., 2003; Flaherty, 2005; Abraham and Windmann, 2007; Jung et al., 2013). We hypothesize that fluency would be associated with creativity as assessed on a measure of divergent thinking, and that fronto-subcortical brain networks would constrain such relationships.

Materials and Methods

Sample

This study was conducted according to the principles expressed in the Declaration of Helsinki. The study was approved by the Institutional Review Board of the University of New Mexico (IRB#11-531). All subjects provided written informed consent before collection of samples and subsequent data analysis. Two-hundred and forty-six subjects (127 males; 119 females) between the ages of 16 and 31 (Mean = 21.8; SD = 3.5) were recruited from the University of New Mexico. Subjects were screened by questionnaire to exclude major neurological injury or disease (e.g., traumatic brain injury) and psychiatric disorder (e.g., major depression). All subjects were administered a 4 hours battery of measures including tests of intelligence, personality, and aptitude, and received $100 compensation for their time.

Behavioral Measures

All subjects were administered a broad battery of tests; here we focus on the relationship between measures of divergent thinking (Foresight) and other measures of intelligence (Wechsler Abbreviated Scale of Intelligence II, WASI-II), creativity (Creative Achievement Questionnaire, CAQ), and personality (Big Five Aspect Scale, BFAS) relevant to our hypotheses (Wechsler, 1999; Acton and Schroeder, 2001; Carson et al., 2005; DeYoung et al., 2007). Foresight (reliability = 0.96) measures subjects' creative thinking ability and comes from the Johnson O'Connor battery of tests of aptitude[1]. Here, subjects are presented with a design and asked to write as many things that the design "makes you think of, looks like, reminds you of, or suggests to you," in 45 s, over six different designs (**Figure 1**). This measure of divergent thinking over a period of seconds (as opposed to several minutes) is analogous

[1] http://www.jocrf.org

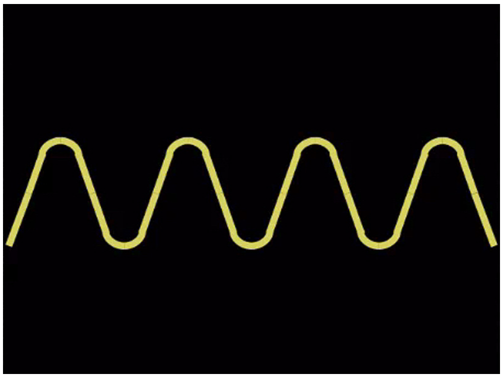

FIGURE 1 | Example of Foresight figure used to elicit responses from subjects. Subjects are asked to describe what the figure "makes you think of, looks like, reminds you of, or suggests to you."

and appropriately comparable to those administered within functional neuroimaging settings.

We used the Consensual Assessment Technique (CAT, Amabile, 1982) to rate subject responses on a scale from 1 to 5 with 1 being least creative and 5 being most creative. Importantly, we used Silvia's method of "snapshot scoring" wherein all six subject responses were given a single holistic score by three judges (Silvia et al., 2009). This method allows for the extraction of "creative" responses as opposed to merely "unique" responses as is customary in scores of divergent thinking ability (Silvia et al., 2013). The WASI is a standardized measure of intelligence consisting of measures of word knowledge (Vocabulary), verbal associations (Similarities), design construction (Block Design), and non-verbal problem solving (Matrix Reasoning). We did not administer the Vocabulary section of this measure and the Full Scale Intelligence Quotient (FSIQ) was derived from the remaining three subtests. The Creative Achievement Questionnaire (CAQ), has demonstrated adequate reliability and validity as a measure of creative productivity across ten domains including visual arts, music, creative writing, dance, drama, architecture, humor, scientific discovery, invention, and culinary arts (Carson et al., 2005). It has been described as "the most promising" measure of creativity, spanning domain, ability, and conforming to BVSR processes (Simonton, 2012). The BFAS was used to assess personality (DeYoung et al., 2007), particularly the subscale of Openness, which has been consistently related to both divergent thinking and creative cognition (McCrae and Ingraham, 1987).

Neuroimaging

Structural imaging was obtained using a 3 Tesla Siemens scanner using a 32 channel head coil. We obtained a T1 five echo sagittal MPRAGE sequence (TE = 16.4 ms; 3.5 ms; 5.36 ms; 7.22 ms; 9.08 ms; TR = 2530 ms; voxel size = 1.0 mm × 1.0 × mm 1.0 mm; slices = 192; acquisition time = 6:03). Methods for cortical reconstruction and volumetric segmentation were performed with the FreeSurfer image analysis suite[2] and are described in detail elsewhere (Fischl et al., 2002, 2004; Han and Fischl, 2007). Briefly, this process includes motion correction and averaging of volumetric T1 weighted images, removal of non-brain tissue, automated Talairach transformation, segmentation of the subcortical white matter and deep gray matter volumetric structures, intensity normalization, tessellation of the gray matter, white matter boundary, automated topology correction, and surface deformation following intensity gradients to optimally place the gray matter/white matter boundary and gray matter/cerebrospinal fluid borders (also known as the pial surface). Thickness measurements were obtained by reconstructing representations of the Gray Matter/White Matter boundary and the pial surface and then calculating the distance between those surfaces at each point across the cortical mantle (Dale et al., 1999). The results of the automatic segmentations were quality controlled and any errors were manually corrected. The cortical thickness parcellation yields 33 measures per hemisphere (i.e., 66 across the surface of the brain) as well as seven subcortical volumes per hemisphere (i.e., fourteen across the brain) including bilateral caudate, putamen, globus pallidus, nucleus accumbens, thalamus, amygdala, and hippocampus (Fischl et al., 2002).

Analysis

We used bivariate correlation to determine relationships between behavioral measures. Linear regression, controlling for age, sex, handedness, and FSIQ, was used to determine the relationship between measures of fluency (Foresight – total number produced) and Creativity (Foresight – CAT) and measures of cortical thickness and subcortical volumes across the entire brain. CAQ scores were log10 transformed before further analysis as this measure was highly skewed. We did not control for multiple comparisons, although with 66 cortical regions and 14 subcortical regions being analyzed, there are 80 contrasts being made per regression. Given that five in 100 Type I errors are considered to be generally acceptable in research designs, we would expect roughly four regions of 80 to be related to our measures by chance. We have adjusted our significance levels to $P < 0.005$ to account for such possible chance relationships.

Results

Subjects were higher than average in terms of intellectual ability (Mean = 111.7; SD = 12.1), as is characteristic of a college cohort, and ranged in IQ from 80 to 153. Creativity scores on the Foresight measure were reliable across the three judges with scores being "good" in terms of internal consistency (Cronbach alpha = 0.76). The relationship between "fluency" and "creativity" scores obtained from the Foresight measure of divergent thinking and other behavioral measures of intelligence, creativity, and personality are presented in **Table 1**. The significant relationship observed between measures of both "fluency" and "creativity" with other proxy measures of creativity, including the CAQ, and Openness, demonstrates convergent validity of this divergent thinking measure. Importantly,

[2] http://surfer.nmr.mgh.harvard.edu/

TABLE 1 | Bivariate relationships between Foresight measures of fluency and creativity.

	Age	Full scale intelligence quotient	Openness	Creative achievement questionnaire
Fluency	0.09	0.01	0.15	0.17
Creativity	0.07	0.05	0.18*	0.26*

*$p < 0.05$.

"fluency" was highly related to "creativity" in this sample ($r = 0.73$, $p < 0.001$), supporting our hypothesis that ideational quantity is associated with ideational creativity. The relationship between "fluency" and "creativity" on the Foresight measure, across all 246 subjects, is presented in **Figure 2**.

Next, we regressed all brain measures of cortical thickness and subcortical volumes against measures of "fluency" and "creativity," controlling for age, sex, handedness, and FSIQ. "Fluency" was negatively correlated with the volume of the right thalamus ($\beta = -0.24$) as well as with the cortical thickness of the right inferior parietal lobe ($\beta = -0.20$; **Figure 3**), and caudal anterior cingulate ($\beta = -0.13$; **Figure 4**). In contrast, "fluency" was positively correlated with the cortical thickness of the left frontal pole ($\beta = 0.25$; $F = 5.02$, $p < 0.001$, $r^2 = 0.15$).

"Creativity" was negatively correlated with the volume of the left entorhinal cortex ($\beta = -0.20$). In contrast, "creativity" was positively correlated with volume of the left frontal pole ($\beta = 0.17$) and left parahippocampal gyrus ($\beta = 0.12$; $F = 3.3$, $p = 0.002$, $r^2 = 0.09$; **Figure 5**).

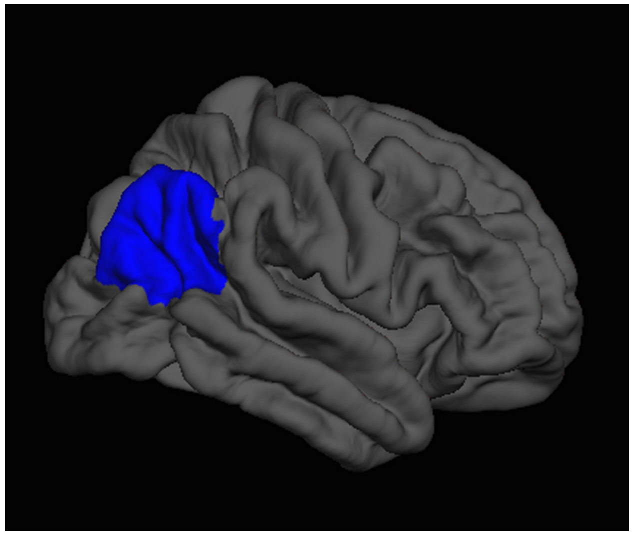

FIGURE 3 | FreeSurfer rendering of the right hemisphere pial surface with the inferior parietal region indicated in blue, showing decreased cortical thickness in this region associated with increased fluency on the Foresight task.

Discussion

We found that quantity was associated with quality on measures of divergent thinking customarily associated with creative

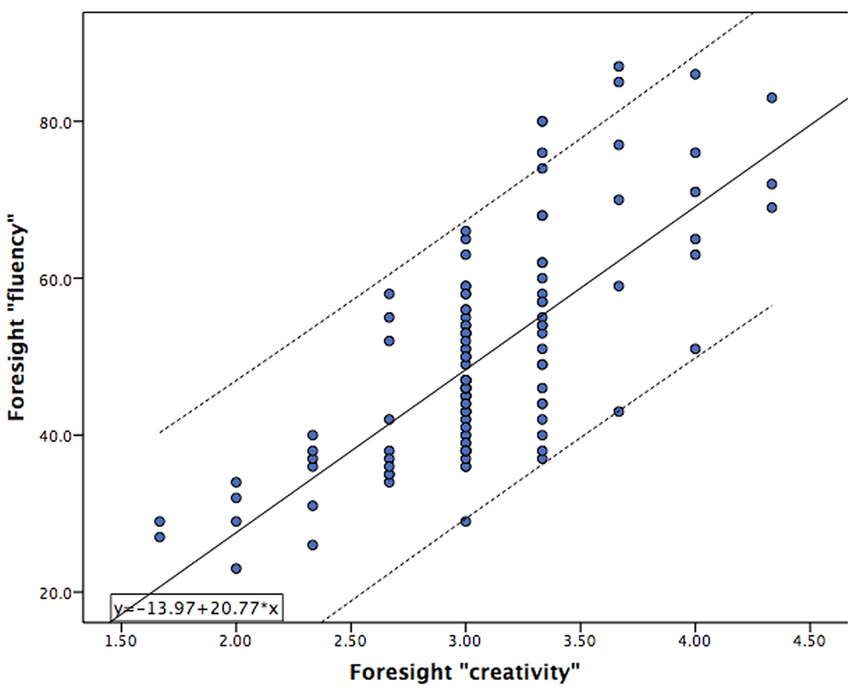

FIGURE 2 | Scatterplot of "fluency" measures from the Foresight task (y-axis) versus the "creativity" measure (x-axis) obtained from 246 subjects. Significant overlap in subject scores results in fewer than 246 individual points being observed on the graph.

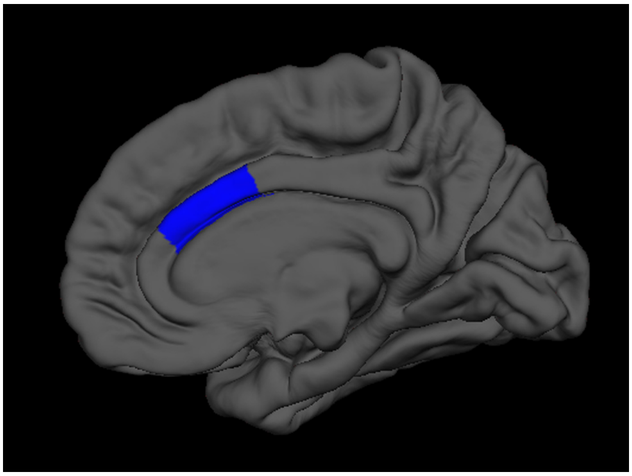

FIGURE 4 | FreeSurfer rendering of the right hemisphere pial surface with the caudal anterior cingulate indicated in blue, showing decreased cortical thickness in this region associated with increased fluency on the Foresight task.

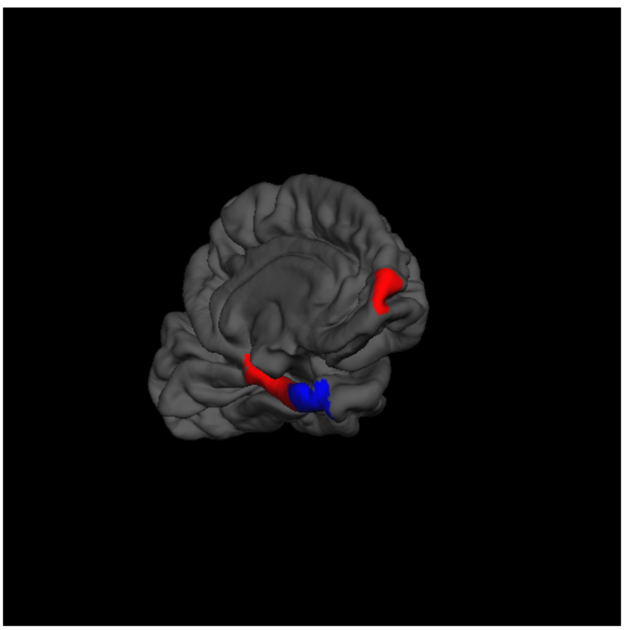

FIGURE 5 | FreeSurfer rendering of the left hemisphere pial surface with the left frontal pole, parahippocampal gyrus, and entorhinal gyrus indicated (inferior frontal view), showing positive (red) and negative (blue) associations between cortical thickness and increased creativity on the Foresight task.

cognition. Subjects who produced more descriptions of abstract visual designs produced more creative descriptions of the designs as measured by judges who were blind to subject demographics. These results provide compelling support for the equal-odds rule which underlie BVSR theories of creative cognition, and which have been demonstrated repeatedly in Big C cohorts throughout history. Importantly, these results were obtained in a college sample ranging in creative achievement (0–144), and intellectual capacity (80–153), thus spanning the normal ranges of both creative and intellectual abilities. We found that fluency and creativity were highly related to one another when measured using a test of divergent thinking and the consensual assessment technique. Finally, we found that fronto-subcortical brain networks were implicated in performance of both fluency and creativity measures, with a common locus across both measures being the frontal pole.

These results partially replicate our previous findings where we found an inverse relationship between fluency measures of Foresight and volume of the right thalamus in a smaller sample of 107 subjects (Jung et al., 2014). This result is now confirmed in a much larger sample ($N = 246$) that includes those original subjects, and extends these findings into cortical thickness measures. Specifically, we found that a thicker left frontal pole was associated with both higher fluency and higher creativity across subjects. Of interest to this finding, a network that includes the frontal pole and the medial temporal lobes has been implicated in thinking about one's own future (Okuda et al., 2003). More specific studies undertaken with patients suffering brain lesions have found that frontal pole damage is associated with (1) preference for immediate versus future reward (Bechara et al., 1996), (2) abnormal strategy application (Shallice and Burgess, 1991), and (3) disrupted decision making (Damasio et al., 1991). Researchers have further parcellated the frontal lobe to indicate time valence when thinking about the near future versus far future, and integration with parahippocampal regions when "extracting future prospects" (Okuda et al., 2003). Thus, our results, implicating both left frontopolar and parahippocampal thickening appear to comport well with this particular network implicated in "thinking about the future." In a large meta-analysis of all functional neuroimaging studies of "episodic future thinking" (EFT) researchers noted the specificity of the medial prefrontal cortex in EFT, indicating its likely role in (1) adaptive decision making processes, (2) the creation of abstract knowledge or schemas, and (3) the integration of novel experiences into pre-existing knowledge networks (Stawarczyk and D'Argembeau, 2015). Our results, demonstrating cortical thickening in the medial frontal lobe, is interpreted to reflect strengthening of neural networks underlying such cognitive processes.

We have previously interpreted thalamic volume decrements and right inferior parietal thinning within a "disinhibitory framework of brain regions associated with increased behavioral output," and the current findings are consistent with our previous findings implicating thalamic and inferior parietal regions with increased creative capacity (Jung et al., 2013). Other researchers have found lower thalamic dopamine D2 receptor densities to be inversely related to creative cognition in healthy individuals (de Manzano et al., 2010). Importantly, these researchers used a measure of divergent thinking, and the results were related to fluency of uses (as opposed to originality). These authors noted that the thalamus contains the highest level of dopamine D2 receptors in the brain, and that decreased D2 binding has been linked with decreased "filtering and autoregulation of information flow," as well as decreased inhibition of prefrontal pyramidal neurons (Seamans and Yang, 2004; Trantham-Davidson et al., 2004). They refer to this decreased inhibition as producing a "creative bias" which benefits tasks requiring continuous generation and increases fluency and flexibility of associations. Our results, reflecting both lower thalamic and anterior cingulate volume (Bush et al., 2000) would be broadly consistent with this hypothesis, and provides further neurobiological support to better explain the equal-odds phenomenon underlying variation/selection mechanisms associated with creativity.

There are several limitations to our approach. First, we utilized a relatively young, healthy sample, and whether our results would generalization to older populations and/or clinical samples is unknown. Second, we are making inferences regarding brain function in spite of using measures of brain structure. These inferences may or may not be correct, although some studies suggest correspondence between structure and function (Segall et al., 2012). Our measure of divergent thinking is not one commonly used in the creativity literature, although it was found to have high reliability, as well as correspondence to other measures commonly used as proxy measures (e.g., CAQ, Openness) for creativity. Finally, we have not conducted full Bonferroni correction for all possible multiple corrections (which would increase Type II error), but have adopted an intermediate approach of adjusting our significance level to $p < 0.005$ to account for the 80 contrasts being made per regression (leaving possible Type I error). This balance between Type I and Type II error was seen as appropriate for this exploratory study. Future studies using broader samples comprised of both older and younger subjects, using other well-validated measures of fluency-originality, and exploiting multimodal neuroimaging measures [e.g., structural Magnetic Resonance Imaging (MRI), functional MRI, diffusion tensor imaging] would help significantly to support these findings and to implicate particular brain networks associated with BVSR.

This study supports the notion that BVSR is a central component of creative cognition, working via an equal-odds rule, wherein higher output of ideas is associated with higher likelihood of creative ideas. This paradigm is amenable to both psychological and neuroscientific manipulation to determine the interaction of fluency–creativity relationships with other cognitive components hypothesized to be relevant to creative cognition (e.g., cognitive control, flexibility, etc.). Our results demonstrate key nodes within the brain, including the right thalamus, right caudal anterior cingulate, left medial temporal lobe, left medial frontal cortex, and right temporo-parietal junction that constrain both fluency and originality in a manner that would suggest mutually inhibitory network interactions constraining both variation and selection processes. Specific nodes (e.g., medial fronto-temporal cortices) within this network have been implicated in highly adaptive human cognitive processes including EFT and extracting future prospects, while other regions (e.g., thalamus, anterior cingulate) have been implicated in modulating the fluency and flexibility of ongoing cognition. Future research will be critical in determining the specific roles that these structures play in the interactions between broad cognitive networks that have been implicated in creative cognition (e.g., default mode network).

In summary, early theories regarding creative cognition have broadly implicated fronto-temporal and fronto-subcortical networks that operate in "mutually inhibitory" balance that, when disease (Miller et al., 1998) or lesion (Shamay-Tsoory et al., 2011; Abraham et al., 2012) disrupt this balance, can result in greater creative drive and/or novelty generation (Flaherty, 2005). More current theories implicate an interaction between broad networks of the brain including the default, executive control, and salience, which interact in service of variation and selection tasks organized around adaptive behavior (Jung et al., 2013; Beaty, 2015; Liu et al., 2015). Research is converging around two main aspects of creative cognition involving variation (i.e., divergence, fluency, elaboration) on the one hand and selection (i.e., convergence, usefulness, constraint) broadly conforming to notions of BVSR (Campbell, 1960). This "variation-selection" model is evolutionarily sound, conforms to humans and other living species, and produces adaptive behaviors within "design space" (Dennett, 1996).

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Zooming into creativity: individual differences in attentional global-local biases are linked to creative thinking

Sharon Zmigrod[1,2], Leor Zmigrod[3] and Bernhard Hommel[1,2]*

[1] Cognitive Psychology Unit, Institute for Psychological Research, Leiden University, Leiden, Netherlands, [2] Leiden Institute for Brain and Cognition, Leiden University, Leiden, Netherlands, [3] Department of Psychology, University of Cambridge, Cambridge, UK

While recent studies have investigated how processes underlying human creativity are affected by particular visual-attentional states, we tested the impact of more stable attention-related preferences. These were assessed by means of Navon's global-local task, in which participants respond to the global or local features of large letters constructed from smaller letters. Three standard measures were derived from this task: the sizes of the *global precedence effect*, the *global interference effect* (i.e., the impact of incongruent letters at the global level on local processing), and the *local interference effect* (i.e., the impact of incongruent letters at the local level on global processing). These measures were correlated with performance in a convergent-thinking creativity task (the Remote Associates Task), a divergent-thinking creativity task (the Alternate Uses Task), and a measure of fluid intelligence (Raven's matrices). Flexibility in divergent thinking was predicted by the local interference effect while convergent thinking was predicted by intelligence only. We conclude that a stronger attentional bias to visual information about the "bigger picture" promotes cognitive flexibility in searching for multiple solutions.

Keywords: creativity, attention, individual differences, thinking and reasoning, intelligence

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****Correspondence:***
Bernhard Hommel
hommel@fsw.leidenuniv.nl

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INTRODUCTION

Like an adjustable camera lens or a microscope, attention constantly zooms in and out between large objects or events and the smaller elements that comprise them. This is a reflection of the hierarchical structure of events in the world, whereby global objects are recursively constructed from local features. Although people are typically faster at detecting information at the global level than the local level (holistic vs. analytical view; Navon, 1977; Kimchi, 1992), there are also striking individual differences and situational factors that shape the perception of hierarchical stimuli. Studies have illustrated that the manner in which people allocate attention to these local or global levels is influenced by temporary states such as mood (Gasper and Clore, 2002; Huntsinger et al., 2010) or alertness (Van Vleet et al., 2011; Weinbach and Henik, 2014), as well as by factors such as age (Thomas et al., 2007), culture (Colzato et al., 2010a; Lao et al., 2013), religion (Colzato et al., 2008), and sexual orientation (Colzato et al., 2010b). Furthermore, clinical investigations have demonstrated that abnormal global processing is exhibited in clinical populations such as in schizophrenia (Carter et al., 1996; Granholm et al., 2002), severe depression (de Fockert and Cooper, 2014), obsessive compulsive disorder (Yovel et al., 2005) and cocaine users (Colzato et al., 2009). These individual differences in biases toward global or local processing appear to be stable over time (Dale and Arnell, 2013), and related to the individual's sensitivity to the perceptual organization of gestalt laws (Poirel et al., 2008) as well as the way in which they systemize rules (Billington et al., 2008).

Of particular interest for the present study, global vs. local processing styles have been assumed to affect mental flexibility and creativity. For instance, Rowe et al. (2007) reported evidence suggesting that inducing positive mood does not only lead to the consideration of more spatially distributed visual information but also to better performance in a convergent-thinking task [the Remote Associates Task (RAT); Mednick, 1962]. These observations are consistent with the theoretical considerations of Derryberry and Tucker (1994), who postulate a direct connection between visual and conceptual attention, in the sense that the foci and integrational breadth of the two are related. Unfortunately, however, the observation that positive mood broadens the attentional scope could not be replicated in several studies (Huntsinger, 2012; Bruyneel et al., 2013). Another line of research seemed to have provided evidence suggesting that inducing global or local processing styles by means of perceptual tasks (e.g., having participants process the global or local aspect of visual stimuli) leads to a widening of the conceptual scope and the generation of more, and more creative ideas (Förster, 2012). Unfortunately, however, the article reporting some of the most relevant studies on this issue had to be retracted (Förster and Denzler, 2012), which again raises the question of how reliable the reported data are. Moreover, some of the supportive findings are relatively indirect. For instance, even if affective states can be taken to impact both attention to external stimuli and internal memory, they may do so in very different ways.

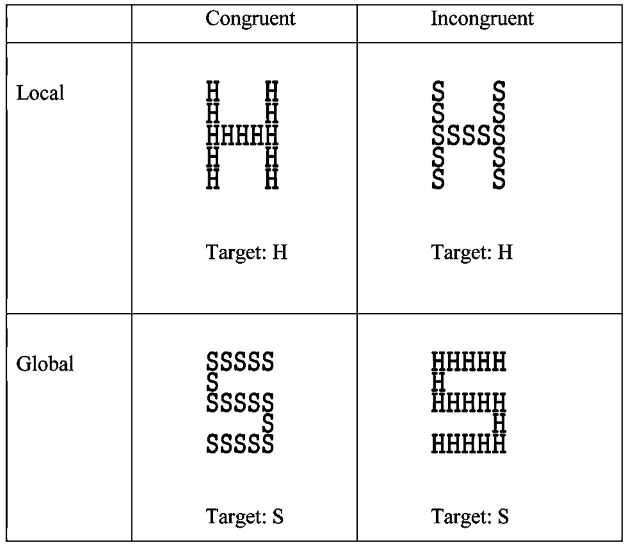

FIGURE 1 | Stimuli in the global–local task. The participants were instructed to attend in the global block to the global level and in the local block to the local level and identify the target ("H" or "S"). The stimuli could be congruent (same letter in both levels) or incongruent (different letters for each level).

Aim of Study

Recent studies on the possible connection between visual and conceptual attention were focusing on attentional states, with the idea that inducing a particular visual-attentional state might affect conceptual processing. In contrast, the present study was focusing on individual differences—i.e., traits rather than states. As discussed already, there is ample evidence that people differ with respect to the way they attend to and process the global and local aspects of visual information. This suggests that attentional control is affected by systematic and relatively long-lasting biases toward the global or the local aspect of visual information (Hommel and Colzato, 2010). If so, a connection between the control of visual attention and the control of conceptual attention (Derryberry and Tucker, 1994) should allow one to predict the latter from the former. In other words, the individual characteristics of processing the global and local aspects of visual stimuli should statistically predict the individual characteristics of conceptual processes.

To assess the characteristics of visual attention, we employed the widely used global-local task (Navon, 1977). In this task, compound stimuli of large letters (global level) constructed from smaller letters (local level) are presented to participants, and come in two flavors; congruent, where the large and small letters are identical, and incongruent, where these differ (see **Figure 1**). Participants are instructed to focus their attention either to the large letter (global task) or the small letters (local task), and identify the correct letter (e.g., Granholm et al., 1999). This task allows for the extraction of three measures (see Navon, 1977) that we considered particularly informative regarding the individual processing style. First, the Navon task is known to produce the *global precedence effect*, i.e., people are more efficient in reacting to the global than to the local aspect of the stimuli (Navon, 1977). More interestingly for our purposes, people differ with respect to the size of this effect (e.g., Dale and Arnell, 2013), which reflects the degree to which their attentional control is biased toward the global aspect of visual stimuli. Second, performance on local aspects of stimuli is often hampered by incongruent information at the global level (e.g., if a local set of S's is forming a global H; see **Figure 1**). We will refer to this observation as the *global interference effect* and take its size to represent the degree to which the nominally irrelevant global task set (i.e., the goal to process global information) affects local processing. Third, performance on global aspects of stimuli is sometimes hampered by incongruent information at the local level (e.g., if a global S is formed by local H's). Given the dominance of global processing, this *local interference effect* is commonly considerably smaller than its global counterpart, suggesting that interference from incongruent stimuli is asymmetric and level-dependent (Navon, 1977). We take the size of this effect to represent the degree to which the irrelevant local task set affects global processing.

To assess the characteristics of conceptual attention we used creativity tasks (Ashby et al., 1999). While some creativity tests try to integrate various aspects of creativity, experimental studies have shown that at least some of these components are rather different and independent both theoretically and empirically (Dietrich, 2004; Hommel, 2012). In the present study, we consider the two main components, convergent and divergent thinking (Guilford, 1967). Convergent thinking consists in searching for a single solution to a well-defined problem in an analytic fashion, while divergent thinking consists in searching for many possible solutions to a vaguely defined problem (Guilford, 1967). In this study, we assessed convergent thinking by means of the RAT developed by Mednick (1962). Each item of this task is comprised of three words (such as: *boot, summer, ground*), all of which can be related to a fourth through the formation of compound words or the identification of a semantic associate (*camp*). Divergent thinking was assessed by means of the Alternate Uses Task (AUT: Guilford, 1967), in which participants are to generate as many possible uses for an everyday object such as *brick* or *newspaper*. In previous studies, performance in these two tasks was uncorrelated and differentially correlated to other aspects of cognitive performance (Akbari Chermahini and Hommel, 2010), supporting the idea that they assess orthogonal components of creativity.

Given that authors claiming a connection between visual and conceptual attention (Derryberry and Tucker, 1994; Förster, 2012) did not explicitly differentiate between convergent and divergent thinking, it is difficult to derive clear-cut predictions, but a number of expectations present themselves. Generally speaking, one would expect that an analytical thinking style goes with an attentional bias toward the local level of visual stimuli, while a more divergent thinking style should go with a bias toward the global level. If so, one would expect that RAT performance would be better for individuals with a rather small global precedence effect, which should come with little global interference but strong local interference. One would also expect that AUT performance would be better for individuals with a pronounced global precedence effect, strong global but weak local interference[1]. To test this, we had participants perform a Navon-style global-local task, a RAT, and an AUT, together with a Raven test to assess fluid intelligence—which has been shown to correlate with RAT performance (Akbari Chermahini and Hommel, 2010). The global-local task served to derive individual scores for the global-precedence effect, as well as global and local interference, which were then used to statistically predict performance in the RAT and the AUT, and vice versa.

[1]Note that it is difficult to derive precise predictions regarding the relationship between global and local interference. One problem is that global interference is commonly more pronounced than local interference (Navon, 1977), which implies that individual local-interference scores rely on lesser variability than global-interference scores–which is a problem for correlational analyses. Indeed, we will see that the two measures did not correlate significantly in our study. Another, but related problem is that the relative size of the two scores for a given individual is likely to be mediated by his or her degree of global precedence. Individuals with considerable global precedence are likely to have large global-interference scores but small local-interference scores, and the opposite is true for individuals with a small global-precedence effect. This means that estimates of global and local interference are likely to differ in reliability for each given individual. As a consequence, we did not try to present separate predictions for global and local interference and their associations with other measures, but considered the possibility that (depending on the role of global precedence) some associations may express themselves through correlations with global interference scores while other associations may have a stronger impact on local interference scores.

MATERIALS AND METHODS

Participants

In total, 124 native Dutch Leiden University students (60 men; mean age = 20 years; *SD* = 2.3 age range: 17–28 years) took part in the study for course credits or a financial reward. Three participants were excluded from the analysis, one due to misunderstanding of the divergent task, and two as a result of procedural error. All participants were right-handed with normal or corrected-to-normal vision. Exclusion criteria included: history of psychiatric disorders, drug abuse, and active medication. The study conformed to the ethical standards of the declaration of Helsinki and was approved by the Ethical Committee of Leiden University. Participants gave their written informed consent to participate.

Stimuli and Materials

Global-local Task

The global-local task was modeled after Navon (1977; see **Figure 1**). In this task, participants are instructed to identify targets ("H" or "S") either at the global level (the large letter) or the local level (the small letters that comprise the large letter) during separate experimental blocks (global block and local block). The letters can be either congruent (identical letters in the local and global levels) or incongruent (different letters in the local and global levels). The global letters were created from 5 × 5 matrices of the local letters. The height of the global letter was seven times as tall as the local letters, and both global and local letters had a ratio of 1:1.5 width to height. All stimuli were black on a light screen. Each trial began with a 500-ms tone signaling the beginning of the task followed by the stimulus that appeared in the center of the screen for 3000 ms. Participants responded by pressing on the keyboard buttons "H" or "S" with the index finger as quickly and accurately as possible. The experimental blocks were counterbalanced between subjects and prior to each experimental block; the participants read the instructions and completed four training trials. Each experimental block consisted of 72 trials.

Remote Association Task (RAT; Convergent Thinking)

A computerized Dutch 30-item version of the RAT was adapted from Akbari Chermahini et al. (2012; Cronbach's alpha = 0.85). In this task, each item includes three unrelated words, and participants are asked to write a common associate as an answer (e.g., *hair, stretch, time* → *long*) within 30 s. After giving the solution, participants were requested to identify which problem-solving strategies they used (analytical vs. insight; cf., Bowden et al., 2005).

Alternate Uses Task (AUT; Divergent Thinking)

A computerized Dutch version of Guilford's (1967) Alternative Uses Task was used. This task requires participants to list within as many possible uses for three common household items (brick, shoe, and newspaper) as possible within a span of 2 min each. Performance is scored along four measures: fluency (the total number of responses), flexibility (the number of different categories used), elaboration (the amount of detail in the responses), and originality (the amount of unusual responses). The flexibility score can be considered the theoretically most transparent and empirically most reliable of these measures (Akbari Chermahini and Hommel, 2010).

Raven's Advanced Progressive Matrices Task

The Raven's Advanced Progressive Matrices task (APM: Raven, 1965) was used to assess and estimate fluid intelligence and Spearman's g. The task was composed of non-verbal visual patterns with one element missing. Participants choose one out of six possible answers. In this task, we used 30 items which progressively increased in difficulty over the 20 min during which the APM was administered.

Procedure

The experiment was controlled by a Targa Pentium 3, attached to a Targa TM 1769-A 17 inch CRT monitor. Participants were tested in a small cubical room, and they were instructed to sit upright on a wooden chair and look at a fixation point. The experimenter ensured that participants faced the monitor at a distance of about 60 cm with the same visual angle. The participants read and signed the informed consent form before the beginning of the experiment. All the participants completed the four tasks. Half of the participants completed the creativity tasks (RAT and AUT) first and half of the participants completed the global-local task first. The creativity tasks were also counterbalanced between participants. The Raven task was performed last.

RESULTS AND DISCUSSION

Statistical Analysis

To investigate the relationship between global–local attentional biases and creative thinking styles, performance on each task was calculated per participant. For the global-local task, mean response time of correct responses and accuracy were calculated separately for each block (global vs. local) and condition (congruent vs. incongruent). An ANOVA was performed to confirm that basic findings could be replicated (see below). For the correlation and regression analyses, various scores were calculated. Global precedence effects were computed by subtracting the mean reaction time (RT) for trials in the global task from the mean RT for trials in the local task. Global and local interference effects were computed by subtracting the RTs in congruent trials from those in the incongruent trials, separately for the local and the global task. As a measure of general response speed, we computed the average over both tasks. For the RAT and the Raven task, we calculated the number of correct items. For the AUT, two independent judges scored fluency, flexibility, and elaboration. Originality was calculated through a set of functions where each response is compared to the total amount of responses for that item from all participants. Pearson correlation coefficients were computed for all combinations of scores. **Table 1** provides an overview, for a detailed presentation of the findings see below.

Global Precedence and Global/Local Interference Effects

As a manipulation check, we tested whether the well-established effects of the global–local task could be replicated. Mean RTs and accuracy were analyzed by repeated measures ANOVAs as a function of the task (attending to global vs. local level) and stimulus congruency (congruent vs. incongruent) as within-subjects factors. Main effects of task, in RT, $F(1,120) = 62.35$, $p < 0.0001$, $\eta_p^2 = 0.342$, and accuracy $F(1,120) = 5.99$, $p < 0.05$, $\eta_p^2 = 0.048$, indicating faster and more accurate responses to global targets than to local targets (see **Figure 2**), replicated the global precedence effect (Navon, 1977; Kimchi, 1992). In addition, main effects of stimulus congruency in RTs $F(1,120) = 363.83$, $p < 0.0001$, $\eta_p^2 = 0.752$, and accuracy $F(1,120) = 93.93$, $p < 0.0001$, $\eta_p^2 = 0.439$, were observed. These effects replicated the global and local interference effects (see **Figure 2**). Furthermore, there was a significant interaction between task and stimulus congruency in RTs, $F(1,120) = 16.12$, $p < 0.0001$, $\eta_p^2 = 0.118$, indicating that the global interference effect (global interference in local task, GI = 52.95) was larger than the local interference effect (local interference in global task, LI = 35.19; see **Figure 2**). The correlations between the measures from the global–local task also provide a coherent picture (see **Table 1**). As one would expect, interference from the global level correlates positively with the size of the global precedence effect, which again is negatively correlated with interference from the local level.

Predicting Convergent Thinking (RAT)

Performance on the RAT was significantly correlated with three scores: First, the positive correlation with the Raven score confirms earlier observations that fluid intelligence predicts RAT performance (Akbari Chermahini and Hommel, 2010). Second, the convergent-thinking score was positively correlated with global interference, indicating that more interference from the global level on local performance went along with better convergent thinking performance. Note that this is opposite to what we expected, as we hypothesized that RAT performance would be better for individuals with a small global precedence effect, accompanied by weak global but strong local interference. The third significant correlation gives a hint toward a possible explanation. We can see that RAT performance is negatively correlated with the general RT level. Follow-up analyses showed that the global-precedence effect was negatively correlated with the RT level in the global task, $r = -0.34$, $p < 0.001$, but positively correlated with the RT level in the local task, $r = 0.41$, $p < 0.001$. To test whether the actually expected pattern would be more apparent if only trials with analytical solutions are considered (Bowden et al., 2005), we reran the analyses after eliminating all data from trials with intuitive solutions. However, this merely rendered all correlations insignificant, $ps > 0.23$, presumably due to the data loss and the resulting increase in intra-individual variability.

TABLE 1 | Correlations between global–local measurements in directed attention condition and creative style.

	Global precedence	Global interference	Local interference	Raven's matrices	RAT	Fluency	Elaboration	Flexibility	Originality
RT overall	0.044	−0.153	0.127	−0.091	−0.221*	−0.029	−0.035	−0.152	−0.015
Global precedence		0.338**	−0.279**	−0.013	0.089	0.056	0.093	0.112	0.137
Global interference			0 .043	0.093	0.242**	0.066	0.075	0.131	0.114
Local interference				0.101	0.037	−0.070	−0.136	−0.198*	−0.090
Raven's matrices					0.237**	0.010	0.071	−0.020	0.004
RAT						0.117	−0.091	0.096	0.054
AUT fluency							0.156	0.801**	0.829**
AUT elaboration								0.391**	0.399**
AUT flexibility									0.795**

*N = 121, *p < 0.05, **p < 0.01.*

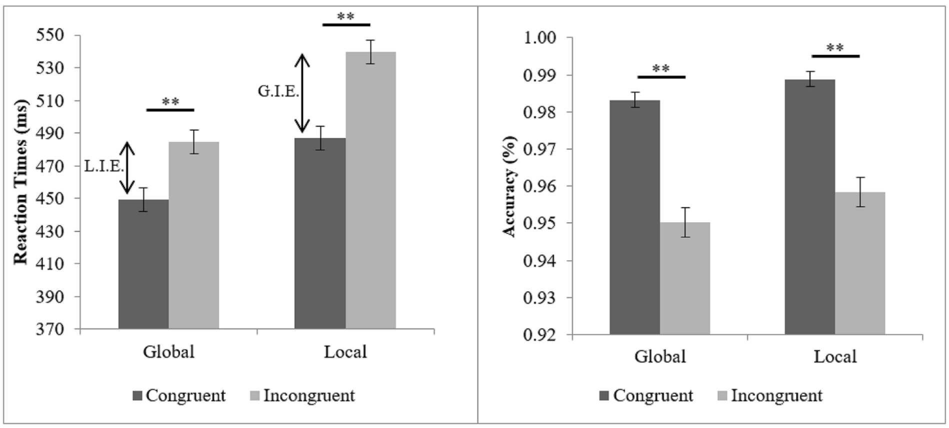

FIGURE 2 | Mean reaction times (RTs; with standard error bars) as a function of task (global vs. local) and stimulus congruency (congruent vs. incongruent). LIE, Local interference effect; GIE, Global interference effect. $^{**}p < 0.001$.

Taken together, this pattern suggests the following possibility: The observation that faster participants produce stronger precedence effects implies that overcoming the dominant global bias takes time. If so, the impact of the global bias on performance in the local task decreases over time, so that faster reactions to local stimulus aspects suffer more from incongruent global information than slower reactions do. A similar temporal dynamic has been observed for the Simon effect, which is also more pronounced for fast than for slower reactions (Hommel, 1993). If this scenario applies, it follows that the correlation between convergent-thinking performance and global interference does not reflect any commonalities between visual and conceptual attention. Rather, it seems to be due to that people who are fast in the global-local task (and therefore happen to suffer more from global interference) are also good convergent thinkers. This would fit with the positive correlation of convergent thinking and fluid intelligence, which also has been shown to correlate positively with general response speed (Jensen, 1998).

Predicting Divergent Thinking (AUT)

Table 1 shows that the four scores derived from the AUT are strongly intercorrelated but that the only score that correlates with other measures is flexibility. This is consistent with previous observations, which also found this score to be the most systematic and replicable (Akbari Chermahini and Hommel, 2010). We see that flexibility is negatively correlated with local interference, indicating that better performance in the AUT comes with a weaker impact from irrelevant local information (see **Figure 3**). This observation fits with our expectations: the brainstorming-like divergent-thinking task should benefit from a more global bias rather than from attention to detail. While this did not lead to a significant positive correlation between flexibility and the global-precedence effect (which, however, goes in the right direction), it did yield the expected reduced impact from the local level.

As suggested by one of the reviewers, in order to ensure that our counterbalancing in the global–local task as well as RT did not contribute to the individual differences predicting the RAT and the Flexibility, a two-stage liner regression was performed on both RAT and Flexibility as the dependent variables and task order and RT in the first stage and global–local effects as the independent variable in the second stage. The correlational findings were not affected by task order and RT (see **Table 2**).

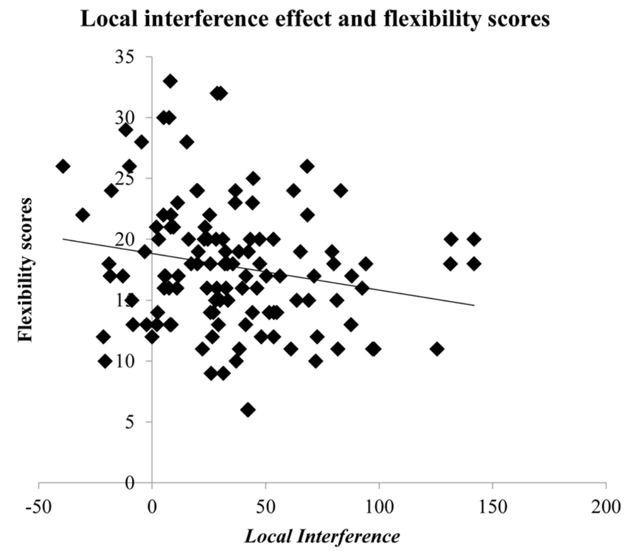

FIGURE 3 | scattered plot depicting the negative correlation between the local interference effect and the flexibility scores from the divergent thinking task (AUT).

Gender Differences

We carried out additional explorative analyses to identify possible gender effects. However, RTs and accuracy in the global–local task did not differ between males and females, as revealed by one-way ANOVAs with gender as a between-subjects factor, all *p*s > 0.05, replicating previous findings (Kimchi et al., 2009). The same was true for overall RAT scores, the four AUT scores, and Raven's Matrices scores, all *p*s > 0.05.

CONCLUSION

The aim of the study was to explore possible links between core functions of attention and creativity. Using the global–local paradigm (Navon, 1977), we observed that attention allocation biases to particular levels of hierarchical stimuli can predict one's performance characteristics in some aspects of creative thinking. Importantly, we found that convergent and divergent thinking, the two components of human creativity that we considered, were related to characteristics of performance in the global–local task in very different ways. This suggests that all creativity tasks should not be considered the same, and it also raises doubts in attempts to integrate different factors into one measure—as various creativity tests have tried.

More specifically, we found that the local interference effect was a reasonably good predictor of divergent thinking performance, at least with respect to the most transparent score flexibility. This suggests that individuals whose attention was not significantly diverted by the irrelevant local elements (the smaller letters) of the hierarchical stimulus while attending to the global aspect (the larger letter) were more likely to find varied and wide-ranging solutions to a given problem. That is, a stronger bias to the bigger picture with respect to visual events lends itself to greater cognitive flexibility in searching for multiple solutions in the divergent thinking task. It is interesting to note that studies of populations exhibiting diminished cognitive flexibility have found the reverse pattern: here, the local interference effect was *positively* correlated with obsessive-compulsive cognitive style (Yovel et al., 2005) and the effect was significantly more pronounced in individuals with autism and Asperger's syndrome in comparison to controls (Rinehart et al., 2000; Muth et al., 2014). Furthermore, individuals displaying high systemizing tendencies have also shown greater susceptibility to local interference (Billington et al., 2008). Taking together these findings and the present results suggest that individual variability in the local interference effect may be used as an index for cognitive flexibility. High values of the local interference effect might be taken to denote rigid, narrow, obsessive-compulsive tendencies, whereas low values reflect enhanced flexibility and a capacity for divergent thinking. More research into the possibility of the local interference measure as an index for cognitive flexibility is needed, however.

In contrast to the divergent-thinking task, no systematic connection between visual and conceptual attention emerged from the convergent-thinking task. While there was a correlation between convergent-thinking performance and the global

TABLE 2 | Results of linear regression analyses for RAT scores and Flexibility scores with task order and RT as first step of the linear regression and global and local interferences as the second step of the linear regression.

	RAT scores			Flexibility scores		
	B (SE B)	**β**	***t***	***B (SE B)***	**β**	***t***
Step 1						
Task order	0.635 (0.60)	0.095	1.058	−0.776 (0.988)	−0.072	−785
RT	−0.009 (0.004)	−2.11	−2.342*	−0.011 (0.006)	−0.160	−1.753
Step 2						
Task order	0.632 (0.590)	0.095	1.07	−0.766 (0.972)	−0.071	−0.788
RT	−0.008 (0.004)	−0.185	−2.05*	−0.008 (0.006)	−0.117	−1.278
Global interference	0.020 (0.009)	0.210	2.358*	0.019 (0.014)	0.122	1.352
Local interference	0.005 (0.008)	0.053	0.594	−0.029 (0.014)	−0.189	−2.097*

N = 121, $^*p < 0.05$ $R^2 = 0.058$ for step 1; $R^2 = 0.105$ for step 2 ($ps < 0.05$) $R^2 = 0.028$ for step 1; $R^2 = 0.075$ for step 2 ($ps < 0.05$)

interference effect, the sign of the effect and the overall pattern including measures of general response speed strongly suggest that this correlation does not reflect mechanistic commonalities between processes underlying performance in the global–local task and the RAT. There was also no indication of a possible connection to the global-precedence effect and local interference. Taken altogether, this suggests that the RAT may not be suitable for identifying relationships between visual and conceptual attention.

Although much remains to be learned about possible connections between visual and conceptual attention, there are hints toward a shared neurobiological basis for global/local processing and divergent/convergent thinking. With respect to attentional processing, neuropsychological studies demonstrate that right hemisphere damage often leads to impairments in global processing whereas left hemisphere lesions can disrupt local processing (Delis et al., 1986; Robertson et al., 1988; Lamb et al., 1990). There is also evidence from imaging studies supporting this hemispheric asymmetry (Fink et al., 1996; Volberg and Hübner, 2004; Gable et al., 2013). Interestingly, comparable patterns are also emerging in the study of creative thinking styles. In spite of the complexities associated with neuroimaging research into creativity (Arden et al., 2010), neurostimulation experiments are beginning to reveal a similar hemispheric lateralization in creativity. It has been illustrated that convergent thinking can be enhanced by stimulating the left prefrontal cortex with anodal transcranial direct current stimulation (Cerruti and Schlaug, 2009; Metuki et al., 2012; Zmigrod et al., in press), and complementarily, divergent thinking performance can be improved by anodal tDCS over right frontal regions (Mayseless and Shamay-Tsoory, 2015). These parallels could suggest that zooming into the brain could provide a fruitful basis for future research into the links between attentional processing biases and creative thinking styles.

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Insightful Imagery is Related to Working Memory Updating

Edward Nęcka[1,2], Piotr Żak[1] and Aleksandra Gruszka[1]*

[1] *Institute of Psychology, Jagiellonian University in Krakow, Krakow, Poland,* [2] *The University of Social Sciences and Humanities, Warsaw, Poland*

Available body of evidence concerning the relationship between insight problem solving and working memory (WM) is ambiguous. Several authors propose that restructuring of the problem representation requires controlled search processes, which needs planning and involvement of WM. Other researchers suggest that the restructuring is achieved through the automatic spread of activation in long-term memory, assigning a limited role to WM capacity. In the present study we examined the correlations between insight problem solving performance and measures of WM updating function (n-back task), including general intelligence (as measured by Raven's Advanced Progressive Matrices). The results revealed that updating function shared up to 30% of variance with the insight problem task performance, even when the influence of general mental ability was controlled for. These results suggest that insight problem solving is constrained by individual ability to update the content of WM.

Keywords: creativity, insight, imagery, working memory, n-back

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David G. Pearson,
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****Correspondence:***
Edward Nęcka
edward.necka@uj.edu.pl

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INTRODUCTION

In this paper we suggest that insightful problem solving depends on the efficiency of working memory (WM) functioning. In order to justify such a hypothesis, we first review the theoretical models of insight as an essential phenomenon in creativity and problem solving. Then, we summarize the existing empirical evidence, which is ambiguous in reference to the role of WM in insightful problem solving. We discuss possible sources of these ambiguities. Finally, we report the results of an empirical study, which suggests that the ability to solve insight problems may share as much as 30% of common variance with the updating function of WM, assessed with the n-back task.

Creativity is usually investigated within the framework of creative cognition (Finke et al., 1992; Smith et al., 1995). This approach assumes that creative outcomes occur through the application of "regular" cognitive processes, organized in a specific way so that their final output meets the criteria of novelty or originality. Numerous cognitive processes have been investigated within the creative cognition approach, including imagery (Finke et al., 1992; Ward, 1994; Finke, 1996; Palmiero et al., 2011), attention (Nęcka, 1999), executive control (Beaty et al., 2014; Benedek et al., 2014), or associative memory (Benedek and Neubauer, 2013). In the present study we focus on the relationship of creativity with a specific module of human memory called WM (Baddeley and Hitch, 1974; Baddeley, 2002). We also focus on a specific aspect of creativity, namely insight (Scheerer, 1963).

Historically, the psychology of creativity has been developing within two traditions. The first one descends from the Gestalt theory of productive thinking (Wertheimer, 1945), according to which creativity necessitates restructuring of the original mental representation of the problem

(Ohlsson, 1984a,b). In empirical studies, the proponents of this tradition typically use the so-called insight tasks, which have one well-defined solution but involve an element of a "mental trap" that must be eliminated or overcome (Weisberg, 1995). For instance, in order to solve the task: "Create four equilateral triangles with six matchsticks," one has to imagine a pyramid in the three-dimensional space rather than attempting in vain to remain on the one-dimensional plane. Similarly, the matchstick task, which requires rearrangement of just one matchstick in order to obtain a valid equation expressed in Roman numeric symbols (e.g., nonsensical III + III = III can be rearranged into tautological but valid III = III = III, DeCaro et al., 2015), needs imaginary transformation of the symbol "+" into "=". Regardless of their being verbal or non-verbal in nature, insight problems usually need active engagement of mental imagery, as the above-mentioned problems show clearly.

The second tradition of creativity studies descends from the theory of divergent thinking (Guilford, 1950, 1967; Wallach and Kogan, 1965), according to which creativity is connected with unconstrained search for solutions in many different directions. Ideas generated in the process of divergent thinking differ in their value, originality, or simply appropriateness to the problem at hand. Therefore, they must be selected and elaborated upon in order to find out the really creative ones. The well-known rule of brainstorming, stating that "quantity breeds quality" (Osborn, 1953; Parnes and Meadow, 1959), also known as the "equal-odds rule" (Simonton, 1997; Jung et al., 2015), seems to be compatible with this approach. The proponents of this tradition typically investigate creativity using the so-called divergent problems, which have many acceptable solutions and need fluency of thinking rather than restructuring. For instance, the question of unusual uses of a brick (i.e., "How many unusual and uncommon uses can you come up with for a *brick*?", Guilford, 1967) does not have any "correct" solution nor does it need any type of restructuring. It just relies on the problem solver's ability to think in a fluent and flexible way.

In mature real-life creativity both insight-based and divergent thinking processes are probably intertwined but in laboratory studies one has to decide on a particular approach in order to adopt the appropriate research paradigm. In this study, we decided to investigate the cognitive correlates of insight.

Insight is defined as a sudden realization that the hitherto unresolved and seemingly very difficult problem can be easily solved if it is perceived from a new perspective (Scheerer, 1963; Dominowski and Dallob, 1995; Ansburg, 2000; Chu and MacGregor, 2011). Such a change of perspective cannot be achieved through conscious effort and planning, so suddenness is its typical attribute (Davidson, 1995). Subjectively, insight is usually accompanied with the "Aha!" experience. It is preceded by many unsuccessful attempts to resolve the problem in the routine way. Since the routine approaches do not work, the experience of impasse is inevitable. The period after the impasse is called "incubational break," during which no apparent mental activity is observed, both objectively and in introspection (Sio and Ormerod, 2009). Then, an entirely new idea appears in one's mind, as if coming from "nowhere." This pattern of creative problem solving can be found in many instances of scientific discoveries (Simonton, 1988; Dunbar, 1995; Csikszentmihalyi, 1996). Being a pivotal moment of creativity, insight has been extensively studied by psychologists in hope of revealing its cognitive mechanisms.

In contemporary models, the cognitive machinery of insight amounts to restructuring (Ohlsson, 1984a,b; Ash and Wiley, 2006). This phenomenon can be described as rearrangement of elements of the problem's cognitive representation. Suddenly, elements of the cognitive representation that up to now seemed crucial appear unimportant, whereas those that seemed irrelevant gain utmost importance. In other words, a new pattern, or Gestalt (Wertheimer, 1945), comes to one's mind, thus suggesting a new and productive way of thinking. What causes such a rearrangement is not clear yet. The theory of selectivity (Davidson, 1995) claims that the problem solver's ability to selectively encode, compare, and combine the elements of cognitive representation leads to restructuring. It is not clear what is the nature and origin of this ability to think selectively, although there are suppositions that it might be the matter of conscious and controlled efforts to process information in the selective way (e.g., Ash and Wiley, 2006). According to Simon (1977), insight occurs when irrelevant aspects of the problem are selectively forgotten, thus making the complex and difficult problem familiar and simplified enough (see also: Simon et al., 1981; Langley and Jones, 1988). Another group of theories underscores the role of opportunistic assimilation of information (e.g., Seifert et al., 1995). Accidental stimuli appearing in the environment are opportunistically assimilated with the original mental representation, thus producing a new, rearranged pattern of relationships between separate elements of the problem representation. They may also suggest a novel solution thanks to the analogical transfer of knowledge (Ormerod et al., 2006).

Taking into account the cognitive characteristics of insight, we hypothesize that its occurrence should depend significantly on WM processes. WM is responsible for active maintenance of information relevant to the problem at hand. It is also believed to enable active manipulation with the elements of the problem's mental representation (Baddeley and Hitch, 1974; Cowan, 2001, 2010; Baddeley, 2002; Engle, 2002; Unsworth and Engle, 2007a). Active maintenance is possible thanks to the modules called articulatory loop and inner scribe, connected with verbal and non-verbal material respectively, whereas manipulation with the problem's elements is ascribed to the central executive (Baddeley, 2002). If insight amounts to restructuring of mental representation of the problem, its cognitive machinery must rely greatly on the WM mechanisms. Restructuring probably starts with the decomposition of distinct elements of the problem's structure. Then, it requires the maintenance of these elements in active WM in order to use them in multiple attempts to build up a new structure. Finally, new structures are constantly built and rebuilt, which is a process resembling the creation of temporary bindings among the elements kept in the primary memory (Oberauer et al., 2007; Oberauer, 2009). New structures typically utilize elements that were formerly ignored as ostensibly irrelevant or redundant. Since the problem solver does not realize from the very beginning which elements are relevant or not relevant, he/she must keep in active memory as many elements as possible. So, capacious WM should increase the likelihood of the occurrence of insight. Moreover, formerly "irrelevant" chunks of information are probably kept in less active parts of WM, i.e., outside of the focus of attention (Cowan, 2001), or even in the LTM store, that is, in the inactive state of mental representation. If so, they must be activated and transferred to the focus of attention in order to be fully prepared for immediate utilization in thinking processes. Hence, executive aspects of WM, also called "controlled attention" (Engle et al., 1999a; Engle, 2002; Unsworth and Engle, 2007a), should contribute to the likelihood of insight and its quality, too. To sum up, the cognitive analysis of insight leads us to the hypothesis that insightful thinking, or insightful imagery, is almost synonymous to WM processes, as they are conceptualized in the most influential theoretical models (e.g., Engle et al., 1999a; Cowan, 2001, 2010; Baddeley, 2002).

Available empirical evidence is quite ambiguous in this respect. On the one hand, there are studies reporting at least moderate correlations between batteries of insight tasks and various measures of WM. For instance, Murray and Byrne (2005) used the battery of eight insight tasks and obtained the correlation of $r = 0.39$ with backward-digit task and $r = 0.51$ with the span task. Gilhooly and Fioratou (2009) also report positive correlations between insight problems and both verbal and non-verbal WM span tasks (r coefficients ranged between 0.27 and 0.38), although correlations with non-insight problems were approximately at the same level. Interestingly, this study demonstrated that executive control, in contrast to WM, entered into much weaker associations with insight problem solving, a result reported in other studies, too (Paulewicz et al., 2007). De Dreu et al. (2012) showed that WM contributed to creative outputs in general, and correct solutions to insight problems (i.e., Remote Association Rest's items) in particular. Yeh et al. (2014) demonstrated that WM capacity helped to solve insight problems in interaction with attention and eye movements. Arguments for the essential role of WM capacity in insightful problem solving can also be found in other studies (e.g., Chein et al., 2010; Chein and Weisberg, 2014).

On the other hand, many studies report the results that are not compatible with our hypothesis. For example, Gilhooly and Murphy (2005), using a painstakingly selected set of "pure" insight problems, did not observe any significant correlation with the backward-digit tasks. They reported a weak correlation with the span task ($r = 0.23$) but, notably, analytical problems, which did not require any insight, correlated with the span task at the same level. Other studies also support the supposition that WM capacity may predict analytical rather than creative thinking processes. For instance, Lavric et al. (2000) asked people to solve insight and analytical problems while simultaneously counting tones generated by the computer. They found that engagement of WM through counting did not affect insight problem solving, contrary to analytical problem solving. DeCaro et al. (2015; see also: Van Stockum and DeCaro, 2013) go as far as to argue that "WM capacity constraints insight" because it leads people to employ complex thinking strategies, whereas insight, according to them, needs remote associations rather than resource-dependent complex thinking. It is also argued that insight cannot be reached through deliberate planning (Chein et al., 2010), which is one of the vital functions ascribed to WM (Gilhooly, 2005).

A question arises, what are the causes of such inconsistencies in the available literature. The answer lies probably in the methodological weaknesses, which are notorious in the insight problem solving studies (Gilhooly and Murphy, 2005). To begin with, in many studies the authors used just one category of problems, such as the tasks which require rearrangement of just one matchstick in order to obtain a valid equation expressed in Roman numeric symbols (DeCaro et al., 2015), remote association tasks (De Dreu et al., 2012), or compound remote association tasks (Chein and Weisberg, 2014). It seems that, for psychometric reasons, more diversified batteries of insight tasks should be applied. Additionally, the batteries of insight tasks are sometimes very short, consisting of one (Chein et al., 2010), four (DeCaro et al., 2015), six (Ash and Wiley, 2006), eight (Murray and Byrne, 2005), or ten (Paulewicz et al., 2007) items. It seems that psychometric properties of short batteries can be criticized, especially if a particular study is designed according to the individual differences approach. Purity of the insight task batteries may also be questioned, as they happen to involve the tasks that can be solved analytically as well (Weisberg, 1995; Gilhooly and Murphy, 2005). Finally, familiarity of insight tasks is usually not controlled, although prior knowledge makes them entirely non-problematic. As to WM measures used in the insight studies, they tend to be rather complex and multifaceted, thus excluding the opportunity to investigate specific cognitive processes involved. Moreover, complex WM measures, such as the span tasks, may be interpreted as proxies for intelligence tests, since their results are usually strongly correlated with intelligence tests' results. Finally, the span tasks refer to the "mnemonic" aspects of WM, performed by the articulatory loop or the inner scribe, rather than to its "processing" aspects, carried out by the central executive. We have not been able to find a study of insight in which some specific function of WM would be investigated, such as the function of updating (Morris and Jones, 1990).

Updating consists in constant rearrangements of the temporal order among the items kept in the primary memory. Participants are asked, for instance, to recall the last n items of a long list of elements (Morris and Jones, 1990) or to decide whether the current element of the running list has been already presented n items back (McElree, 2001). In order to do such tasks, one has to revise the temporal order of the list of elements, since the element presented two items back is going to take the position of three items back, and then four items back, and so forth. In other words, one has to keep in active memory as many elements as possible but also rearrange their temporal order. The function of updating predicts individual differences in complex cognitive skills (Miyake et al., 2000; Friedman et al., 2006; Ecker et al., 2010), although insight problem solving has not been studied extensively from this perspective. Moreover, the processes hypothesized to operate during updating, such as retrieval, transformation, and substitution of elements (Ecker et al., 2010), or binding (Wilhelm et al., 2013), resemble the processes involved in insightful restructuring. It is therefore interesting to investigate possible relationships between the efficiency of the function of updating and the ability to solve insight problems.

In our study, we selected a quite large battery of insight problems. We also focused on the function of WM updating rather than using a complex span measure of WM capacity. Finally, we decided to assess the general intelligence level, so as to be able to look for potential relationships between WM capacity and insight problem solving when general intelligence is controlled for. Apart from being determined by WM processes, intelligence is by definition the general ability to solve problems, particularly the complex and abstract ones. Therefore, investigation of the relationships between WM and insightful problem solving needs checking for possible correlations confounded by the general intelligence.

MATERIALS AND METHODS

Participants

We investigated 91 male volunteers. Their age ranged between 18 and 26, $M = 21.36$, $SD = 3.62$. They were high school and university students outside of psychology department. We recruited them through advertisements disseminated at their residences. One participant's data were not saved on the disk, another one resigned before completing the tests. Both had to be excluded, leaving 89 persons in the final sample.

Ethical Statement

The committee for ethics in studies involving human participants, assigned by the Department of Psychology, Jagiellonian University in Krakow, approved this study on the basis of extended description of methods, materials, and procedure. According to the Helsinki declaration, participants signed written informed consent forms.

Tests and Materials

Insight Tasks

In order to investigate the participants' ability to solve insight problems, we selected a set of 31 tasks that are believed to require insightful skills. In the beginning, we gathered all available tasks reported in the literature, particularly in the works by Metcalfe and Wiebe (1987), Schooler et al. (1993), Dominowski and Dallob (1995), Gick and Lockhart (1995), Isaak and Just (1995), Weisberg (1995), and Gilhooly and Murphy (2005). We also took into account a 68-item test used in the study on training insight problem solving (Dow and Mayer, 2004). Some tasks overlapped across the analyzed studies. Others raised doubts concerning their theoretical validity. Therefore we decided to reduce the number of items on the basis of three criteria. First, we excluded the items that failed empirical verification as insight tasks (Dow and Mayer, 2004; Gilhooly and Murphy, 2005). Second, we excluded the items that have been discussed in the literature as questionable concerning their insight nature. Third, we excluded the items that were culturally specific, for instance, the ones that could be solved only if a person would possess specific knowledge concerning culture, tradition, or religion.

In such a way, we obtained 66 items that have been subjected to the procedure suggested by Davidson (1995). We asked 52 judges to solve and evaluate these 66 tasks. The judges were graduate students of psychology enrolled in MA or Ph.D. programs who had at least moderate experience with cognitive psychology and problem solving. The judges were presented with a standard definition of insight and asked to evaluate the extent to which a given task complies with such a definition and requires insight problem solving. They were also asked to assess the familiarity of tasks, their logical and grammatical consistency, and their difficulty level on the 1–7 scale. In this way we tried to eliminate tasks the solutions to which would be known in advance to potential participants, tasks that would be unclear or ambiguous, as well as tasks that would be too easy or too difficult to solve. As a consequence, we obtained 31 tasks which did not raise any reservations from the judges' side and whose difficulty level did not touch the extremes (items with 0 or 100% correct solutions were eliminated). As to the subjective ratings of difficulty, 11 tasks were judged quite difficult, difficult, or very difficult (on a scale of 5–7), 16 tasks were judged very easy, easy, or quite easy (on a scale of 1–3), whereas four tasks obtained the middle ratings of 4. This final pool of 31 items was used in the study proper (see Appendices 1 and 2 in Supplementary Material).

N-Back Task

Working memory updating was assessed with an experimental task called n-back (McElree, 2001; Owen et al., 2005). Participants were presented with two-digit numbers that appeared in the center of the screen and remained there either for 1800 ms or until the response. These stimuli were masked with random patterns of dots. Numbers filled in the 50 cm × 30 cm square with no apparent edges. After 500 ms of masking, another stimulus appeared on the screen. The task was to press the space key if and only if a given stimulus had been presented two ($n = 2$) or four ($n = 4$) items back. For instance, in the following stream of stimuli: 31 **56** 34 **56** 42 12 and so forth, the number 56 is repeated and a participant is supposed to recognize it as being presented two items back. Similarly, in the stream: **23** 45 34 56 **23** and so forth, the repeated number 23 has been presented previously four items back. There were six series of the n-back task, each consisting of 88 stimuli, out of which 16 would reappear in the proper position. Three series were prepared according to the easier rule of detection ($n = 2$), and three series required the more demanding rule ($n = 4$). The location of repeated stimuli (i.e., signals) within every series was prearranged in the quasi-random way and fixed for all participants. The procedure started with the $n = 2$ series, next it switched to the $n = 4$ series, back to the $n = 2$ series, and so on. Participants were instructed to update the contents of their WM in order to be able to know whether a given stimulus has been presented before at the predefined location. Updating is crucial for this task because of the fact that stimuli are constantly changing their position in the series. For instance, the stimulus that is now at the screen has the position $n = 0$ but after its disappearance it gains the position $n = 1$, next $n = 2$, and so forth. Participants were told which position was valid in every series: $n = 2$ or $n = 4$. They were also asked to ignore stimuli that did not match to the pattern kept in WM in the valid position.

Two indices of performance have been registered: the number of omissions and the number of false alarms. The former took place when a participant did not press the space key in spite of the fact that a given number had been repeated in the predefined position ($n = 2$ or $n = 4$). In contrast, false alarms were registered when a participant pressed the space key unnecessarily, that is, in response to a stimulus that had not been repeated at all. In this version of the n-back task we did not present participants with lures, that is, stimuli reappearing in wrong positions. In the $n = 2$ condition, they could be repeated too early ($n = 1$) or too late ($n = 3$). Such versions of the n-back task are particularly demanding for the cognitive control processes, as they required active inhibition of the prepotent albeit wrong response. Since we were primarily interested in WM updating rather than cognitive control, we decided to get rid of lures.

Raven's Advanced Progressive Matrices

For intelligence assessment, we used Raven's Advanced Progressive Matrices (RAPM, Raven et al., 1983) in the Polish adaptation by Jaworowska and Szustrowa (1991). This test consists of 10 introductory items and 36 main items, arranged according to the increasing difficulty. Each task requires the grasp of analogical relationships between abstract symbols. It allows good estimation of the general fluid intelligence, defined as the eduction of relations ability (Spearman, 1927). Due to time restrictions we administered only the main 36 items.

Procedure

Participants first completed the computerized n-back test, which took about 15 min. There were short training sessions preceding the proper testing. Then, they completed Raven's Matrices (25 min) and Insight Tasks (60 min). They were tested in a computer room equipped with separate cubicles.

RESULTS

Descriptive statistics are reported in **Table 1**. Both Raven's Matrices and Insight Tasks were solved at the average level, without any indication of either floor or ceiling effects. Mean and median values were in the middle of the absolute range of results, which was between 0 and 36 in the case of Raven's matrices and between 0 and 31 in the case of insight tasks. Both tests provided distribution not differing from normal, which was checked with the K–S test.

As to the computerized n-back task, the average proportion of omissions was 0.34 in the $n = 2$ condition and 0.37 in the $n = 4$ condition. Proportion of false alarms was 0.04 and 0.11, respectively in the $n = 2$ and $n = 4$ conditions. A closer look at the data suggested that eight participants, whose results did not differ statistically from the 50% chance level, lowered the average accuracy scores. Some of them also surpassed the "three sigma" criterion concerning the number of false alarms. These participants were excluded from further analyses on the basis of the argument that probably they did not follow the instruction or their cognitive skills were too low for the task's requirements. In consequence, further analyses were applied to the sample of 81 people. Descriptive statistics concerning the final sample of 81 participants are presented in **Table 1**, too (the lower lines).

Both conditions of the n-back task differed in difficulty, which was checked with *t*-test for dependent samples. For the proportion of omissions, the difference between $n = 2$ and $n = 4$ conditions was significant at the $p < 0.01$ level, $F(1,88) = 7.83$. For the proportion of false alarms, this difference was significant at the $p < 0.001$ level, $F(1,88) = 39.16$. These differences were expected as confirmation of the theoretical validity of the n-back task.

In the next step, we checked reliability of the battery of Insight Tasks. The internal consistency measure (Cronbach's α) for the whole battery was 0.62, which is a results usually interpreted as questionable (George and Mallery, 2003). A closer examination of items revealed that there were five tasks whose elimination increased the α index of the whole battery. After their removal, Cronbach's α of the battery of the remaining 26 tasks was 0.71, which is an acceptable level of internal consistency (George and Mallery, 2003). All further analyses were therefore performed with the use of the 26-item version of the battery.

In order to verify our hypotheses, we computed correlation coefficients referring to the main variables of the study (**Table 2**). We found strong negative correlations between the number of correct responses in the battery of Insight Tasks and the proportion of omissions, both in the $n = 2$ and in the $n = 4$ conditions ($r = -0.48$ and $r = -0.53$, respectively). Relationships of the IT battery and the proportion of false alarms were much weaker, surpassing the level of statistical significance only in the

TABLE 1 | Descriptive statistics for the initial sample ($N = 89$, upper lines) and the final sample ($N = 81$, lower lines).

	Mean	*SD*	Median	Minimum	Maximum
RAPM	19.81	3.04	20	12	26
	20.12	2.83	20	14	26
IT	20.63	3.77	21	11	28
	21.05	3.56	21	13	28
OM $n = 2$	0.34	0.09	0.35	0.07	0.51
	0.35	0.09	0.35	0.07	0.51
OM $n = 4$	0.37	0.12	0.38	0.08	0.60
	0.38	0.12	0.39	0.08	0.60
FA $n = 2$	0.04	0.05	0.03	0.00	0.24
	0.03	0.03	0.02	0.00	0.15
FA $n = 4$	0.11	0.08	0.10	0.00	0.38
	0.10	0.05	0.09	0.02	0.29

RAPM, Raven's Advanced Progressive Matrices; IT, Insight Tasks; OM, proportion of omissions; FA, proportion of false alarms; n = 2, n-back task, signals first appearing two items back; n = 4, n-back task, signals first appearing four items back.

TABLE 2 | Correlations matrix ($N = 81$).

	OM $n = 2$	OM $n = 4$	FA $n = 2$	FA $n = 4$	RAPM
OM $n = 4$	0.71***				
FA $n = 2$	−0.08	−0.07			
FA $n = 4$	−0.30**	−0.42***	0.31**		
RAPM	−0.54***	−0.58***	0.03	0.27*	
IT	−0.48***	−0.53***	−0.23*	0.16	0.41***

OM, proportion of omissions; FA, proportion of false alarms; n = 2, n-back task, signals first appearing two items back; n = 4, n-back task, signals first appearing four items back; RAPM, Raven's Advanced Progressive Matrices; IT, Insight Tasks; *$^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.*

relatively less demanding $n = 2$ condition. At the same time, we found even stronger relationships between the proportion of omissions and the Raven's test scores ($r = -0.54$ and $r = -0.58$, respectively for the $n = 2$ and $n = 4$ conditions). All these correlations were negative, suggesting that the higher the scores in the IT or RAPM tests the better accuracy in the computerized n-back task. Strength of the observed relationships suggests that the ability to solve insight tasks shares about 25% of common variance with the ability to update the contents of WM, as long as the latter is measured with the proportion of omissions. The percentage of common variance was much smaller (about 5%) if WM task performance is assessed with the proportion of false alarms. By the way, these two aspects seem to be quite separate, since the proportion of omissions in the $n = 2$ condition was not correlated at all with the proportion of false alarms ($r = 0.08$), whereas in the $n = 4$ condition it was correlated negatively ($r = -0.42$, $p < 0.001$). These results suggest that omissions and false alarms, being both indicators of accuracy in the $n =$ back task, refer to quite distinct aspects of WM functioning.

It is also worth noticing (**Table 2**) that both ability measures were correlated positively at the moderate level ($r = 0.41$). If so, their correlations with n-back measures may be confounded by their mutual influence. Therefore, we computed partial correlation coefficients between n-back performance and the IT battery while controlling for RAPM. We also computed analogical correlations for RAPM, controlling for IT. We found that all significant correlations remained significant; however, their strength was a bit reduced. For IT, its partial correlations with OM were −0.36 and −0.47, respectively for the $n = 2$ and $n = 4$ conditions. For RAPM, respective partial correlations were −0.45 and −0.48. So, we can conclude that zero-order correlations reported in **Table 2** lost part of their strength with IT when RAPM was controlled for, and vice versa. However, the "pure" relationships, represented by partial correlations, were strong enough to justify a conclusion that the ability to solve insight tasks depends on WM updating, regardless of the confounding influence of general intelligence.

In the next step, we looked at the difficulty level of the tasks included in the IT battery. It appeared that eight of them obtained very high percentages of correct responses, thus not being able to differentiate the participants' level

TABLE 3 | Zero-order and partial correlations between the reduced IT battery and n-back performance measures ($N = 81$).

		OM $n = 2$	OM $n = 4$	FA $n = 2$	FA $n = 4$	RAPM
IT	(Zero-order)	−0.45***	−0.63***	−0.24*	0.14	0.37***
IT	(Partial)	−0.31*	−0.54***	−0.28*	0.04	–

OM, proportion of omissions; FA, proportion of false alarms; n = 2, n-back task, signals first appearing two items back; n = 4, n-back task, signals first appearing four items back; RAPM, Raven's Advanced Progressive Matrices; IT, Insight Tasks; *$^*p < 0.05$; $^{***}p < 0.001$.*

of the ability to solve insight problems (see Appendix 3 in Supplementary Material). We suspected that, regardless of the fact that the whole battery did not reveal any indications of the ceiling effect, these eight items of reduced difficulty might contribute to lowering the values of correlation coefficients. Items without enough power to differentiate participants usually reduce variation and thus make correlation coefficients artificially low. Having removed eight items that appeared too easy, we checked for the correlation matrix again. The results are reported in **Table 3**.

As expected, the removal of eight easy tasks from the IT battery resulted in strengthening the correlations with n-back task measures. The correlation between IT and OM in the $n = 4$ condition seems particularly interesting because it increased from −0.53 (**Table 2**) to −0.63 (**Table 3**). Moreover, this correlation remained strong (−0.54) after partialling out the effects of Raven's scores. It may then be concluded that the ability to solve insight problems shares about 30% of common variance with the ability to update the contents of WM, even if the influence of general mental ability is controlled for.

DISCUSSION

Most creativity researchers agree that insight problem solving requires restructuring of the problem representation. A marked lack of agreement concerns the mechanisms by which the restructuring occurs. Some authors propose that restructuring of the problem representation relies upon controlled search processes, suggesting an essential role for WM and planning in insight problem solving (MacGregor et al., 2001; Chein et al., 2010; Chein and Weisberg, 2014). Other researchers suggest that restructuring is achieved through the automatic spread of activation in long-term memory, assigning a limited role to WM processes (Ash and Wiley, 2006). The results of the present study reinforce the view that insight problem solving is related to WM involvement. Since we used the n-back task to investigate WM processes, we suggest that the function of WM updating is involved in insight problem solving. Although n-back, as many cognitive tasks, suffers from impurity, it is believed to engage at least two out of three postulated components of updating, namely *recognition* of already presented items and *substitution* of old items with new ones (Ecker et al., 2010). Interestingly, when comparing two indices of n-back, omission errors and false alarms, they both seemed to refer to distinct processes, with the former sharing much more common variance with insight problem solving then the latter (25 and 5% respectively). Finally, our results indicate that when controlled for IT task difficulty, a measure of updating function accounts for up to 30% of variance in the solution of insight problems, even when the influence of general mental ability is controlled for. To the best of our knowledge, this is the first study revealing the relationship between insight problem solving and WM updating function.

Let us analyze possible cognitive mechanisms responsible for the contribution of WM updating to insight problem solving. According to MacGregor et al. (2001), the difficulty in solving insight problems stems from the fact that a concrete goal is defined in abstract terms and therefore cannot be foreseen and used for progress monitoring. In such circumstances a successful strategy of problem solving depends critically on applying maximization and progress-monitoring heuristics. People may succeed only if, at each stage of the task, they try to choose a move that maximally reduces the difference between the current state and the sub-goal, and constantly monitor their progress against solution criteria (and not against the desired final goal, which is impossible). Consequently, the critical component of insight problem solving is the ability to envisage the situation that will be achieved after a series of steps. Thanks to this ability, the insightful move can be inspired not just by actual failure, but instead by the anticipation of failure. In the formal information-processing model proposed by MacGregor et al. (2001) this ability was implemented in a form of *lookahead* parameter. The suggestion that people use maximization and progress-monitoring heuristics with *lookahead* was supported empirically. MacGregor et al. (2001) revealed that human participants and computer models spend more time on solving the nine-dot problem, and its modifications varying in number of dots, if the problems are related to greater *lookahead*.

Building up on this work, Chein et al. (2010) and Chein and Weisberg (2014) operationalized *lookahead* mechanisms in terms of WM capacity. In the direct test of the role of *lookahead* in nine-dot performance, using an individual-differences approach, Chein et al. (2010) found that spatial WM capacity predicted the tendency to draw lines outside the configuration of dots, the solution of a hint-aided version of the problem, and shorter solution times of the nine-dot problem. In the subsequent study the authors (Chein and Weisberg, 2014) explored the contributions of WM and attention to the solution of compound remote associate problems (CRA). In the CRA, participants are required to find a solution word that is associated with three stimuli words provided (see also: Mednick, 1962, 1968). Particular solutions can be accompanied with the 'aha' experience, or not. Chein and Weisberg (2014) firstly divided the CRA problems into those whose solution was accompanied by a subjective feeling of insight on the basis of the participants' self-reported insight ratings provided. Then, they examined the correlations between problem performance and measures of verbal WM and spatial WM capacity, as well as attentional control (by means of Stroop and antisaccade tasks). The results indicated that individual differences in both modality-specific and executive components of WM (i.e., those associated with the control of attention) explained a significant portion of variation in overall CRA problem solving and, most importantly, in the cases when problem solutions were accompanied by a subjective feeling of insight.

The results of the current study support the conclusion offered by Chein et al. (2010) and Chein and Weisberg (2014) by providing convergent evidence based on different methods, and extends their account by specifying further the nature of WM involvement in insight problem solving. In the present study WM updating was assessed with the n-back paradigm, as opposed to the OSPAN task used by Chein and Weisberg (2014). In OSPAN task the participants are required to perform a simple mathematical verification and then read a word or letter. After several such processing-and-storage presentations, a recall grid is presented, and people are required to indicate in serial order the words or letters they had seen previously. Operation span is determined on the basis of the highest number of words that can be recalled by the participant. In terms of construct validity, complex span tasks have been consistently shown to have stronger relations to memory tasks requiring information manipulation than to those demanding mainly rehearsal (e.g., Engle et al., 1999b). Therefore it is believed that WM span is a reliable predictor of complex cognitive behavior across domains, including problem solving, reasoning, and reading comprehension, because it is related to executive control (Engle et al., 1992; Conway et al., 2005).

Although n-back and OSPAN are similar in that they both require simultaneous storage and processing of the material, it is still a matter of debate whether they reflect primarily a single construct and whether findings from one of these tasks can be easily applied the to the other (Roberts and Gibson, 2002; Oberauer, 2005; Kane et al., 2007; Jaeggi et al., 2010; Redick et al., 2012). Several recent psychometric tests have shown a full range of results. In some cases n-back and WM span were shown to correlate weakly (Kane et al., 2007; Redick et al., 2012). For example, in the study by Kane et al. (2007) these tasks shared only 2–5% of their variance. Moreover, even though both tasks predicted variance in RAPM, they primarily did so independently, with less shared than unique predictive variance between them (see also: Oberauer, 2005; Redick et al., 2012). These results favor interpretation, according to which complex span tasks rely heavily on executive attention but do not involve updating, which, in contrast is strongly implicated in n-back performance.

In contrast, Schmiedek et al. (2009) obtained strong positive correlation between a latent factor measured by three complex span tasks and a latent factor represented by three different working-memory updating tasks (including figural n-back). Wilhelm et al. (2013) obtained a similar high construct overlap of recall-n-back and complex span, as well as a very strong relationship with the latent factor for updating. Noteworthy, these correlational studies measured WM through multiple indicators and evaluated their relationship through structural equation modeling (SEM). Hence, it was possible to overcome the shortcomings of other studies where WM and executive attention were tested with a single experimental paradigm, conflating variance due to individual differences in executive control with task-specific variance and resulting in null correlations (Wilhelm et al., 2013).

Moreover, the findings from our lab support the claim that n-back task reflects primarily the updating function of WM that is statistically identical to storage capacity (Chuderski and Nęcka, 2012; Chuderski et al., 2012). This conclusion was based on the observation that, in the above-mentioned studies, updating as measured by figural n-back task did not account for any amount of variance above and beyond the variance accounted for the scores reflecting maintenance of the pattern of a few items for several seconds (as measured by the array comparison task) or construction and maintenance of temporary bindings among perceptually available items (as measured by the two monitoring tasks). In fact, on the basis of these data the authors have questioned the existence of a distinct executive function of updating, amounting it to storage capacity (see also Wilhelm et al., 2013).

In sum, we believe that the relationship between n-back and insight problem solving, as revealed by the current investigation, concerns primarily the updating function of WM. Considering the results by Chuderski et al. (2012), updating function measured by n-back task used here amounts to storage capacity. Therefore it seems that insight problem solving ability may be crucially limited either by the number of items maintained in active memory or by the number of bindings which the individual is able to maintain in active memory (plus possible interaction of these factors). Presumably binding compromises storage and vice versa, in analogy to the relationship between primary memory and secondary memory proposed by Unsworth and Engle (2007b).

Obviously, on the basis of the current data we are unable to distinguish between the two aspects of updating: maintenance and binding (see: Chuderski et al., 2012). Speculating, one can assume that the maintenance component of the WM can be conceptualized in terms of the '*n*' value in the n-back task: the higher the '*n*' is, the more items have to be stored in memory simultaneously in order to generate correct match, and consequently, the more difficult the tasks becomes. Indeed, our results revealed that IT performance showed stronger correlation with the four-back condition of the current memory task than with the two-back condition. Interestingly, this relationship was observed only for omission errors. Arguably, such errors occur either due to a failure to maintain to-be-remembered item in active memory, or due to a failure to generate proper binding within a series of items. The mechanism of false alarms seem much more elusive, as it amounts to "seeing" an item or a binding which is simply not there, possibly due to some source of proactive interference that emerges across task trials. In this case, proactive interference drove the association between insight problem solving and WM updating as measured by false alarms. Alternatively, false alarms may have reflected an individual's impulsive strategy to overreact (Saunders et al., 2008).

The idea offered here that insight problems solving depends heavily on maintenance and binding processes corresponds clearly to the binding hypothesis of WM capacity offered by Oberauer et al. (2007), and Wilhelm et al. (2013) in the context of fluid intelligence: "WM is important for reasoning because reasoning requires the construction and manipulation of representations of novel structures. The limited capacity of WM arises from interference between bindings, which effectively limits the complexity of new structural representations, and thereby constrains reasoning ability" (Wilhelm et al., 2013, p. 4).

The current study has certain limitations. In methodological terms, the most important limitation is that we did not study insight directly, and more importantly, we did not assess its critical aspects: impasse and restructuring (see Chein and Weisberg, 2014). Instead, we used a correlational design allowing us only to relate such a global measure as the IT index to WM updating performance. Although the IT task items used here were carefully selected and judged, it is still possible that IT index used here conflates many factors. One important factor overlooked in the present study relates to the characteristics of the problems included into the IT task. It has been suggested that different types of insight tasks require different forms of restructuring (Ohlsson, 1984a,b, 1992; Weisberg, 1995), e.g., the requirement for figure-ground type reversals, the degree of misdirection involved, the need to redefine spatial assumptions, and so on (see Cunningham et al., 2009). Clearly some insight problems are more difficult to solve than others, and this difficulty is affected by characteristics of the restructuring processes required (Cunningham et al., 2009). Problem characteristics may also mediate the relationship between insight problem solving and WM. Ash and Wiley (2006) found that high WM capacity (as measured by WM span tasks) predicted an individual's ability to successfully solve problems that involve both the initial search phase and the restructuring phase. However, individual differences in WM capacity did not predict success on problems that isolated the restructuring phase only. The current data supports these claims indirectly, that is, when several IT items were excluded from the analysis due to their insufficient discriminating power, the correlation between IT and WM updating increased. This finding suggests that the relationship between insight problem solving and WM updating depends on the level of task difficulty, which, in turn, may be related to restructuring characteristics of the task.

In summary, our results point to the conclusion that insight problem solving depends on WM updating, i.e., maintenance of items in WM and rapid binding of the incoming information with current sub-goals maintained in WM. WM updating, conceptualized as the combination of maintenance and binding, probably allows to form a new representations of a problem space. Investigation of insight problem solving in terms of updating function with an inclusion of restructuring characteristics may be the promising direction for future research on individual differences in insight problem solving.

AUTHOR CONTRIBUTIONS

All authors listed, have made substantial, direct and intellectual contribution to the work, and approved it for publication.

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Imagery As a Core Process in the Creativity of Successful and Awarded Artists and Scientists and Its Neurobiological Correlates

Rosa Aurora Chavez[1,2,3]*

[1] *Washington International Center for Creativity, Washington, DC, USA,* [2] *Department of Psychiatry and Behavioral Health, George Washington University, Washington, DC, USA,* [3] *Instituto Nacional de Psiquiatría Dr. Ramón de la Fuente Muñiz, Mexico City, Mexico*

This perspective paper presents an integration of neuroimaging and phenomenological data obtained in a sample that included highly creative, internationally awarded scientists and/or artists. The cerebral blood flow was evaluated during the performance of standardized creativity tasks from the Torrance Tests of Creative Thinking Verbal Form. The phenomenological data comprised both, their experiences and processes related to their creative careers and their experiences during the performance of the creative thinking tasks during the acquisition of the brain imaging data. Highly creative individuals presented a significantly higher activation of areas involved in motor imagery and described that their creative process is frequently triggered by the spontaneous and often surprising emergence of what is being named here as *primordial imagery*: a sudden, multimodal, multiintegrative, highly condensed representation that is germinative, unleashing insight and multiple associations and possibilities for meaning. As evidenced in creativity, imagery is a process through which we perceive our own minds, allowing us further symbolization and access to our thoughts, possibly facilitating neural pathways.

Keywords: creativity, imagery, creative cognition, phenomenology, neurobiology of creativity

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Correspondence:
Rosa Aurora Chavez
drchavezra@yahoo.com

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While he was looking closely at me, piercing my eyes with his lucid sight, he said: "Hold on to this thought you've just mentioned. What I've found to be at the core of creativity is imagery. Imagery is what ignites the spark." (Torrance, personal communication). Several years have passed, and the vivid image of E. Paul Torrance in the intimacy of his home office, reclined in his chair with his calico cat at his side, columns of files of his own papers, and a sign with the picture of some vegetables stating 'innovate or vegetate' at the threshold, reverberates like a music ostinato within my own brain. Perhaps my words have pierced you, and you have now a mental representation of that moment, popping like corn triggering associations. I was a visiting scholar, using the Torrance Tests of Creative Thinking (TTCT), trying to find out what happens in our brain when we are creative.

In the upcoming section I will briefly describe the study that followed up and our results, which have been published elsewhere (Chávez-Eakle et al., 2007). Afterward I will present phenomenological data that was also gathered but has not been previously published. In the last section I will discuss these results aiming for understanding the role of imagery in creativity, proposing new directions.

CEREBRAL BLOOD FLOW (CBF) AND CREATIVE THINKING

Twelve individuals were invited to participate in the study, the sample was recruited from a cohort of 100 participants and included eminent, internationally awarded, artists and/or scientists in the peak of their production. In addition to their actual highly creative performance, their creative potential had been assessed using the TTCT Figural form B. These psychometric tests have been used to evaluate divergent thinking (Torrance and Safter, 1999), have shown high reliability and high predictive validity (Torrance, 1988, 1990, 1993) and their structure and scoring categories have been the template for multiple subsequent tests developed in the field of creativity. The TTCT provide a creativity index (CI) and also scores for the following dimensions of the creative process: fluency, originality, and flexibility for the verbal form; and fluency, originality, elaboration, resistance to premature closure, and abstractness of titles for the figural form. In the latter, a cluster of additional points are scored by the presence of other creative strengths such as emotional expressiveness, story telling articulateness, movement or action, expressiveness of titles, synthesis of incomplete figures, unusual visualization, internal visualization, extending or breaking boundaries, humor, richness of imagery, colorfulness of imagery, and fantasy. The CI obtained with the figural TTCT was used as the parameter for the selection of the participants. Group I was integrated by individuals with a CI equal or greater than 139 (above percentile 95). Group II was composed of individuals with CI = 103–111, the middle of the normal distribution. cerebral blood flow (CBF) imaging was performed using SPECT. Two TTCT verbal-A tasks: "Just Suppose" as a warming-up activity, and "Unusual Uses" administered immediately after the injection of the radiotracer. The purpose of this study, as it was designed, was to compare the CBF between individuals with outstanding vs. average creative performance. As it has been described in a previous publication (Chávez-Eakle et al., 2007) subjects with a high creative performance showed significantly greater CBF activity in right precentral gyrus, right culmen, left, and right middle frontal gyrus, right frontal rectal gyrus, left frontal orbital gyrus, and left inferior gyrus (BA 6, 10, 11, 47, 20), and cerebellum; confirming bilateral cerebral contribution. These structures have been involved in cognition, emotion, working memory, imagery, and novelty response; suggesting an integration of perceptual, volitional, cognitive, and emotional processes in creativity. For more details please see the original source (Chávez-Eakle et al., 2007). Some of the areas presenting greater CBF in highly creative individuals correspond to what has been described as the Default Mode Network (DMN), particularly medial prefrontal cortex, the dorsomedial subsystem, and the medial temporal lobe. DMN activation has been associated to daydreaming, mind wandering, envisioning future (Cole and Schneider, 2007; Buckner et al., 2008), cognitive flexibility and conceptual shifts (Vatansever et al., 2015). Interestingly, at the same time, some activated areas correspond to what has been described as the Cognitive Control Network (CCN), particularly dorsolateral prefrontal cortex and parietal structures (Alexopolus et al., 2012) which could be related to the intentionality also involved in creativity. The cerebellum and the cortical structures involved in working memory are activated as well, which could suggest that these networks are facilitated.

THE ROLE OF IMAGERY

Although the mentioned verbal tasks of the TTCT are not regarded as imagery tasks, they rely on it. For the first task ("Just Suppose") the participants were asked to imagine a given improbable situation, and all the things that would happen as a consequence if that situation became real. For the second task ("Unusual Uses") they had to think about all the possible different uses for cardboard boxes, and how would they transform these objects. Those individuals with higher creativity scores showed significantly grater activation of the right precentral gyrus (BA 6) premotor and supplementary motor cortex, and left middle frontal gyrus (BA 6), and area that integrates cognition and emotion, affect and meaning; these areas participate in the assimilation of sensory information, modulate the impulses transmitted to primary motor areas, and are involved in the learning of new motor programs, motor imagery (Parsons et al., 1995; Malouin et al., 2003), and auditory imagery (Zatorre et al., 1996). Increased activity in BA 6 has been observed even when subjects are only imagining complex movements in hands and fingers (Rhawn, 1996), phantom-limb movements (Roux et al., 2003), and during sexual arousal (Mouras et al., 2003). High creative performance, and in particular creative fluency correlated to a higher activity in the left parietal cortex (BA 40), a multimodal assimilation area that is also involved in imagery. This area was found to be bigger in Albert Einstein's brain (Afifi and Bergman, 2005), a highly creative individual whose vivid imagery (e.g., seeing himself riding a rocket at light speed) led him to the elaboration of his theories. Einstein's expanded parietal regions were related to his preference for thinking in sensory impressions, including visual images rather than words (Falk, 2009).

There were not significant differences in the activation of primary visual cortex between the groups, which could be related to the facts that: (a) They all visualized images, (b) They did not focus on the detail of those images, they focused on their transformations. When a task requires imagining high resolution detail it is more likely to observe activation of the primary visual cortex (Kosslyn and Thompson, 2003; Kosslyn et al., 2010), but when a task requires spatial judgment -which is mediated by the parietal lobe- activation of the primary cortex is less likely (Kosslyn and Thompson, 2003; Kosslyn et al., 2010). (c) We used SPECT. The more sensitive the neuroimaging technique, the more likely to observe activation of the primary visual cortex (Kosslyn et al., 2001; Kosslyn et al., 2010).

However, there were significant differences in the activation of areas related to motor imagery (what they imagine themselves doing). These participants were imagining themselves manipulating and transforming the materials they were required to visualize. They imagined themselves performing actions,

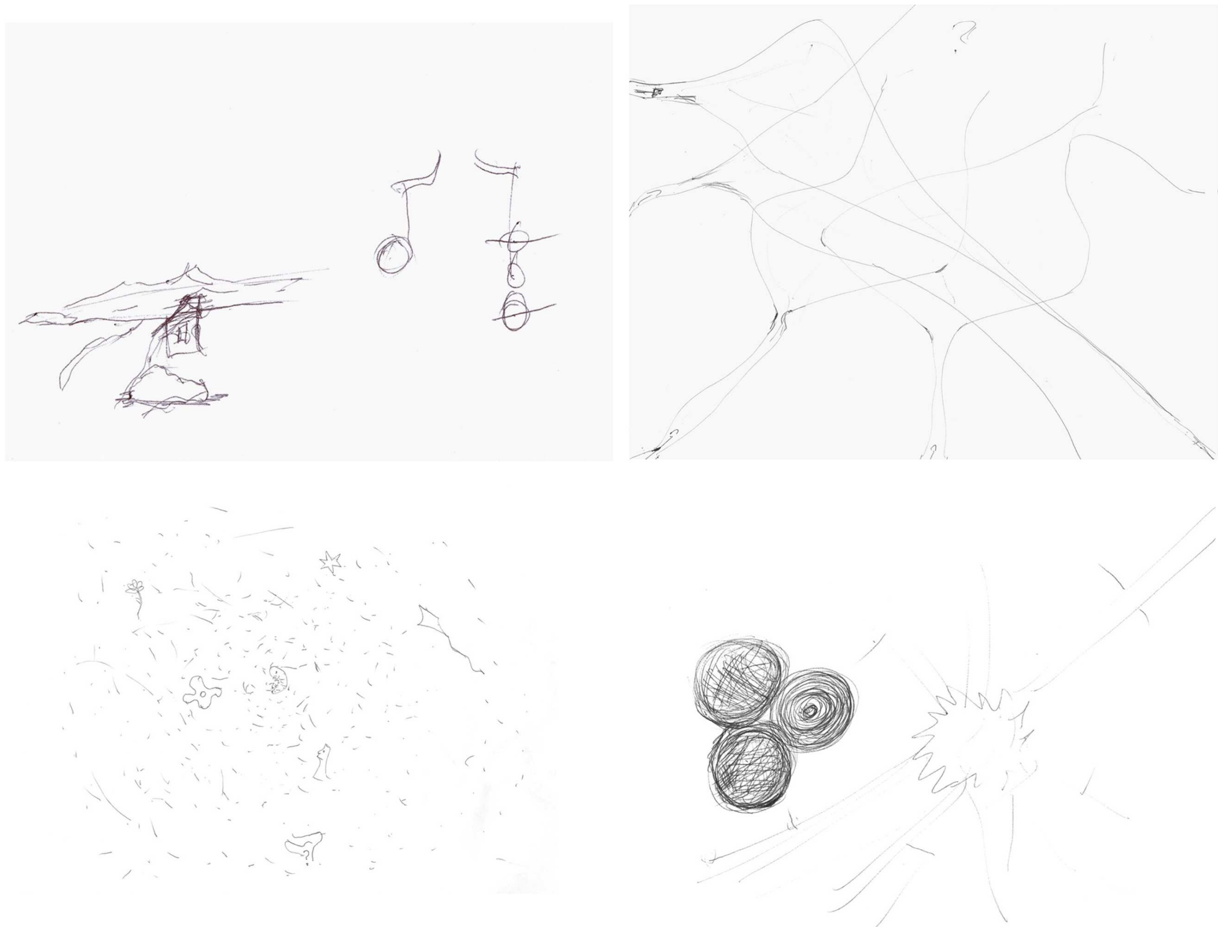

FIGURE 1 | Representations of the Creative Process, Creativity Index percentile 99.

building and moving, which involves kinaesthetic perceptual representations.

PHENOMENOLOGICAL DATA

The phenomenological data that was gathered before, during and after the brain imaging acquisition has not been published before. These data comprise the phenomenological description of their own creative process, and the phenomenological description of their experience answering the TTCT verbal tasks during the SPECT.

Phenomenological Descriptions of their Creative Process: The participants were interviewed using an open ended questionnaire *ad hoc* that started with the question: "Describe the moment when you felt the most Creative." Highly creative individuals reported vivid imagery as a key component of their creative process, regardless the domain. Artists, writers, composers, and even scientist often developed their works from the sudden presentation of imagery, which will be named here as a *primordial imagery:* a sudden, multimodal, multiintegrative, highly condensed representation that is germinative, unleashing insight and multiple associations and possibilities for meaning. Followed by further engagement, evoking more detail or related images, sensations, sounds, smells, and/or actions, triggering new associations. Their creative process at early stages involved creating a narrative to represent and/or understand these imagery contents. For instance, a writer described how an image popped up in his head almost like a dream while being awake, and from there he began to wonder what else. Imagining and describing. Some composers had visual representations within their minds and used musical sounds as the medium to narrate these images. Others had sudden auditory primordial imagery and they continued threading sounds from there. One painter said that painting from life was just the training to be able to paint internal images that popped in her mind like sudden visions. She often completed the painting it in her mind before attempting to represent it in the canvas, nonetheless, representation always fails and the actual painting is always a bridge, a compromise between the primordial imagery and what can be represented. Perhaps the following description will be striking, since it was communicated by a molecular biologist: *I was in the train. Coming into a tunnel. And there was a curve. Looking at how the train was coming into the tunnel and the light around it brought* *to my mind the clear image of the receptors binding. And I was able to see the mechanism that I had not been able to decipher before. I was seeing my self in the lab with results. I wrote then the main part of the paper and the discussion. I just went to the lab to prove it. I became famous for that, but I didn't think the editors would have allowed me to describe this process in the methodology; how I had first envisioned the results vividly in my mind.*

At the end of the questionnaire, all the participants were required to think about an image that represented their creative process. They could write and/or draw. Every verbal response was audio recorded. Researchers have been puzzled by individual differences in the intensity or quality of imagery. Creativity has a normal distribution that could be the case of imagery as well. Highly creative participants developed predominantly visual representations (**Figure 1**). One scientist draws a volcano and said: *the volcano is the image, and the image becomes words. A fire in the brain. Everything starts with a sensation that finds its own words to be described.* A composer and film maker draw a whirlpool saying: *my work is the spin within the whirlpool, the space is the mind in blank, and there's suddenly a rhythm, and the hands and the mind find each other again*. A painter draw three ascending lines saying: *it is a match, an ignited moment, holly pyrotechnics!* A scientist draw his own head open and a flow chart emerging, the first share contained the label: image, sound, idea, through an arrow it led to the label memory, another arrow to discipline, knowledge, technique, and the final arrow led to something tangible. Another painter draw a labyrinth of neurons with narrow and open spaces, saying: *through narrow spaces, feelings, and images collide at high speed*. Another scientists said while she was drawing: *first it is the white page, all possibility and all uncertainty, then millions of dots, images colliding faster than I can develop. Suddenly the agglutinate gives birth to shapes: a face, a comet, a star, an embryo, in a fast an spontaneous movement as if they popped out by themselves, then I search for meaning*. A sculptor drew himself inside of a sac and said: *this is me within the cosmos perceiving it from within, the internal world communicates through sudden symbols*. A scientist just wrote: it's pop corn! Interestingly, those individuals with creative performance on the 50 percentile tended to draw diagrams (**Figure 2**), words, and arrows such as: identify the problem, resources, experiment, results, statements, writing. Another example: problem, idea, combinations of ideas. Another one just wrote: follow the scientific method.

Phenomenological description of their experience answering the TTCT during the SPECT: those individuals scoring higher on the TCCT also described a more vivid experience of their imagined scenarios, as if they were seeing, hearing, touching, and smelling with the eyes of the mind. Experiencing this imagery often provoked their heart beat to go faster. They also spontaneously described feeling "high" happier, energized by the experience of coming up with ideas.

DISCUSSION

Combining both, neuroimaging data with phenomenological descriptions allows us to have a more panoramic view of how imagery is a core process in creativity. It also allows us to challenge traditional views. The imagery displayed by highly creative individuals seems to go beyond the conceptualization of imagery as the retrieval of memories of perception (Guillot and Collet, 2010) and provides further evidence to other approaches

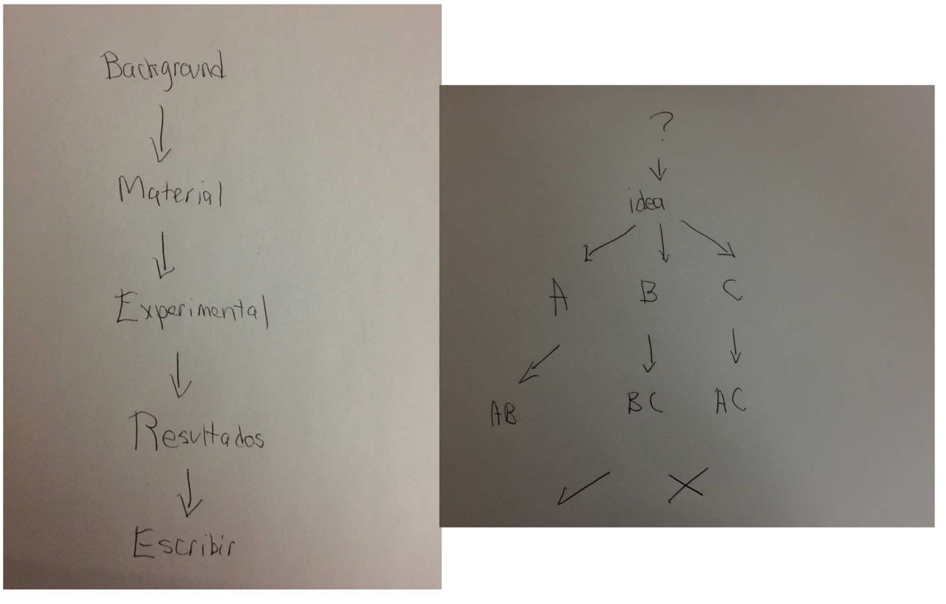

FIGURE 2 | Representations of the Creative Process, Creativity Index percentile 50.

that consider that imagery does not necessarily result only from the recall of previous perception but it can also be created by combining and modifying stored perceptual information in novel ways (Kosslyn et al., 2001). One of the key requisites for creativity is novelty. Sometimes having as result making a leap beyond what was thinkable in a given era, allowing us to expand conceptual fields. According to the data obtained in this sample, the more imagery diverges and goes beyond stored perceptual information the more novelty results. Furthermore, a breakthrough corresponded to imagery that was apparently not related to stored perceptual information; its newness was experienced as striking.

Since creativity has such evolutionary relevance and the production of primordial imagery seems to trigger the creative process, imagery could be the immediate way we perceive our own minds, in a condensed, polysemic way. Imagery engages brain mechanisms that are used in perception and action (Kosslyn et al., 2010) and mechanisms that control physiological processes such as heart rate and breathing (Guillot and Collet, 2010), having effects much like those that occur with the corresponding perceptual stimuli. Imagery is an integrative process involving pathways of memory, emotion, perception, and action. The participants described how imagery allowed them to achieve more complex responses over a given time which suggests that imagery could facilitate neural pathways. Evidence in this direction has been described in the literature where imagery has been found to enhance performance and memory (Kosslyn et al., 2001), and skill acquisition allowing the development of a mental blueprint (Holmes et al., 2010). In addition, several techniques of facilitation used in the field of creativity to potentiate or to unlock creative processes (e.g., Creative Problem Solving; the Incubation Model of Teaching; Future Problem Solving, among others) rely on imagery to trigger associations. They require a state of free floating attention where judgment is deferred in order to continue associating. A state that promotes both imagery and free association.

CONCLUSION

The creative process is frequently triggered by the spontaneous and often surprising emergence of what is being named here as *primordial imagery*: a sudden, multimodal, multiintegrative, highly condensed representation that is germinative unleashing insight and multiple associations and possibilities for meaning. As evidenced in creativity, imagery is a process through which we perceive our own minds, allowing us further symbolization and access to our thoughts, possibly facilitating neural pathways.

ETHICS STATEMENT

All the procedures were performed in compliance with the relevant laws and institutional guidelines and were approved by the National Institute of Psychiatry "Ramón de la Fuente" (INPRF) Ethics and Scientific Committees. Informed consent was obtained and signed by all the subjects.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and approved it for publication.

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Where do bright ideas occur in our brain? Meta-analytic evidence from neuroimaging studies of domain-specific creativity

Maddalena Boccia[1,2], Laura Piccardi[2,3], Liana Palermo[2,4], Raffaella Nori[5] and Massimiliano Palmiero[3]*

[1] Department of Psychology, "Sapienza" University of Rome, Rome, Italy, [2] Neuropsychology Unit, I.R.C.C.S. Fondazione Santa Lucia of Rome, Rome, Italy, [3] Department of Life, Health and Environmental Sciences, University of L'Aquila, L'Aquila, Italy, [4] School of Life and Health Sciences, Aston University, Birmingham, UK, [5] Department of Psychology, University of Bologna, Bologna, Italy

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****Correspondence:***
Maddalena Boccia, Department of Psychology, "Sapienza" University of Rome, Via dei Marsi 78, 00185 Rome, Italy
maddalena.boccia@uniroma1.it

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Many studies have assessed the neural underpinnings of creativity, failing to find a clear anatomical localization. We aimed to provide evidence for a multi-componential neural system for creativity. We applied a general activation likelihood estimation (ALE) meta-analysis to 45 fMRI studies. Three individual ALE analyses were performed to assess creativity in different cognitive domains (Musical, Verbal, and Visuo-spatial). The general ALE revealed that creativity relies on clusters of activations in the bilateral occipital, parietal, frontal, and temporal lobes. The individual ALE revealed different maximal activation in different domains. Musical creativity yields activations in the bilateral medial frontal gyrus, in the left cingulate gyrus, middle frontal gyrus, and inferior parietal lobule and in the right postcentral and fusiform gyri. Verbal creativity yields activations mainly located in the left hemisphere, in the prefrontal cortex, middle and superior temporal gyri, inferior parietal lobule, postcentral and supramarginal gyri, middle occipital gyrus, and insula. The right inferior frontal gyrus and the lingual gyrus were also activated. Visuo-spatial creativity activates the right middle and inferior frontal gyri, the bilateral thalamus and the left precentral gyrus. This evidence suggests that creativity relies on multi-componential neural networks and that different creativity domains depend on different brain regions.

Keywords: creativity, musical improvisation, divergent thinking, verbal processing, visuo-spatial processing, idea generation, open-ended problems, executive functions

Introduction

The ability to form novel ideas is crucial for human civilization, progress, and innovation. Creativity has been defined as "the introduction of something innovatively new and positive for society that goes beyond the familiar and accepted" (Zaidel, 2014, p. 1) and concerns many domains of human activities (Gonen-Yaacovi et al., 2013), such as science, technology, economy, and arts. However, creativity concerns not only exceptional realizations, such as scientific discoveries or the production of artworks, but also everyday activities, such as finding new solutions and thinking away from ordinary ideas. Furthermore, creativity includes the appropriateness (Sternberg and Lubart, 1999; Runco and Jaeger, 2012) of the new ideas and solutions. The product of creativity must, in fact, involve an actual use in a specific context, rather than a hypothetical use.

Evolution has strongly fostered creativity. Bio-social pressures toward creativity are thought to have shaped the evolution of the human brain (Zaidel, 2014). Previous neuroimaging studies failed to find a clear neuroanatomical localization of creative processes (for a review, see Dietrich and Kanso, 2010; Mihov et al., 2010): creativity does not appear to critically rely on any single brain area and it is not especially associated with the right or left brain hemispheres (Dietrich and Kanso, 2010). The failure to find any clear neuroanatomical localization is likely due to the fact that creativity is a multifaceted process, which is supported by high-level mental operations, both independent (for example, abstraction; Welling, 2007) and dependent (for example, domain-specific operations) on the specific domains of knowledge. Palmiero et al. (2010) found that verbal creativity is mostly domain-specific, but can also be affected by processes in the visual domain, whereas visual creativity is domain- and task-specific. Various different approaches and tasks have been used to explore creativity. Some rely on the ability to find one correct solution to closed problems, such as insight problem solving, others rely on the ability to find new, appropriate, and different answers to open-ended problems, such as divergent thinking, creative cognition, and artistic creativity.

The divergent thinking approach was introduced by Guilford (1950, 1967). The Alternative Uses Task (AUT), which requires individuals to generate as many different alternative uses of a specific object (e.g., a brick) as possible, was initially used to assess divergent thinking in terms of ideational fluency (the number of ideas), flexibility (the number of categories that encompass ideas), originality (infrequency of ideas), and elaboration (the number of details added to basic ideas). In the wake of Guilford's (1950, 1967) work, Torrance (1974) developed the Torrance Test of Creative Thinking (TTCT), which was aimed at measuring divergent thinking in verbal and visual forms. Recently, the idea that divergent thinking is an indicator of creative potential without guaranteeing actual creative achievement has emerged (Runco and Acar, 2012). In addition, divergent thinking is supported by convergent thinking for the evaluation of the novelty of ideas (Cropley, 2006).

The creative cognition approach is mainly based on the 'Geneplore' model (Finke et al., 1992; Smith et al., 1995) that focuses on mental operations involved in visual creativity. This approach assumes that generative (e.g., memory retrieval, mental synthesis) and exploratory (e.g., conceptual interpretation, functional inference) processes support creativity. Specifically, generative processes support the construction of visual pre-inventive ideas, whereas exploratory processes examine and interpret the pre-inventive ideas. The Geneplore model was operationalized by means of the creative synthesis task (Finke, 1990, 1996), which allows individuals to imagine and manipulate visual elements (e.g., square, wire, and bracket), in order to create an object belonging to a specific category. Independent judges are then asked to score the inventions on the basis of different criteria, such as originality and practicality, according to the Consensual Assessment Technique developed by Amabile (1983). Investigations based on this Model have highlighted, among other things, that mental imagery – a complex cognitive process arising when perceptual information is accessed from the memory, giving rise to the experience of "seeing with the mind's eye" (Kosslyn, 1980; Farah, 1989) – seems to have a pivotal role in directing creative processes. This is confirmed by several scientific studies (e.g., Finke, 1990; Palmiero et al., 2011).

Artistic creativity has been described in terms of an altered state of mind, beyond conscious awareness (Dietrich, 2004). This makes it more difficult to investigate artistic creativity and its cognitive and neural underpinnings. In these last years, the neural processes underlying free generation and selection of possible alternatives have been investigated by using simpler model behaviors, which resemble valid examples of creativity in musical (Bengtsson et al., 2007) and visual domains (Kowatari et al., 2009).

Despite the variety of creativity domains, and of the approaches and tasks used, many pivotal processes supporting creativity can be identified. First, executive functions, such as planning, working memory, attention, and semantic memory retrieval are required. These processes facilitate both the selection (Gabora, 2010) and evaluation of the utility of novel ideas (Howard-Jones and Murray, 2003). Accordingly, the prefrontal cortex recruitment (e.g., the dorsolateral prefrontal cortex – DLPFC) has been widely shown as being involved in verbal divergent thinking based on ideational fluency (e.g., Carlsson et al., 2000; Seger et al., 2000), story generation (Bechtereva et al., 2004; Howard-Jones et al., 2005), metaphor production (Benedek et al., 2014a), creative objects production (Ellamil et al., 2012; Aziz-Zadeh et al., 2013), visual art (Kowatari et al., 2009; Huang et al., 2013), and musical improvisation (e.g., de Manzano and Ullén, 2012; Villarreal et al., 2013; Pinho et al., 2014). Second, creativity also relies on an associative mode of processing (Ellamil et al., 2012), which is supported by the default mode network (e.g., the medial prefrontal and posterior cingulate cortices, temporoparietal junction, part of the medial temporal lobe and the inferior parietal cortex – Buckner et al., 2008). Interestingly, the default mode network is activated during different creativity performances (e.g., Bechtereva et al., 2004; Howard-Jones et al., 2005). Third, memory processes also support creativity. The medial temporal lobe (hippocampal and parahippocampal regions) is recruited during verbal divergent thinking (Fink et al., 2009), creative writing (Shah et al., 2013), metaphor production (Benedek et al., 2014a), visual creativity (Ellamil et al., 2012), and visual art (Kowatari et al., 2009). According to Dietrich (2004) the connections between the dorsolateral prefrontal cortex and the temporal, occipital and parietal cortices, sites of long-term memory storage (e.g., Gilbert, 2001), are essential for creativity. Furthermore, brain areas generally involved in mental imagery, such as the middle occipital gyrus and parietal lobes (Sack et al., 2005; Olivetti Belardinelli et al., 2009; Boccia et al., 2015), can be recruited during creativity, suggesting a top–down control on the construction of the images, even if visual information is not directly manipulated.

Here we aimed to find the neural correlates of creativity in general and those more strictly correlated with the cognitive domain. In the present study creativity is operationally defined as the ability to find new, appropriate, and different answers to open-ended problems, focusing on the idea that a valid assessment of creativity requires tasks that are sufficiently open-ended to encourage divergent production (Green et al., 2015). We applied a general activation likelihood estimation (ALE) meta-analysis of fMRI experiments on creativity based on open-ended mental problems, to find converging evidence for a neural network for creativity in the human brain. Furthermore, three individual ALE analyses were performed to assess whether creativity in different domains (i.e., Musical, Verbal, and Visuo-spatial) involves different brain areas. The decision to explore Musical, Verbal, and Visuo-spatial creativity was made because these were the only domains in which the number of experiments and critical contrasts was sufficient for statistical testing.

Following Dietrich and Kanso's (2010, p. 822) idea of functionally subdividing different types of creativity "to make creativity tractable in the brain," we hypothesized that, beyond a common pattern of brain activations generally underpining idea generation in the attempt to solve open-ended problems, different brain regions underpin different domains of creativity and that a multi-componential neural system underpins creative thinking in humans.

Materials and Methods

Inclusion Criteria for Papers

A systematic method was adopted to review the literature. The search was carried out with the aid of PubMed, using the following string: "creativity and fMRI." A total of 56 studies were found.

Our *a priori* inclusion criteria for papers were: (1) Inclusion of whole-brain analysis performed using functional magnetic resonance imaging (fMRI); thus, we excluded positron emission tomography (PET) studies, electrophysiology studies and papers that reported only results from ROI analysis. (2) Provision of coordinates of activation foci, both in the Montreal Neurological Institute (MNI) and the Talairach reference space. (3) All participants in the studies had to be young and healthy. (4) Only studies focusing on open-ended mental problems were included in the meta-analysis; thus we excluded studies exploring neural correlates of idea generation based on closed-ended problems, such as problems based on the combination of remote semantic associations, which generally underpin insight (a stage of the creative process) rather than creativity *per se*. This decision was made following the idea that the "rigorous investigation of creativity requires tasks that are suitable for quantified psychometrics but also sufficiently open-ended to be construct-valid assays of creativity (i.e., they must allow freedom for divergent production)" (Green et al., 2015, p. 924). (5) Only group studies involving a sample size of at least five participants were included. (6) There could be no pharmacological manipulation. (7) Only activation foci were considered. Thus, studies reporting only deactivation foci were excluded from our meta-analysis. (8) Only peer-reviewed original articles were included. Using these criteria we selected 24 articles. The studies are summarized in **Table 1**, where the subdivision according to domains (Musical, Verbal, and Visuo-spatial) is also shown (see below).

Activation Likelihood Estimation

The coordinates from studies identified in 24 published papers were used for ALE, which models the uncertainty in the localization of activation foci using Gaussian probability density distributions (Fox et al., 2014). In other words, ALE assesses the overlap between foci by modeling the probability distributions centered at the coordinates of each one (Eickhoff et al., 2009). This is calculated at each voxel and results in a thresholded ALE map. The probabilities of all activation foci in a given experiment were combined for each voxel, yielding a modeled activation map (Turkeltaub et al., 2012). ALE scores quantified the convergence across experiments at each particular location in the brain. ALE scores were compared against an empirical null distribution reflecting a random spatial association between the model activation maps (Eickhoff et al., 2009).

We performed a general ALE meta-analysis on the foci derived from the selected studies (**Table 1**). The coordinates of the foci were taken from the original papers. A total of 492 foci were reported in 45 experiments involving 1007 participants.

We also performed three separate ALE analyses to assess the neural correlates of creativity in different cognitive domains (i.e., Musical, Verbal, and Visuo-spatial). The experimenters (Maddalena Boccia, Laura Piccardi, Liana Palermo, Raffaella Nori, and Massimiliano Palmiero) independently classified the studies. Studies including different cognitive domains were excluded from these analyses: the data from these studies were included in the general analysis but not in the further analyses. Separate ALE analyses were performed on (1) 13 studies assessing musical creativity (219 participants, 197 activation foci), (2) 24 studies assessing verbal creativity (575 participants, 207 activation foci), and (3) six studies assessing visuo-spatial creativity (164 participants, 52 activation foci).

The ALE meta-analysis was performed using GingerALE[1] 2.3.1 with MNI coordinates (Talairach coordinates were automatically converted into MNI coordinates by GingerALE), according to Eickhoff et al.'s (2009) procedure. The Full-Width Half-Maximum (FWHM) value was automatically computed, as this parameter is empirically determined (Eickhoff et al., 2009). The thresholded ALE map was corrected for multiple comparisons using False Discovery Rate (FDR), at a 0.05 level of significance. Moreover, a minimum cluster size of 200 mm^3 was chosen. The ALE results were registered on an MNI-normalized template[1] using MRICRO. Hereafter the link to access MRICRO[2].

Tasks and Contrasts Taken into Account

Regarding the musical domain, participants were instructed to improvise music of various kinds (Classical, Jazz, etc.) on simple piano keyboards designed for usage in the scanner. In particular, music improvisation performed by modification of a melodic template was contrasted with the memorized improvisation

[1] http://www.brainmap.org

[2] http://www.mccauslandcenter.sc.edu/mricro/index.html

TABLE 1 | List of papers included in the meta-analysis for each domain.

Paper	Experiments	Subjects	Approach	Task
Musical domain				
Bengtsson et al. (2007)	1	11	Artistic creativity	Melody Improvisation (Piano)
Berkowitz and Ansari (2008)	3	12	Artistic creativity	Melody and Rhythmic Improvisation
de Manzano and Ullén (2012)	2	18	Artistic creativity	Melody Improvisation
Limb and Braun (2008)	2	6	Artistic creativity	Melody Improvisation (Scale/Jazz)
Liu et al. (2012)	1	12	Artistic creativity	Lyric Improvisation
Pinho et al. (2014)	2	39	Artistic creativity	Musical Improvisation (Classical/Jazz Piano): Tonal/Atonal; Happy/Fearful
Villarreal et al. (2013)	2	24	Artistic creativity	Rhythmic Creation A synthetic sound was used with a timbre similar to sound produced by the cymbal
Verbal domain				
Abraham et al. (2012)	1	19	Divergent Thinking	Alternative Uses
Abraham et al. (2014)	4	28	Divergent Thinking	Alternative Uses
Benedek et al. (2014a)	2	35	Divergent Thinking	Metaphor production
Benedek et al. (2014b)	3	28	Divergent Thinking	Alternative Uses
*Chrysikou and Thompson-Schill (2011)	1	24	Divergent Thinking	Alternative Uses
Fink et al. (2010)	1	31	Divergent Thinking	Alternative Uses in three conditions: Standard, Incubation, Exposure to other people's ideas
Fink et al. (2012)	3	24	Divergent Thinking	Alternative Uses stimulated by other people's ideas
*Green et al. (2015)	1	55	Divergent Thinking	Verb Generation
*Howard-Jones et al. (2005)	2	8	Divergent Thinking	Creative Story Generation
Seger et al. (2000)	1	7	Divergent Thinking	Unusual Verb Generation cued by novel and repeated nouns
*Shah et al. (2013)	3	28	Divergent Thinking	Planning and Writing a Story
*Zhang et al. (2014)	2	18	Divergent Thinking	Inventive Conception Generation involving remote semantic relatedness
Visuo-spatial domain				
*Asari et al. (2008)	1	68	Divergent Thinking	Generating unusual answers to Rorschach Figures
Aziz-Zadeh et al. (2013)	1	13	Creative Cognition	Creative Synthesis Task
Ellamil et al. (2012)	1	15	Creative Cognition	Designing book cover illustrations
*Huang et al. (2013)	1	28	Divergent Thinking	Imaging pictures visually cued
Kowatari et al. (2009)	2	20	Artistic creativity	Designing new pens

Studies marked with an asterisk are based on the divergent thinking approach, but participants were instructed to generate only one response rather than providing many different responses to the same problem (standard divergent thinking task requires ideational fluency).
Studies on artistic creativity enrolled professional artists, such as pianists, or subjects with artistic training.

previously made (Bengtsson et al., 2007); music improvisation using notes within the C major scale with over-learned tracks (Limb and Braun, 2008); lyric improvisation using an 8-bar instrumental track at 85 beats per minute with the memorized lyrics (Liu et al., 2012); melody improvisation and pseudo-random key presses production with sight reading of a musical score (de Manzano and Ullén, 2012); rhythmic (note choice constrained) and melody (note choice free) improvisation with or without metronome click synchronization with the reproduction of simple pre-learned 5-note patterns (Berkowitz and Ansari, 2008); rhythm improvisation (based on a rhythm listened to) with the reproduction of the rhythm heard (Villarreal et al., 2013); music improvisation (tonal, atonal, happy, and fearful) with the rest condition (Pinho et al., 2014).

Regarding the verbal domain, the ability to find alternative uses for an object, such as 'a brick' (AUT), was contrasted with fluency objects for location (indicating different objects in a specific place, such as an office), using the AU vs. 2-back memory (Abraham et al., 2012) as inclusive mask; the AUT with the fluency object for location and both these tasks with 1- and 2-back memory tasks in males vs. females and vice versa (Abraham et al., 2014). Furthermore, new ideas (unknown) provided by the AUT were contrasted with old ideas (recruited from the memory), and both new/old ideas vs. zero (Benedek et al., 2014b), whereas common or uncommon uses of objects were contrasted with a perceptual baseline task (Chrysikou and Thompson-Schill, 2011). The AUT was also contrasted with the object characteristic task (find typical characteristics of objects), the Incubation-AUT (reflect on ideas and elaborate them) with the standard AUT and vice versa, the Stimulation-AUT (the stimulus word was presented with three other people's ideas) with the standard AUT (Fink et al., 2010); the Stimulation-AUT (original/common ideas of other people) with the control condition (the stimulus word was presented with two pseudowords) and the Stimulation-AUT (original) with Stimulation-AUT (common), (Fink et al., 2012). In addition, the generation of metaphor was contrasted with the production of literal responses (synonyms of adjectives; Benedek et al., 2014a); the unusual or creative generation of verbs in response to specific nouns with the generation of verbs that first came to mind (Seger et al., 2000) or with uncreative verbs (Green et al., 2015); the generation of creative stories from three words with uncreative stories and the generation of stories from unrelated words with stories from related words in the set (Howard-Jones et al., 2005); the creative writing was contrasted with the copying of a given text (Shah et al., 2013); the generation of inventive conceptions (biological functional feature associations) with ordinary conceptions (non-biological functional feature associations) and with baseline (Zhang et al., 2014).

Regarding the visuo-spatial domain, the generation of unique responses to Rorschach's test was contrasted with the generation of frequent responses (Asari et al., 2008); the creative synthesis task (combination of three shapes, such as a circle, an '8' and a 'C, to form a creative object) with the reconstruction of a shape by combining three distinct stimuli in which the original shape was trisected (Aziz-Zadeh et al., 2013); the generation of ideas while designing book cover illustrations with the evaluation of ideas generated (Ellamil et al., 2012); the generation of creative pictures based on given visual clues with the generation of uncreative figures not necessarily unique (Huang et al., 2013). Finally, Kowatari et al. (2009) explored the neural correlates of designing of a new pen in experts and novices.

Results

Neural Correlates of Creativity

The general ALE meta-analysis showed clusters of activations ranging from the occipital to the frontal lobe (**Table 2**), in both the left and the right hemispheres (**Figure 1**). Specifically, we found consistent activations in the bilateral inferior, middle and medial frontal gyri as well as in the bilateral middle occipital gyrus. In the left hemisphere we found consistent activations in the precentral gyrus, superior frontal gyrus, inferior parietal lobule, supramarginal gyrus, insula, cingulate gyrus, and middle temporal gyrus. In the right hemisphere we found clusters of activation in the superior temporal gyrus. We also found consistent activation in the right posterior cerebellum.

Neural Correlates of Musical Creativity

The ALE meta-analysis performed on studies assessing musical creativity showed clusters of activation in the bilateral medial

TABLE 2 | Regions showing consistent activations across fMRI studies of creativity, as resulting from the general activation likelihood estimation (ALE) analysis.

Region	Hem[a]	BA[b]	ALE extrema value	Cluster size[c]	x[d]	y	z
Insula	L	13	0.027	5896	−44	18	−2
Middle frontal gyrus	L	6	0.024		−38	6	44
Middle frontal gyrus	L	6	0.023		−40	2	50
Inferior frontal gyrus	L	9	0.022		−44	8	20
Middle frontal gyrus	L	9	0.022		−50	18	24
Precentral gyrus	L	6	0.019		−52	4	48
Precentral gyrus	L	6	0.018		−38	6	32
Precentral gyrus	L	44	0.017		−48	16	8
Insula	L	13	0.016		−34	24	0
Superior frontal gyrus	L	6	0.026	2408	−6	18	48
Medial frontal gyrus	L	6	0.025		−2	8	60
Middle temporal gyrus	L	22	0.025	2032	−48	−40	6
Supramarginal gyrus	L	40	0.026	1568	−48	−52	24
Supramarginal gyrus	L	40	0.024		−54	−50	32
Middle frontal gyrus	R	9	0.027	872	48	18	26
Middle occipital gyrus	L	18	0.022	840	−22	−90	−4
Middle occipital gyrus	L	18	0.019		−30	−90	2
Inferior orbitofrontal cortex/insula	R	47	0.022	776	42	24	−8
Inferior frontal gyrus	R	47	0.016		40	32	−12
Cingulate gyrus	L	32	0.021	760	−2	28	32
Medial frontal gyrus	R	6	0.040	520	12	−14	78
Middle occipital gyrus	R	18	0.019	424	22	−90	−2
Inferior parietal lobule	L	40	0.031	368	−66	−28	32
Posterior cerebellum	R		0.022	320	6	−50	−38
Middle frontal gyrus	L	8	0.024	272	−36	44	36
Middle frontal gyrus	R	6	0.018	272	28	0	50
Inferior frontal gyrus	L	46	0.019	248	−36	36	8
Superior temporal gyrus	R	22	0.021	224	52	−28	0

[a]*Hemisphere;* [b]*Brodmann's areas if applicable;* [c]*Cluster volume (mm^3);* [d]*MNI coordinates.*

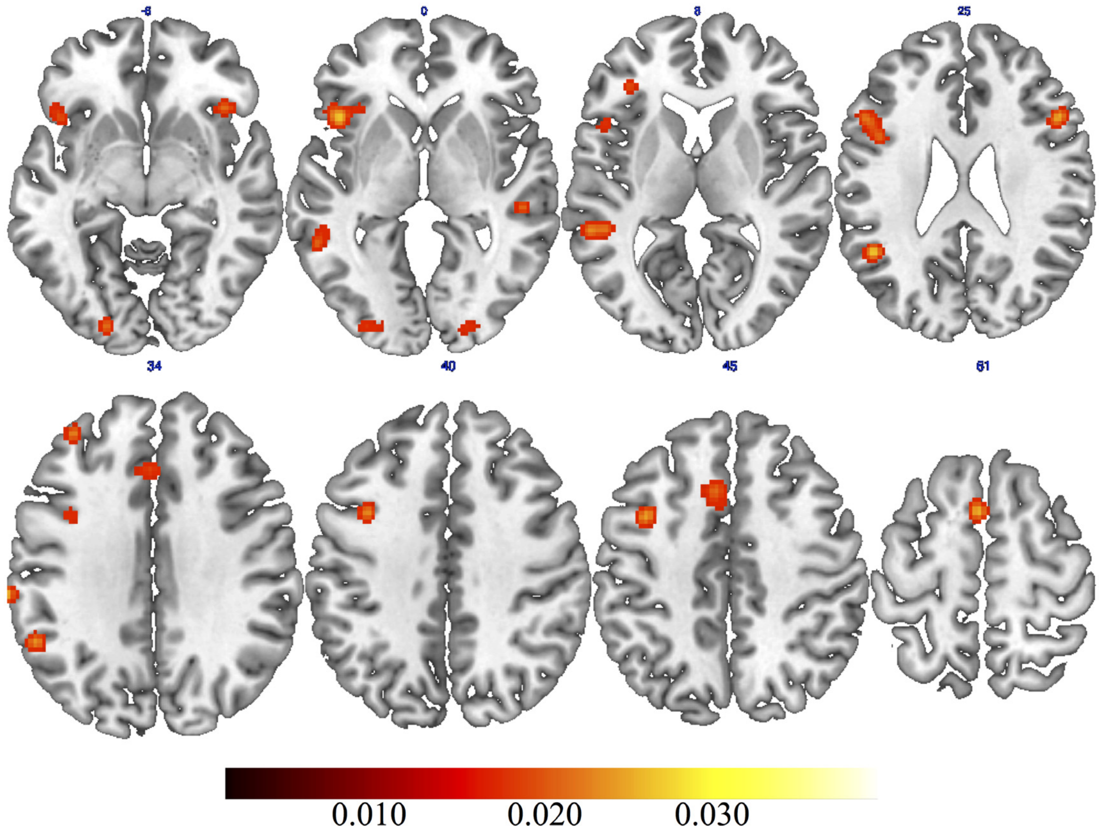

FIGURE 1 | Results of general activation likelihood estimation (ALE) meta-analysis on creativity.

frontal gyrus (**Figure 2**). Consistent activations were also found in the cingulate gyrus, middle frontal gyrus and inferior parietal lobule in the left hemisphere (**Figure 2**). In the right hemisphere we found activation in the postcentral and fusiform gyri (**Figure 2**). Furthermore, we found cerebellar activations, in the anterior lobe of the left hemisphere and in the posterior lobe of the right hemisphere (**Table 3**).

Neural Correlates of Verbal Creativity

The ALE meta-analysis performed on studies assessing verbal creativity showed clusters of activations mainly located in the left hemisphere (**Table 4**). We found consistent activation in the inferior and middle frontal gyri, middle and superior temporal gyri, inferior parietal lobule, postcentral and supramarginal gyri, middle occipital gyrus, and insula in the left hemisphere (**Figure 2**). We also found activation in the inferior frontal gyrus and lingual gyrus of the right hemisphere (**Figure 2**) as well as in the right posterior cerebellum.

Neural Correlates of Visuo-Spatial Creativity

The ALE meta-analysis performed on studies assessing visuo-spatial creativity showed clusters of activation in the middle and inferior frontal gyri of the right hemisphere as well as in the bilateral thalamus (**Table 5**). We also found consistent activation in the left precentral gyrus (**Figure 2**).

Discussion

The main aim of the present study was to find converging evidence for a multi-componential neural system for creativity based on open-ended mental problems in different cognitive domains. First of all, we performed a general ALE analysis to give a general picture of the brain networks involved in creativity. Then three separate ALE analyses were performed in order to assess the neural correlates of creativity in Musical, Verbal, and Visuo-spatial domains. We found a wide network of areas, ranging from the occipital to the frontal lobe, in both left and right hemispheres. A functional specialization was found within this network for different types of creativity, confirming Dietrich and Kanso's (2010, p. 822) idea that distinguishing different types of creativity is valuable "to make creativity tractable in the brain." This is also in line with the hypothesis of the existence of a functional multi-componential system in the human brain for creative thinking. Even if previous quantitative meta-analyses on creativity have been made (Gonen-Yaacovi et al., 2013), to our knowledge this is the first meta-analysis clearly disentangling the brain regions underpinning musical, verbal, and visuo-spatial creativity, based on the generation of creative solutions to open-ended problems.

Specifically, the recruitment of executive functions is crucial for creativity. The activations found in the left anterior cingulate

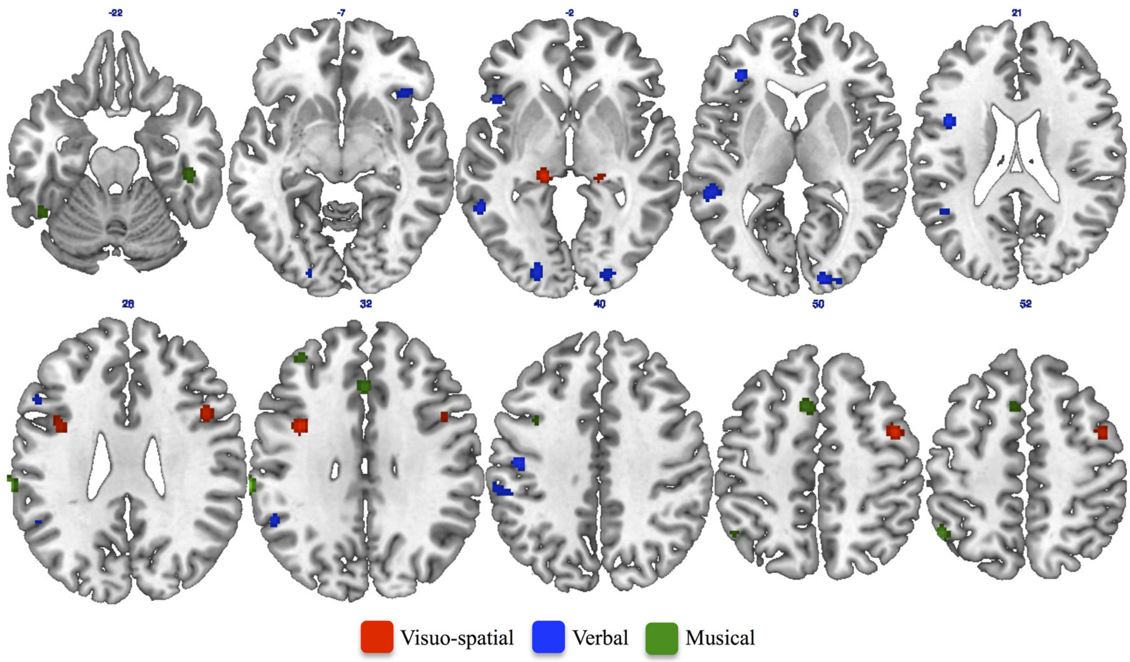

FIGURE 2 | Results of single ALE meta-analysis on studies assessing Musical (green patches), Verbal (blue patches), and Visuo-spatial (red patches) creativity.

TABLE 3 | Regions showing consistent activations across fMRI studies of musical creativity.

Region	Hem[a]	BA[b]	ALE extrema value	Cluster size[c]	x^d	y	z
Medial frontal gyrus	R	6	0.040	640	12	−14	78
Posterior cerebellum	R		0.022	512	4	−50	−38
Medial frontal gyrus	L	32	0.018	456	−6	16	48
Inferior parietal lobule	L	40	0.030	368	−66	−30	30
Middle frontal gyrus	L	8	0.024	360	−36	44	36
Fusiform gyrus	R	20	0.016	344	46	−28	−22
Cingulate gyrus	L	32	0.017	336	0	28	32
Inferior parietal lobule	L	40	0.025	272	−48	−56	54
Middle frontal gyrus	L	6	0.015	240	−36	8	42
Anterior cerebellum	L		0.015	200	−46	−52	−22
Postcentral gyrus	R	7	0.020	200	20	−48	76

[a]*Hemisphere;* [b]*Brodmann's areas if applicable;* [c]*Cluster volume* (mm^3)*;* [d]*MNI coordinates.*

cortex (ACC), as well as in the bilateral inferior frontal gyri and middle frontal gyri (DLPFC), may be strictly connected to "more executive" aspects of creativity, since these areas are activated during conditions of high cognitive control (Miller and Cohen, 2001). In particular, activation of the DLPFC is correlated with effortful problem-solving, monitoring, and focused attention (Ashby et al., 1999). DLPFC also plays a key role in the selection process (Nathaniel-James and Frith, 2002), being linked to extra working memory load due to keeping in mind different alternatives (Bookheimer, 2002) and comparing many different stimuli. Thus, although these processes were not directed tested, it is not surprising that the DLPFC was found to be consistently activated during Musical (right hemisphere), Verbal (left hemisphere), and Visuo-spatial (right hemisphere) creativity, which generally require effortful problem solving, focused attention, selection process and working memory.

Concerning specific-domain activations, we found that verbal creativity consistently activated the left inferior frontal gyrus. Since verbal creativity has been reported to require the ability to integrate distant semantic concepts or ideas in a new fashion (Benedek et al., 2012; Benedek and Neubauer, 2013; Zhang et al., 2014), by means of semantic retrieval and selection of stored knowledge (Thompson-Schill et al., 1997; Seger et al., 2000; Badre et al., 2005; Moss et al., 2005; Badre and Wagner, 2007), these processes may well have entailed the activation of the left inferior frontal gyrus. On the other hand, attentional processes (Zhang and Li, 2012) and successful response inhibition (e.g., Aron et al.,

TABLE 4 | Regions showing consistent activations across fMRI studies of verbal creativity.

Region	Hem[a]	BA[b]	ALE extrema value	Cluster size[c]	x[d]	y	z
Middle temporal gyrus	L	22	0.014	1360	−54	−38	4
Superior temporal gyrus	L	22	0.014		−56	−40	10
Middle temporal gyrus	L	22	0.014		−56	−48	0
Lingual gyrus	R	17	0.014	928	18	−94	4
Middle temporal gyrus	L	39	0.014	560	−56	−56	10
Superior temporal gyrus	L	22	0.013	520	−46	−52	22
Supramarginal gyrus	L	40	0.013		−52	−50	32
Middle occipital gyrus	L	18	0.015	472	−20	−90	−4
Inferior frontal gyrus	L	45	0.013	440	−46	20	0
Middle frontal gyrus	L	9	0.014	416	−52	20	24
Insula	L	13	0.016	336	−42	6	20
Postcentral gyrus	L	3	0.016	336	−46	−16	42
Insula	R	47	0.012	280	40	24	−8
Inferior frontal gyrus	R	47	0.011		36	22	−10
Inferior frontal gyrus	L	46	0.015	272	−34	36	6
Inferior parietal lobule	L	40	0.012	264	−60	−30	38
Inferior parietal lobule	L	40	0.011		−52	−34	40
Posterior cerebellum	R		0.014	248	32	−82	−32
Inferior frontal gyrus	L	47	0.011	200	−26	30	−20
Inferior frontal gyrus	L	47	0.010		−36	28	−20

[a]*Hemisphere;* [b]*Brodmann's areas if applicable;* [c]*Cluster volume (mm^3);* [d]*MNI coordinates.*

TABLE 5 | Regions showing consistent activations across fMRI studies of visuo-spatial creativity.

Region	Hem[a]	BA[b]	ALE Extrema value	Cluster size[c]	x[d]	y	z
Precentral gyrus	L	6	0.013	584	−38	4	32
Thalamus	L		0.013	464	−16	−28	−2
Middle frontal gyrus	R	6	0.013	464	44	2	50
Inferior frontal gyrus	R	9	0.011	368	45	12	28
Thalamus	R		0.009	232	18	−30	−2
Thalamus	R		0.009		24	−28	2

[a]*Hemisphere;* [b]*Brodmann's areas if applicable;* [c]*Cluster volume (mm^3);* [d]*MNI coordinates.*

2014) may entail activations of the right inferior frontal gyrus. However, these activations were found both during verbal and visuo-spatial creativity, but not during musical improvisation, which seems to rely more upon response inhibition. Thus, although one might claim that the inhibition of competitive responses during the creative act is supported by the right inferior frontal gyrus, the functional role of this area while performing on musical, verbal or visuo-spatial creativity tasks needs to be more fully addressed.

The high cognitive control during musical and verbal creativity also induced activations of the left inferior parietal lobule. Hemispheric specialization has been proposed for this area. Specifically, verbal attention (Jordan et al., 2001), and language-related processes with a focus on semantic and phonological issues (Vigneau et al., 2006) were found to recruit the left inferior parietal lobule, which also belongs to the default mode network (Buckner et al., 2008). Furthermore, although the activations of the left inferior parietal lobule, supramarginal gyrus and insula shown by the general ALE analysis might also indicate multimodal sensory processing and the representation of subjective experience during spontaneous creativity (Csikszentmihalyi, 1996), further study is necessary to better clarify this issue.

Interestingly, musical and visuo-spatial creativity activate regions involved in motor planning, such as the right supplementary and the left premotor cortices, probably indicating that a motor and temporal planning is crucial for creative musical improvisation (Brown et al., 2006; Bengtsson et al., 2007; Berkowitz and Ansari, 2008; Limb and Braun, 2008; Pinho et al., 2014), as well as in the visuo-spatial rotation of objects (Milivojevic et al., 2009) during visuo-spatial creativity.

The posterior activations found in the temporal (left middle temporal gyrus and right superior temporal gyrus) and occipital (bilateral middle occipital gyrus) lobes across different creativity domains deserve consideration. According to Dietrich (2004), the posterior cortices are essential for creativity, being the sites of long-term memory storage (e.g., Gilbert, 2001) and being connected to the prefrontal cortex. Therefore, given that creativity relies on an associative mode of processing, heightening focused attention to stored knowledge that facilitates efficient retrieval and recombination of existing information (Fink et al., 2012), the activation of the posterior cortices may be the neural correlates of such processes. Moreover, given that these areas have a pivotal role in generating mental images (Kosslyn and Thompson, 2003), these results could also support the relationship between creative processes and mental imagery. Specifically, according to the Perceptual Anticipation Theory, mental images arise when an individual "anticipates perceiving an object or scene so strongly that a depictive representation of the stimulus is generated in early visual cortex" (Kosslyn and Thompson, 2003; p. 724). Thus, it may be that information stored in the long-term memory is selectively retrieved and used to form mental images, which subtend the generation of creative ideas. Other brain areas are then needed to explore and finalize ideas in different cognitive domains. In this direction, musical creativity showed the activation of the right fusiform gyrus and parietal postcentral gyrus, whereas verbal creativity showed the recruitment of the left middle and superior temporal gyri, right lingual gyrus, left middle occipital gyrus, and left parietal postcentral gyrus.

Finally, the right posterior cerebellum was recruited in both verbal and musical creativity, indicating searching processes for appropriate responses (Seger et al., 2000). Such a result suggests that the cerebellum may have an important role in creativity. Indeed, by permitting previously executed movements, which have been proved to be advantageous, the cerebellum allows individual motor sequences to be consolidated into more complex patterns underlying the generation of novel creative outcomes (Cotterill, 2001). However, due to the lack of systematic studies on this issue, the specific role of the cerebellum in creativity is still unclear.

Conclusion

The results of the present meta-analysis of fMRI studies of creatvity based on open-ended problems in musical, verbal, and visuo-spatial domains suggest that different domains of creativity roughly correspond to a higher activation in functionally specialized brain areas. In general, frontal areas seem to be crucial for idea generation, although there are slight differences across creativity domains. Activation of the DLPFC was found in all creativity domains under investigation, whereas the inferior frontal gyrus was recruited consistently in verbal creativity and weakly in visuo-spatial creativity. This finding suggests that creativity relies on the activation of the prefrontal cortex, which likely works as an executive engine, managing attentional recourses, retrieving, and selecting appropriate information. Future studies should take into account the 'gateway hypothesis' (Burgess et al., 2007), which highlights the role of the rostral prefrontal cortex on attending behavior that enhances the ability to notice change in the environment (stimulus-oriented cognition) as well as on self-generated or maintained representations (stimulus-independent cognition). Focusing on this latter ability, the lateral rostral prefrontal cortex would work as a 'gateway' between the process of selection of actions or thought operations and the stimulus-independent attending system, ensuring that activation of representations is less affected by sensory input. This is exactly the case of creativity, which is mainly based on stimulus-independent processes, retrieval of information from the memory and selection of the most appropriate responses to satisfy specific criteria, such as originality and appropriateness. Unfortunately the gateway hypothesis has never been directly tested by means of a paradigm investigating creativity.

Interestingly, part of the default network (the left inferior parietal lobule) and different temporal, parietal, and occipital areas were found to be recruited while performing on musical and verbal creativity, but not when performing on visual creativity. Also the right posterior cerebellum was activated during both musical and verbal creative processes. Thus, the present meta-analysis would seem to indicate that musical and verbal creativity share common areas that involve attentional, searching, and associative modes of processing of stored knowledge from the posterior cortices, and temporarily represent information in the working memory buffer with the aid of prefrontal areas. On the contrary, visuo-spatial creativity would appear to rely consistently on the perception and manipulation of visual stimuli, such as the rotation of shapes; in this direction, visuo-spatial creativity strongly yielded activations in the bilateral thalamus and premotor cortices, the former being involved in relaying sensory information, the latter in finalizing in a top–down fashion the goal-directed planning of novel ideas. However, it is surprising that visuo-spatial creativity did not produce the activation of any temporal, parietal, and above all occipital regions, considering that the recruitment of these areas was reported in various studies of visual creativity (e.g., Huang et al., 2013). Probably, given the scarcity of the number of experiments (6–164 participants, 52 activation foci) belonging to the visuo-spatial domain, the ALE analysis did not highlight these results, thus making the findings somewhat less reliable.

Therefore, generally speaking, creativity seems to emerge when the prefrontal cortex, posterior temporal, and parietal areas are recruited. This is also confirmed by studies with dementia patients (for a review, see Palmiero et al., 2012), who show a decline in divergent thinking and artistic creativity when these areas are damaged. On the other hand, it is possible that, since all the studies we included in the ALE meta-analysis checked for early visuo-spatial features by using well-designed control conditions, the ALE statistics only showed brain areas more related to general visuo-spatial creative processes, such as premotor regions supporting mental rotation of stimuli, rather than to visual properties *per se*. This is also true in the case of musical creativity, in which we found no activation of the auditory cortex. It should be stressed, though, that all the included studies compared activations during a creative condition (usually assessed by means of musical improvisation) with those during a control condition (usually assessed by means of the reproduction of conventional pieces). The failure to find any activation of the auditory cortex is likely due to the fact that this area is generally involved in musical and auditory processes but it is not directly entailed in musical creativity.

Regarding the lateralization issue, the unbalanced number of studies across the domains could account for the activations mainly of the left hemisphere in the general ALE analysis. However, looking at the separate ALE analyses, musical and verbal creativity showed predominant activations in the left hemisphere, whereas visuo-spatial creativity in the right hemisphere, but a clear laterality effect was not found. This suggests that inter-hemispheric interaction is required in all domains of creative processes (Dietrich and Kanso, 2010) and supports the idea that creative processes are subtended by different brain areas and functional specialized brain regions rather than by a specific brain area.

Finally, on the basis of the findings outlined above, creativity appears to be a multifaceted process, involving different mental functions, and studied using different approaches and tasks. Although the number of experiments and critical contrasts in each category separately is, at present, insufficient for statistical testing, in the future, in order to reach more reliable conclusions, neural correlates of creativity should be studied considering the interaction among the domains, approaches and tasks used. A higher number of studies will also allow for a contrast analysis and a conjunction analysis among different creativity domains, now impossible due to the paucity of the studies. Different creativity domains should also be explored, such as dance and scientific innovation. Of course this meta-analysis was not aimed at determining the specific executive, default and memory processes supported by cerebral regions during creativity. Further studies should therefore explore whether and how idea generation and evaluation emerge in different creativity domains.

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Measuring creative imagery abilities

*Dorota M. Jankowska and Maciej Karwowski**

Creative Education Lab, Department of Educational Sciences, The Maria Grzegorzewska University, Warsaw, Poland

Over the decades, creativity and imagination research developed in parallel, but they surprisingly rarely intersected. This paper introduces a new theoretical model of creative visual imagination, which bridges creativity and imagination research, as well as presents a new psychometric instrument, called the Test of Creative Imagery Abilities (TCIA), developed to measure creative imagery abilities understood in accordance with this model. Creative imagination is understood as constituted by three interrelated components: vividness (the ability to create images characterized by a high level of complexity and detail), originality (the ability to produce unique imagery), and transformativeness (the ability to control imagery). TCIA enables valid and reliable measurement of these three groups of abilities, yielding the general score of imagery abilities and at the same time making profile analysis possible. We present the results of nine studies on a total sample of more than 1700 participants, showing the factor structure of TCIA using confirmatory factor analysis, as well as provide data confirming this instrument's validity and reliability. The availability of TCIA for interested researchers may result in new insights and possibilities of integrating the fields of creativity and imagination science.

Keywords: creative imagination, vividness, originality, transformativeness, TCIA

Edited by:
Massimiliano Palmiero, University of L'Aquila, Italy

Reviewed by:
Martina Rieger, University for Health Sciences, Medical Informatics and Technology, Austria
Darya Zabelina, Northwestern University, USA
Luis M. Martinez, Spanish National Research Council, Spain

****Correspondence:***
Maciej Karwowski
mackar@aps.edu.pl

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INTRODUCTION

Imagination pervades human experience. The activity of visual imagination encompasses creating, interpreting, and transforming vivid mental representations (Thompson et al., 2011). Its creative function, which stems from engagement in the creative process, is most often discussed in connection with the imaginary games of childhood (Singer and Singer, 1992; Hoff, 2005) as well as artistic and scientific work (Rothenberg, 1995; Root-Bernstein, 2014). However, the belief that creative imagination is one of the major human abilities contributing to the effective use of the creative potential (Runco et al., 1998) is not a matter of recent years only. The first documented study on imagination was conducted among scientists nearly one and a half centuries ago (Galton, 1880), and with the development of research on creativity test instruments measuring visual creative imagination were created. However, the existing tests do not take into account the complexity of creative imagination, which became an impulse for developing the Test of Creative Imagery Abilities (TCIA), whose theoretical assumptions as well as selected aspects of validity and reliability we present in this paper. The instrument we propose enables profile analysis of visual creative imagination, thereby treating imagination as a complex and multidimensional disposition comprising specific characteristics (vividness, originality, transformative ability) distinguished in the conjunctional model of creative imaging ability. In this model, creative imagination is defined as ability to create and transform representations that are based on the material of past observations but that significantly transcend them—by creating the so-called creative representations (see Dziedziewicz and Karwowski, 2015; **Figure 1**). Although creative imagination understood in this

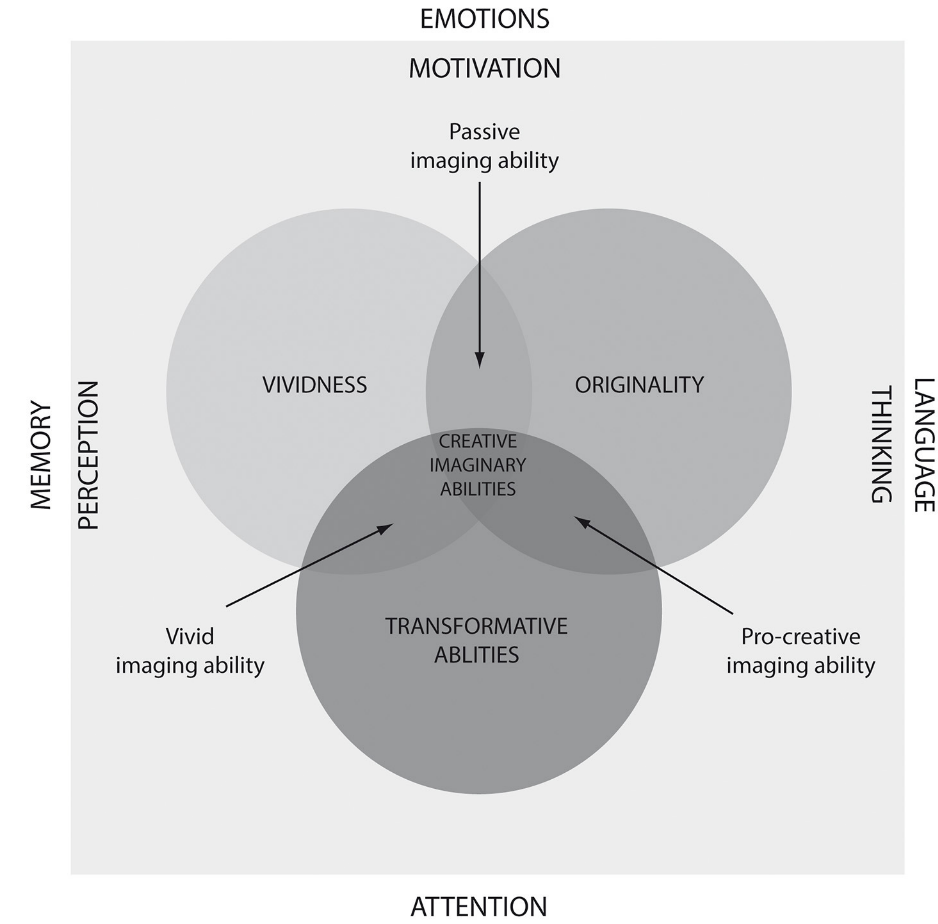

FIGURE 1 | The conjunctional model of creative imaging ability.

way is part of the broad construct of creative cognition (Finke et al., 1992), we perceive creative imagination in a more narrow way, than we do creative cognition.

Problems with Measures of Creative Imagination

Test-based research on creativity originated with Guilford's (1950) theory of divergent thinking. With time, Guilford's tasks measuring the characteristics of divergent thinking gave rise to numerous tests, such as the Torrance Tests of Creative Thinking (TTCT; Torrance, 1974) or Thinking Creatively in Action and Movement (TCAM; Torrance, 1981). For many years, this tradition of creativity research remained the dominant approach. And even though imagination measurement in psychology and related sciences has a longer tradition than research on divergent thinking (Galton, 1880), it was the post-Guilfordian orientation that exerted considerable influence on the testing of creative imagination, not the other way around. The influence was so strong that the contribution of creative imagination was included in the first tests for the assessment of divergent thinking, an example being the "Imaginative Stories Task" in the Minnesota Test of Creative Thinking (MCTC; Torrance, 1962; Goldman, 1965; Millar, 2002), the original version of TCAM. The combination of these abilities in divergent thinking resulted in a blurring of the concept of imagination, previously well defined in the literature. Interestingly, many questionnaires for exploring visual imagination were developed in parallel (e.g., Sheehan, 1967; Marks, 1973; Heckler et al., 1993), measuring mainly the following: (1) imagery vividness—the clarity, complexity, and elaboration of the imagery generated; (2) imagery control—the ability to manipulate the imagery generated; and (3) imagery style—a preference for imagery-based or verbal strategies of encoding and processing information (MacInnis, 1987). The assessment criteria in the newly developed test measures were nearly identical with those in typical divergent thinking tests, for example: flexibility, elaboration, originality, asymmetry, and abstraction in the Franck Drawing Completion Test (FDCT; Schaefer, 1970; Anastasi and Schaefer, 1971), flexibility, elaboration, and originality in the Visual Imagination Test (VIT; McHenry and Shouksmith, 1970), or flexibility and originality in the Creative Imagination Test (CIT; Schubert, 1973). On the other hand, the influence of Guilfordian tests on the practice of testing and creative imagination assessment may not be so obvious as it is described to be. Long before Guilford's (1950) famous address, which gave impulse to the development of the psychology of creativity, Simpson (1922) presented the Test for Creative Imagination (Visual), in which the counterpart of transformativeness was the *creative changes* indicator, which was the prototype for the flexibility of thinking. This measure was computed based on the product of the number of all the drawings produced in the test and the number of changes between the drawings (i.e., the number of transition moments between different categories). It can therefore be supposed that first definitions of imagery transformation ability were positioned within the area of meanings and their interpretations, just like the flexibility of thinking.

With time, many empirical studies appeared that demonstrated a weak relationship between imagination and divergent thinking (Parrott and Strongman, 1985; Campos and Perez, 1989; Campos and González, 1993), which is confirmed by the meta-analysis summing up these studies (LeBoutillier and Marks, 2003). It therefore became justified to treat these constructs as distinct and relatively independent components of creativity, each having its own measurement specificity. Nevertheless, the influence of the post-Guilfordian tradition was still so strong that even after the publication of the Test of Creative Thinking by Jellen and Urban (TCT-DP; Jellen and Urban, 1986), which, in some sense, overcame the dominance of the Guilfordian approach in thinking about creativity, the scoring criteria in new creative imagination tests were still a reproduction of fluency, flexibility, originality, and elaboration. For instance, in Prueba de Imaginación Creativa (PIC; Artola et al., 2004) five scales were distinguished, of which four are repetitions of the components of divergent thinking: fluency of ideas, flexibility of thinking, originality of the responses, elaboration of the responses, and use of creative details (color, shadows, expansiveness, rotations, new perspectives). And while references to fluency, which can be linked with the generativity (fertility) of imagination, are to some extent justifiable, defining the originality of the generated imagery in terms of the rarity of their occurrence is an oversimplification that results from copying the scoring criteria for divergent thinking. The creative aspect of imagery manifests itself in generating new ideas and hypotheses, which are rare by nature, but above all they are innovative (Ward, 1994; Magid et al., 2015). This way of thinking about the originality of imagery is visible in the Test of Creative Imagination (TCI; Karwowski, 2008a,b), where the participant's task is to imagine and draw schematic drawings representing something that does not exist but, in the participant's opinion, should exist.

Reproducing the scoring criteria for divergent in creative imagination tests resulted in the similarity of test tasks. For example, the FDCT matrix is almost an exact copy of the matrix in the figural part of TTCT—Picture Completion. The situation is similar in the case of PIC and the Test of Creative Imagination (TCI, Ren et al., 2012). They all consist of incomplete figures to be completed and captioned, the difference being that FDCT has 12 figures, PIC has 4, and in TTCT and TCI there are 10 of them. This is undoubtedly a reference to the Sketches Test, in which the participant is given a simple basic figure, such as a circle, that he or she is supposed to complement in such a way as to produce a recognizable sign (Guilford and Hoepfner, 1966). A similarity is also observable in verbal tasks. In the version of PIC that is intended for children, the tasks in the verbal part require describing: (1) the possible consequences of all squirrels turning into dinosaurs, (2) new applications of plastic pipes, and (3) various endings of a situation presented in a picture. In the verbal part of the TCI, participants generate alternative endings for a briefly outlined story. It is not difficult to notice that these are typical tasks from the Remote Consequences Tests of the Unusual Uses Tests (Guilford, 1967). However, they are not always a copy of Guilford's tasks. In the TCI test sheet there are 16 elements—in groups of four: dots, semicircles, straight lines, and curved lines—out of which it is easy to make schematic drawings. Just like in the Make a Figure Test, simple linear elements are provided; however, the essence of the task is not to contrive to arrange as many complex figures as possible out of those elements (Guilford, 1967) but to use them for schematically presenting a generated mental image. This shows that the problem of creative imagination tests does not lie in their being inspired by tasks invented by Guilford but in the frequently rather mechanical imitation of their specificity and scoring.

Another problem connected both with the specificity of tasks and with their scoring, is the construct validity of creative imagination tests. Some of those instruments have unclear theoretical roots. FDCT originally served to carry out projective studies of masculinity and femininity characteristics (Franck and Rosen, 1949; Harkey, 1982). Barron (1958) proposed a new version of the test; drawing on the Guilfordian definition of originality, he developed the Originality Scale of FDCT, which placed emphasis on the originality, complexity, and asymmetry of the drawings made. The use of Guilford's theory once again confirms the strong domination of this orientation in the psychology of creativity, since at least two comprehensive theories of creative imagination were already in existence at that time—Ribot's (1906) and Vygotsky's (1930/2004, 1931/1991).

Another problem of creative imagination tests is the time limitations on administering them—from 10 min in PIC, modeled on TTCT, to 30 min in the TCI. Thus, they are mostly tests of speed (MCTC; FDCT; PIC; TCI). As a result, solving these tests requires, above all, quick reaction to tasks. The result obtained in a test may therefore depend not on the actual level of imagery abilities but on intellectual mobility. Individuals with a higher speed of intellectual work will do more test tasks in a specified unit of time, which again indirectly relates to the fluency of thinking, making these tests closer to classic Guilfordian tests in terms of scoring.

The next charge—serious but overlooked by many researchers—is associated with imagery transformation abilities; it concerns the aprocessual character of creative imagination: that is, making inferences about the transformations performed exclusively on the basis of their final outcome, being a reflection of the imagery generated. The simplest schema of inference about transformations is an analysis of the transition from the original image to its final form. In figural tests based on the Sketches Test (FDCT, PIC, TCI), inference about transformations is based on the analysis of changes in the stimuli evoking the imagery; for example, in FDCT the participant gets one point on a three-point scale for making a drawing that is elaborate in form and not rigidly based on the initial symbol. This is a risky kind of inference about imagery transformation, since it concerns the elaboration and complexity of an image—which determine the imagery vividness index—to a greater degree than the transformation abilities responsible for the result of the process of reconfiguring or recombining concepts (Ward, 1994). It is therefore legitimate to venture the statement that a majority of creative imagination tests place emphasis on measuring he ability to generate vivid and complex imagery as well as its originality.

The problems described, associated with the measurement of creative imagery abilities, were an impulse for us to develop a new instrument. Drawing on the long tradition of research on visual and creative imagination and at the same trying to avoid the shortcomings of the existing tools described above, we developed the TCIA, whose assumptions and selected aspects of validity and reliability we will present in the further sections of this paper.

Assessment of Visual Creative Imagination—A New Measurement Instrument

The TCIA measures the intensity of three characteristics of creative imagination distinguished in the conjunctional model of creative imaging ability: (1) vividness—the ability of generating clear and distinctive imagery characterized by high complexity, specificity, and elaboration; (2) originality—the ability of generating creative imagery characterized by novelty; and (3) transformative ability—the ability of modifying and transforming the imagery generated (Dziedziewicz and Karwowski, 2015, see also **Figure 1**). The test can be used in individual and group studies at different age levels—from about the age of 4 years to late adulthood.

The TCIA test booklet is in A3 format and consists of seven tasks. The first stage of solving each task has an exploratory character. The participant (in a group study) is supposed to give, in an oral or written form, as many images generated on the basis of a simple graphic sign, called the initial figure. Next, he or she selects the most original of the images given and, on its basis, makes a drawing accompanied by a brief description. The instruction stresses the possibility of elaborating and changing the selected image and adding any elements to it in such a way as to create something even more original: "You will find an unfinished drawing on every page of the test. Please write what it reminds you of. The more unusual ideas, the better. Next, underline the idea that you like most. Think of what you can change in it, reshape, and develop it in order to create something even more unique. Draw in the box and give your drawing a title. Good luck!" (see **Figure 3**). In an individual interview, the researcher writes down the participant's answers on a specially prepared answer sheet. Regardless of the manner of testing, the time allowed for solving the test is not limited. Usually, solving the TCIA does not require more than 20 min.

The test has two parallel versions (A and B) that differ only in the position of the signs—in version B, each initial imagery-evoking sign is rotated by 180 degrees (see **Figure 2**).

Most tests measuring creative imagination do not have alternative versions (e.g., FDCT, TCI), which was the main impulse to start work on developing parallel versions of TCIA. The possibility of using the parallel versions of the test is of great importance in educational assessment, particularly when checking the effectiveness of various interventions. Their use in experiments involving the initial and final measurements of the dependent variable eliminates the necessity of applying the same instrument and thereby increases the validity of the design.

The drawings and descriptions of imagery made in TCIA are assessed on three scales based on the conjunctional model of creative imaging ability (the Vividness scale; the Originality scale; the Transformativeness scale). Each scale is scored according to the criteria discussed in detail and illustrated with examples in the test manual (Jankowska and Karwowski, 2015). According to these criteria, it is possible to score 0, 1, or 2 points on each scale for a single drawing. The scores on scales are computed by adding up the points given to all the drawings. The total score is the

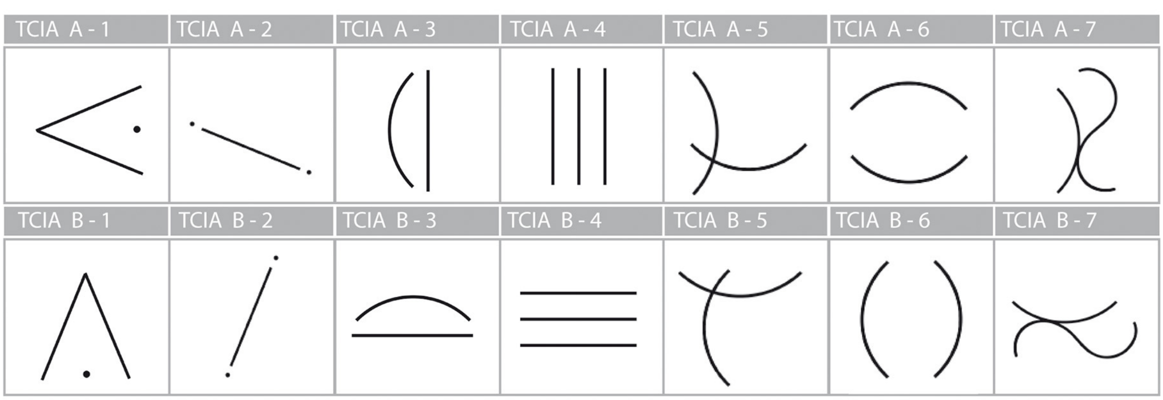

FIGURE 2 | The TCIA test booklet.

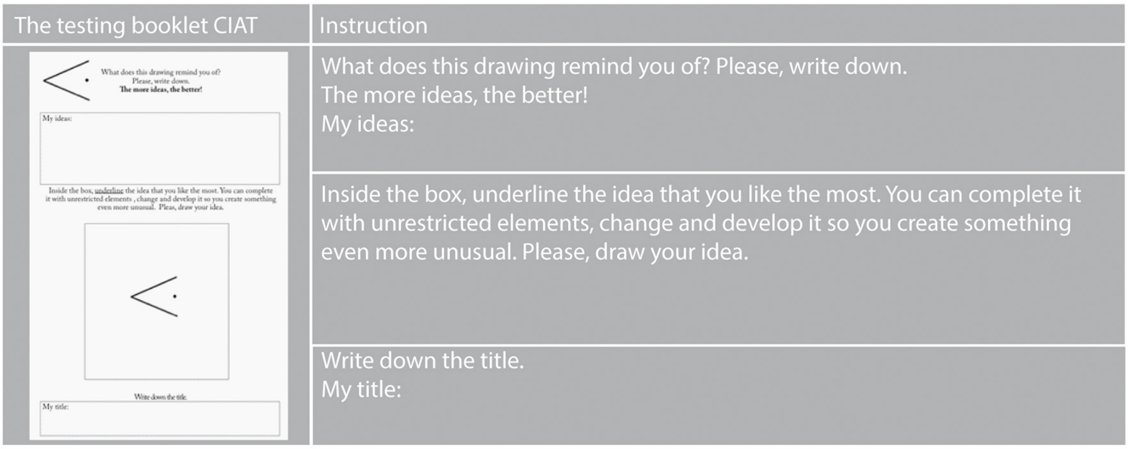

FIGURE 3 | Initial signs of TCIA.

TABLE 1 | Example TCIA assessment criteria.

Scoring	Vividness	Originality	Transformativeness
0	The original figure has not been supplemented, but was interpreted, i.e., it was given the title	Presentation of common objects (things, plants, animals, people, places). Their shapes, functions, and properties are real, and their activities, processes, states, and events are typical	Multiplication of the original figure
1	Simple, frequently schematic completion of the original figure	Individual, simple modifications of shape, functions, and properties of widely known objects (things, plants, animals, people, places) as well as typical activities, processes, states, and events;	Recreation, simple completion of the original figure, and adding to it a relatively independent object(s)
2	Complex, rich in detail completion of the original figure	Complex, significantly altered with respect to reality, modification of shape, functions, and properties of widely known objects (things, plants, animals, people, places) as well as typical activities, processes, states, and events	Complex modification of the original figure—its multi-aspect elaboration

sum of points obtained on the scales: Vividness, Originality, and Transformative Ability. Additionally, the analysis may also cover the index of imagination generativity—Imaginative Fluency (see **Table 1**).

The Vividness scale measures the degree of visualization and elaboration of the imagery generated. A high level of vividness is recognized, for instance, by the following: (A) an abundance of detail in the completion of the initial figure; (B) a clear depiction of motion and dynamics in the drawing; and (C) a complex presentation of metaphorical and symbolic content. The Originality scale measures the novelty of the imagery generated. A high level of originality is attested, for example, by: (D) the depiction of new objects, activities, processes, and events in the drawing that differ considerably from the actually existing ones; (E) surprising and novel presentation of cultural artifacts such as works of art; (F) amusing presentation of contents, suggesting a good sense of humor. The Transformativeness scale measures the ability of modifying the imagery generated. The scoring criteria refer to basic operations of transforming visual imagery, such as: (G) multiplication—multiplying an element of the image; (H) hyperbolization—excessive distortion of proportions, for example by emphasizing an element of the image; (I) amplification—adding detail to the image (see **Figure 4**).

In order to establish the structure of imagery abilities characteristic for a particular person, TCIA scores can be subjected to profile analysis. Each imagery ability is then assessed against the backdrop of the person's other imagination-related skills or against the norms determined for a certain population. The profile thus obtained is useful in predicting the further development of imagination and in deciding on the direction of supportive and stimulatory interventions.

In profile-based analysis, high scores on all the three scales attest creative imagery abilities. In the case of vivid imaging ability, the imagery generated is expressive but imitative—it is almost an exact reflection of previously perceived and memorized images. In cases of this kind, people should be inspired to creatively combine, non-typically link, and modify the generated images so as to give them features of novelty. Individuals with pro-creative imaging ability should be encouraged to create expressive imagery, add detail to it, and make it dynamic.

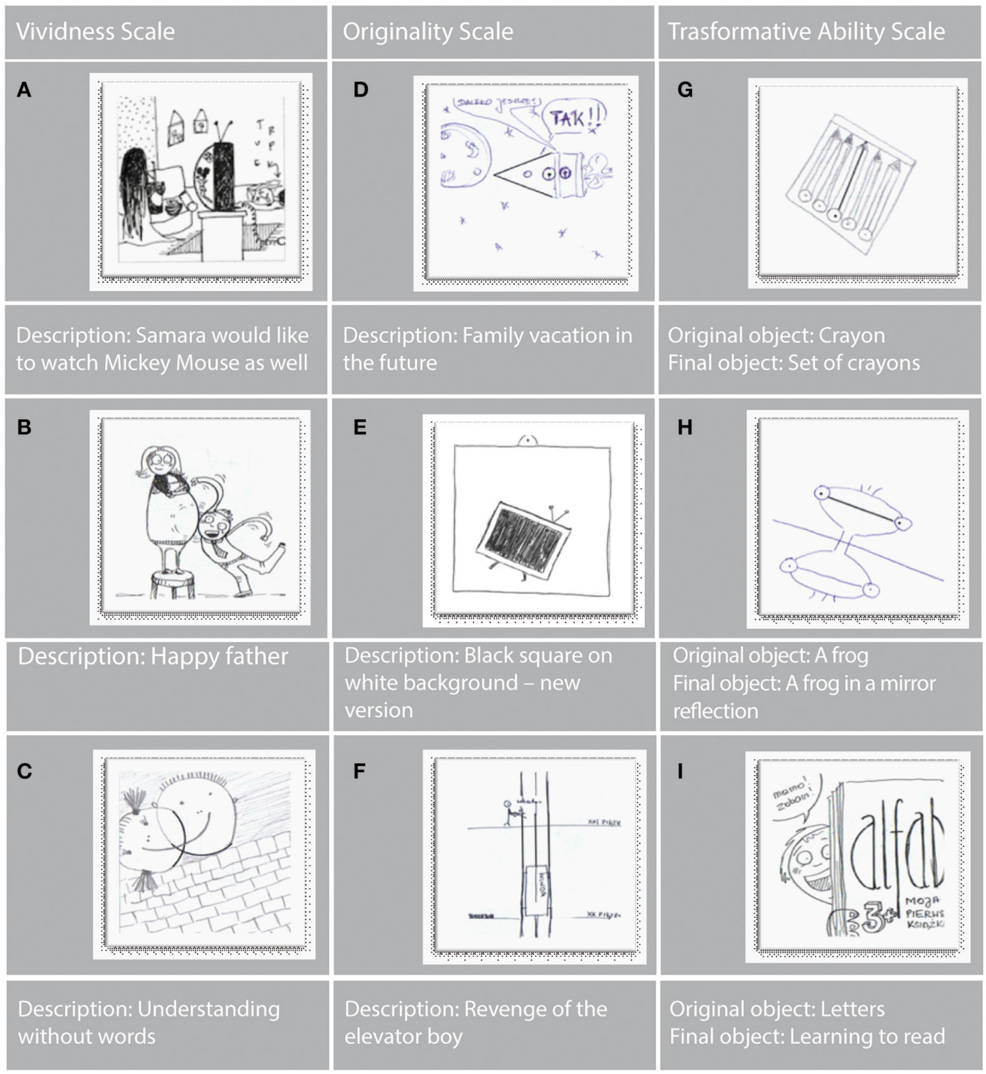

FIGURE 4 | Example drawings from TCIA. See text for A-I description.

By contrast, in the case of passive imaging ability profile, stimulatory interventions should focus on developing the ability of transforming imagery in unconstrained and miscellaneous ways.

THE PRESENT STUDIES

The research program presented below was aimed at testing the psychometric properties of the new test. In nine studies, on a total sample of 1700 participants, we tested criterion validity, juxtaposing TCIA results with other measures of imagination and creative abilities (Studies 1–5) and the discriminant validity of TCIA (Study 6), checking whether and to what extent TCIA dimensions are related to intelligence and school achievement measured using standardized tests as well as GPA. In the next step, using aggregated data, we tested the construct validity of the new test by performing confirmatory factor analysis. We also show the measurement invariance of TCIA among women and men as well as the relations between age and creative imagination.

The other objective of our analyses was to test the reliability of TCIA. In Study 7, we demonstrate the consistency of trained judges' evaluations on TCIA based on the manual (Jankowska and Karwowski, 2015). Study 8 is devoted to the analysis of test-retest reliability, and in Study 9 we present test-retest relations, with version B of TCIA used apart from version A. We conclude the reliability analyses by reaching for aggregated data from all the studies presented in this paper and we present the internal consistency of TCIA scales assessed using a more traditional method (Cronbach's α) as well as the more modern composite reliability (*H*; Hancock and Mueller, 2001), which is the outcome of confirmatory factor analysis. **Table 2** provides an overview of all studies with descriptive statistics.

TABLE 2 | Summary of studies presented in this article, together with sample sizes, instruments, and descriptive statistics.

Goal	Study	*N*	Method used	Dimension assessed by other instruments	Vivid *M* (*SD*)	Orig. *M* (*SD*)	Transf. *M* (*SD*)
Criterion validity	1	100	Vividness of Visual Imagery Questionnaire ($M = 119.87$, $SD = 19.46$)	Vividness of Visual Imagery	7.87 (2.13)	2.25 (2.02)	6.29 (3.92)
	2	57	Franck Drawing Completion Test ($M = 9.60$, $SD = 3.48$)	Creative imagination	7.20 (2.07)	1.95 (1.48)	4.38 (5.41)
			Generating Imaginary Animals ($M = 0.85$, $SD = 2.19$)	Creative cognition			
	3	261	Test of Creative Thinking-Drawing Production ($M = 16.66$, $SD = 9.41$)	Creative Thinking	6.46 (2.33)	1.80 (1.95)	3.62 (3.00)
	4	226	Verbal Alternate Uses Task, scored for: Fluency ($M = 10.41$, $SD = 7.70$), Flexibility ($M = 6.62$, $SD = 3.70$), Originality ($M = 103.29$, $SD = 76.32$)	Divergent Thinking	6.45 (2.51)	1.87 (2.03)	3.55 (3.19)
	5	741	Torrance Tests of Creative Thinking – figural test, scored for: Fluency ($M = 8.53$, $SD = 7.76$), Flexibility ($M = 3.19$, $SD = 3.43$), Originality ($M = 43.63$, $SD = 50.16$)	Divergent Thinking	6.89 (2.20)	1.75 (1.93)	5.17 (3.92)
Discriminant Validity	6	230	Raven's Progressive Matrices ($M = 100$, $SD = 15$)	Intelligence	6.22 (1.97)	1.48 (1.43)	3.22 (2.72)
			Test of School Achievement ($M = 100$, $SD = 15$)	School Achievement			
			Grade Point Average ($M = 4.19$, $SD = 0.81$)				
Interjudge Reliability	7	4 judges	Version A of TCIA	–	4 judges: 6.24 (1.76), 7.05 (2.06), 6.61 (2.17), 7.20 (2.30)	4 judges: 2.21 (1.41), 1.57 (1.54), 2.09 (1.71), 2.13 (1.69)	4 judges: 4.39 (3.21), 4.44 (3.89), 4.51 (3.24), 3.48 (2.52)
Test–retest reliability	8	86	Version A of TCIA used twice with 3 weeks interval	–	Test: 6.51 (2.18) Retest: 7.05 (1.99)	Test: 1.50 (1.74) Retest: 1.98 (1.90)	Test: 5.35 (3.53) Retest: 5.67 (3.35)
Correlation between parallel versions of TCIA	9	39	Version A and B of the TCIA used with 5 weeks interval	–	Ver. A: 7.20 (2.07) Ver. B: 7.13 (1.62)	Ver. A: 1.95 (1.48) Ver. B: 1.75 (1.30)	Ver. A: 4.38 (3.41) Ver. B: 4.08 (3.20)

Criterion Validity (Studies 1–5)

Method

Participants

Study 1. The participants in Study 1 were 100 students (all of them female) aged 19–40 years ($M = 22.73$, $SD = 4.71$). They were students of social sciences at several universities in a big city in central Poland.

Study 2. The participants in Study 2 were 57 female students of education and teaching, aged 20–24 years ($M = 20.85$, $SD = 0.59$). They studied at a university of education in Warsaw, the capital of Poland.

Study 3. The participants in the third study were 261 children (110 girls) aged 5–7 years ($M = 6.02$, $SD = 1.1$). The children attended nursery and elementary schools in Warsaw.

Study 4. The participants in Study 4 were 226 individuals (171 women) aged 11–30 years ($M = 13.10$, $SD = 6.04$). They were students of elementary, middle, and high schools as well as university students from all over Poland.

Study 5. The participants in Study 5 were 741 individuals (425 women) aged 15–25 years ($M = 18.30$, $SD = 3.04$). They were students of middle and high schools as well as university students from all over Poland.

Measures and procedure

In all of the five studies, version A of TCIA was used. Apart from that, in each of those five studies we used different questionnaires and tests measuring characteristics directly related to creative imagination or creative abilities. In each study, the instruments were presented in a random order. The instruments used in particular studies are listed below.

Study 1. Perceived efficacy in using visual imagination was measured by the Vividness of Visual Imagery Questionnaire (VIVIQ) (Marks, 1973, 1995). The questionnaire consists of 32 items that are supposed to measure the degree to which the participant believes himself/herself to be capable of using imagination efficiently. An example item is: "In answering items 1 to 4, think of some relative or friend whom you frequently see (but who is not with you at present) and consider the picture that comes before your mind's eye. (1) The exact contour of face, head shoulders and body." The reliability of the VIVIQ was high ($\alpha = 0.90$).

Study 2. Creative imagination was measured using the Franck Drawing Completion Test (FDCT), successfully applied in earlier research on creativity (Dziedziewicz et al., 2013, 2014). FDCT is composed of 12 figures, placed in separate "windows." The participants' task is to complete the initial figures in such a way that the end result takes the form of interesting drawings. There is no limit on the time taken to complete the task. The test is assessed on a three-point scale (0-1-2): no points are given for a conventional form, one point is given for a fairly complex form which partially stands out in its originality and unconventional approach, and two points are given for drawings with a rich, free, and unconventional form which are not strictly based on the initial symbol. The maximum score on the test is 24 points. The reliability of the FDCT was high ($\alpha = 0.83$).

In the second study we also used a task that is a classic one in experiments concerning creative imagination and consists in drawing animals "from a different planet" (Generating Imaginary Animals; Ward, 1994). The participants were asked to list 20 animals that came to their mind (Listing Real Earth Animals). Next, they were to imagine a planet, completely different than Earth, on which a variety of plant and animal species existed. Based on the imagery generated, they made a detailed drawing of an imaginary creature as seen from the front and from the side, they gave it a name and named all the parts of its body. The images were assessed using an index applied in earlier studies (Ward, 1994; Ward and Sifonis, 1997; Ward et al., 2002)—the presence of untypical sense organs (creature attributes).

Study 3. In the third study, we used the Test of Creative Thinking-Drawing Production (TCT-DP) (Jellen and Urban, 1986). This test measures creative thinking defined in a broad way based on Urban's Components Model of Creativity (1996). The subjects are asked to complete an unfinished drawing. Detailed procedures of the TCT-DP are given in Urban (2004). Briefly, participants in this task are asked to complete an unfinished drawing that consists of a few shapes including a half-circle and a dot. Each participant is given a score of creative abilities based on 14 criteria: (1) continuations, (2) completions, (3) new elements, (4) connections made with a line, (5) connections made to produce a theme, (6) boundary breaking (fragment-dependent), (7) boundary breaking (fragment-independent), (8) perspective, (9) humor and affectivity, (10) manipulation of the material, (11) surreal or abstract drawings, (12) atypical combinations of figures and symbols, (13) non-stereotypical use of a certain element, and (14) speed. The final score given for the TCT-DP is a sum of points from all of these criteria. Previous studies (Gralewski and Karwowski, 2012; Karwowski and Gralewski, 2013) confirmed its value as a valid and reliable measure. In this study, the reliability of the TCT-DP was acceptable ($\alpha = 0.75$).

Study 4. In Study 4, we used the verbal Alternate Uses Task inspired by Minnesota Tests of Creative Thinking (Torrance, 1962). The task was to come up with unusual uses for a can within a specified time (3 min). This task was scored in terms of fluency, flexibility, and originality of thinking.

Study 5. The circle test from the Torrance Tests of Creative Thinking (TTCT; Torrance, 1974) was used to measure divergent thinking (DT). The test consists of 20 empty circles arranged in 5 rows of 4 on the test sheet. The task is to create interesting drawings in them, trying to use all the circles within 10 min. The total number of circles used minus the number used for recurring themes gives an index of fluency (range: 0 to 20 points). This index is generally considered to be absolutely reliable because it relies on mechanical counting. Flexibility is indexed by the number of categories of themes considered; originality is indexed by the inverse of the frequency of occurrence of each concept in the whole sample (unique ideas score highest), and total originality score is the sum of the originality scores for each circle response generated by the participant (see Silvia et al., 2008; Plucker et al., 2011 for the advantages and limitations of different originality scoring methods).

The research program presented in this article was approved by the authors' university's Institutional Review Board. Written permission from the parents of the children participating was obtained prior to data collection. The participants were informed about the study and could withdraw at any time. All tests were scored by 3 research assistants (graduate students of psychology and education), trained in creativity tests scoring.

Results and Discussion

The correlations between the three scales of TCIA and the dimensions of creative imagination and creative thinking are presented in **Table 3**. Additionally, in **Table 4** we present the polychoric correlations between vividness, originality, and transformativeness of the TCIA and each of the 14 TCT-DP criteria.

In the case of measures pullback treated as referring directly to creative imagination (VIVIQ, FDCT, and Generating Imaginary Animals), seven out of nine correlation coefficients turned out to be statistically significant, with a generally substantial effect (median $r = 0.32$). Imagery abilities measured using VIVIQ turned out to correlate fairly consistently and with similar strength with all the three criteria—the most strongly with vividness ($r = 0.42$) and slightly less strongly with originality ($r = 0.36$) and transformativeness ($r = 0.31$). We obtained quite a similar picture of the relationship in the case of FDCT—the scores in this test were mainly linked with vividness ($r = 0.48$), less strongly with originality ($r = 0.30$), and the most weakly (as well as not significantly) with transformativeness ($r = 0.18$). By contrast, the number of untypical sense organs in the Generating Imaginary Animals task was independent of vividness ($r = 0.02$) but strongly related to the TCIA ($r = 0.45$) and transformativeness ($r = 0.32$).

In the case correlations between TCIA scales and measures of creative thinking, the situation was less clear. Only 11 out of 21 correlation coefficients were statistically significant, with a median of $r = 0.12$. The TCIA was related fairly consistently—though less strongly than with measures of imagination—to TCT-DP scores. Both vividness ($r = 0.26$) and originality ($r = 0.32$) as well as transformativeness ($r = 0.20$) were related to the overall score on this test. A more detailed analysis taking into account particular TCT-DP criteria (**Table 4**) unveiled more interesting patterns of relations. TCIA vividness was the most strongly related to TCT-DP unconventional manipulation ($r = 0.44$), perspective ($r = 0.38$), and fragment-independent boundary breaking ($r = 0.30$). Correlations between originality and TCT-DP criteria were weaker: they were the strongest in the case of using abstract elements ($r = 0.30$), introducing new elements into the drawing ($r = 0.28$), continuations of the existing elements ($r = 0.27$), and connections that contribute to a theme ($r = 0.27$). In the case of transformativeness, we found the strongest relations with new elements ($r = 0.22$) and boundary-breaking (fragment-independent) ($r = 0.20$).

Correlations between TCIA scales and the scores on tasks from Torrance's tests were both weaker and less systematic. What is interesting, the measures of creative imagination were almost completely unrelated to the classic scoring criteria of creative thinking tests (fluency, flexibility, originality) in the case of the figural test (only fluency was weakly related to vividness, $r = 0.13$). As regards the verbal test, the scores were the most consistently related to originality, which was related in an identical way ($r = 0.26$) to verbal fluency, flexibility, and originality. The relations between vividness and transformativeness and the measures of creative abilities were weaker, though significant ($0.13 = r = 0.18$).

The results of the first five studies confirm the validity of TCIA. Stronger relationships between the results obtained in the new test and established measures of creative imagination (VIVIQ, FDCT, Generating Imaginary Animals), compared to classic measures of creative abilities (also figural ones)[1], support

[1]**Table 3** presents 95% confidence intervals around Pearson's *r*s, allowing for direct comparisons of different correlations. However, to provide a more synthetic comparison of correlation coefficients obtained between TCIA scales and other tests, we followed a two-step procedure. First, using a multilevel meta-analysis (Cheung, 2014; Karwowski and Lebuda, 2015), we calculated the correlations between TCIA scales and criterion measures (VIVIQ, Generating Imaginary

TABLE 3 | Criterion validity analysis—Correlations of TCIA with VVIQ, FDCT, and creativity tests.

	Vividness	Originality	Transformativeness
Study 1 (*N* = 100)			
VIVIQ	0.42*** [0.24, 0.57]	0.36*** [0.18, 0.52]	0.31** [0.12, 0.48]
Study 2 (*N* = 57)			
Generating Imaginary Animals	0.02 [−0.24, 0.28]	0.45*** [0.21, 0.64]	0.32* [0.06, 0.54]
FDCT	0.48*** [0.25, 0.66]	0.30* [0.04, 0.52]	0.18 [−0.08, 0.42]
Study 3 (*N* = 261)			
TCT-DP	0.26*** [0.14, 0.37]	0.32*** [0.21, 0.42]	0.20** [0.08, 0.31]
Study 4 (*N* = 226)			
Verbal fluency	0.13* [0.00, 0.26]	0.26*** [0.13, 0.38]	0.13* [0.00, 0.26]
Verbal flexibility	0.19** [0.06, 0.31]	0.26*** [0.13, 0.38]	0.15* [0.02, 0.28]
Verbal originality	0.14* [0.01, 0.27]	0.26*** [0.13, 0.38]	0.13* [0.00, 0.26]
Study 5 (*N* = 741)			
Figural fluency	0.14*** [0.07, 0.21]	0.05 [−0.02, 0.12]	0.07^ [0.00, 0.14]
Figural flexibility	0.14*** [0.07, 0.21]	−0.04 [−0.11, 0.03]	0.02 [−0.05, 0.09]
Figural originality	0.16*** [0.09, 0.23]	0.01 [−0.06, 0.08]	0.04 [−0.03, 0.11]

95% confidence intervals are provided in brackets.
*^p < 0.10; *p < 0.05; **p < 0.01; ***p < 0.001.*

TABLE 4 | Polychoric correlations between TCIA criteria and TCT-DP criteria.

TCT-DP Scoring Criteria	Vividness	Originality	Transformativeness
Continuations (Cn)	0.12*	0.18*	0.08
Completions (Cm)	0.20**	0.27***	0.15*
New elements (Ne)	0.19*	0.28***	0.22**
Connections made with a line (Cl)	0.16*	0.12*	0.12*
Connections that contribute to a theme (Cth)	0.25***	0.27***	0.19*
Boundary breaking: fragment-dependent (Bfd)	0.09	0.14*	0.14*
Boundary breaking: fragment-independent (Bfi)	0.30***	0.11*	0.20**
Perspective (Pe)	0.38***	0.08	0.14*
Humor and affectivity (Hu)	0.26***	0.22***	0.10
Unconventionality: manipulation (Uca)	0.44***	0.12*	0.09
Unconventionality: surrealistic, abstract (Ucb)	0.14*	0.30***	0.07
Unconventionality: symbol-figure combination (Ucc)	0.21**	−0.04	0.13*
Unconventionality: symbols, signs (Ucd)	0.18*	0.26***	0.16*
Speed (Sp)	0.24***	0.19*	0.13*

*$p < 0.05$, **$p < 0.01$; ***$p < 0.001$.

the statement that, measuring characteristics important for creativity, TCIA focuses to a greater extent on imagination rather than on the characteristics of thinking. Admittedly, the values of correlations between vividness, originality, and transformativeness and the measurements using other instruments developed for measuring imagination are not spectacularly high (the highest being $r = 0.48$ between FDCT and the vividness of imagination), but they are strong and consistent enough to be treated as confirming the criterion validity of the new measure. What is important, the obtained profile of various relations between the scales of TCIA and other measures also constitutes an argument supporting the validity of the new instrument. It is easy to notice that the attempts made so far to study creative imagination have focused only on its selected elements. For example, FDCT (Dziedziewicz et al., 2013) actually measures the vividness and, to a certain (smaller) extent, originality of creative imagination, but it does not measure transformativeness. The task of Generating Imaginary Animals (Ward, 1994; Ward and Sifonis, 1997; Ward et al., 2002) reveals much about originality and next to nothing about vividness. The new test makes it possible to systematically analyze all the three components important for the functioning of creative imagination without duplicating the measurement performed using any of the previous instruments and remaining relatively independent of creative thinking.

Assuming that the results presented in Studies 1–5 support the criterion validity of the new measure, the next important step was to determine its discriminant validity. For that purpose, we used measures of general intellectual ability (intelligence) and school achievement in different areas. Previous studies and meta-analyses (Kim, 2005; Karwowski and Gralewski, 2013) show that the relations between creativity and intelligence are not particularly strong (however, see Silvia, 2015, for an alternative position), and neither are the relations between creative abilities and school achievement (Gralewski and Karwowski, 2012; Gajda, in press; Gajda and Karwowski, Submitted). This is why we devoted Study 6 to checking the discriminant validity of the new test, correlating the results obtained in it with intelligence and school achievement.

Animals, FDCT). Then, we provided a similar meta-analysis for correlations between the TCIA scales and other creativity measures. The meta-analytically obtained correlation between TCIA and creative imagination measures was estimated at $r = 0.34$ (95% *CI*: 0.27,0.41), while the correlation between TCIA and other creativity measures was at $r = 0.135$ (95% *CI*: 0.038,0.23). Second, as confidence intervals across *r*s do not overlap, we conclude that these coefficients differ significantly from each other.

Discriminant Validity (Study 6)

Method

Participants

The participants in Study 6 were elementary school students. The sample was composed of 110 boys and 120 girls (total $N = 230$), whose mean age was 13.88 years ($SD = 0.36$). The participants were fifth-grade students from elementary schools across the whole Poland. The multilevel and multistrata sample selection made it representative for all Polish fifth-graders, with the exception of special school students and students from very small schools (below 10 students per grade). The sample was drawn from the registers of Polish Educational Information System (PEIS) (http://www.cie.men.gov.pl/index.php/sio.html). Four strata were distinguished according to school location (village, town below 20,000 inhabitants, city 20,000–100,000, city above 100,000) and school size. In each randomly chosen school, two classes were randomly invited to participate in the study.

Measures and procedure

Apart from the TCIA, all participants solved an intelligence test and school achievement test.

Intelligence. In order to measure intelligence, we used Raven's Progressive Matrices (RPM) (Raven et al., 2003). The reliability of RPM in this study was high ($\alpha = 0.85$).

Grade point average. The grade point average for all school subjects from the semester preceding the research was used as a measure of school grades. The GPA was provided by students.

School achievement. As a measure of school achievement, we used the results of a school achievement test developed by the Educational Research Institute. This test measures three spheres of school achievement—math, reading, and overall language awareness. The test was developed and scaled according to item response theory (Rasch models is a one-parameter and graded partial credit model; Rasch, 1980) and has very good psychometrics properties—all items are well- fitted to the Rasch model (infit and outfit measures between 0.8 and 1.2). Moreover, the test information function at the average level of θ (a latent trait of the measured achievement) was high, and the standard error of measurement was low—translating into reliability between 0.86 and 0.88, depending on the scale (Jasińska and Modzelewski, 2012).

Results and Discussion

Correlations between measures of intelligence and school achievement and the three scales of TCIA are presented in **Table 5**. As opposed to the relations with creative abilities, reported earlier, this time the profile of results is less clear. Vividness turned out to be a consistent correlate of intelligence ($r = 0.29$), GPA ($r = 0.33$), and achievement test scores in math ($r = 0.28$), reading ($r = 0.24$), and language awareness ($r = 0.23$). However, in the case of originality and transformativeness, the relations were less unambiguous and clearly weaker. Originality was significantly and positively, though weakly, related to school achievement in reading and language awareness, whereas transformativeness was related to GPA ($r = 0.21$) and competence in math ($r = 0.20$).

The consistently positive relations found between intelligence, school achievement, and vividness suggest that their cause is not only vividness itself but the related ability to work persistently and thoroughly, closer to elaboration (Dziedziewicz and Karwowski, 2015). What may also be interesting is the role of transformativeness in learning math (probably especially geometry), which is confirmed by the relations found between skill in performing transformations in the imagination and achievement in math.

Study 6 brings 15 correlations, of which only nine are statistically significant, and the mean correlation coefficient (as well as median) obtained between intelligence and measures of imagination is $r = 0.17$. This result provides arguments in favor of the new test's discriminant validity.

Studies 1–5 make it justified to consider TCIA an instrument characterized by criterion validity, and Study 6 testifies to a good discriminant validity of the new test. The measurement of creative imagination using TCIA is quite consistently and strongly related to other measures of creative imagination, slightly less consistently and more weakly to creative ability tests, and the most weakly (as well as less systematically) to intelligence and school achievement. However, Studies 1–6 were based on the assumption that the three-factor structure of the test, assumed by the presented theoretical model, is reproduced in the data. In order to verify this assumption, in the next step we tested the construct validity of the new test, subjecting its results to confirmatory factor analysis as well as testing measurement invariance among men and women.

TABLE 5 | Discriminant validity analysis—correlations with intelligence and school achievement.

Study 6 ($N = 230$)	Vividness	Originality	Transformativeness
IQ	0.29***	0.10	0.08
GPA	0.33***	0.09	0.21**
SAT Math	0.28***	0.05	0.20***
SAT Reading	0.24***	0.17*	0.09
SAT Language Awareness	0.23***	0.17*	0.11

*$p < 0.05$, **$p < 0.01$; ***$p < 0.001$.

Construct Validity (Studies 1–9 Aggregated)

Method

Participants

The analysis covered data collected from 1740 people at different ages—the participants in Studies 1–9. In total, the sample consisted of 1200 women (69%) and 540 men (31%); 42 people did not give their gender. The participants' age ranged from 10 to 55 years ($M = 16.33$, $SD = 4.72$); most of them were students or university students taking part in various research projects using TCIA.

Measure and procedure

Sometimes the participants completed TCIA together with other tests, and sometimes it was the only test completed.

Results and Discussion

In the first step, the data collected were subjected to confirmatory factor analysis in a design involving many traits and many methods. More specifically, we tested the fit of the three-factor model assumed on the basis of theory, while at the same time controlling the effect of the test's individual items (**Figure 5**).

The assumed theoretical model was confirmed (**Table 6**). Comparing the measures of fit with the commonly used criteria (Hu and Bentler, 1999; Kline, 2010), the values obtained should be considered acceptable.

The correlations between latent factors were moderately strong (0.39–0.56), and the factor loadings of the model estimated on the basis of polychoric correlations testify to a good validity of individual items (Hu and Bentler, 1999), considerably exceeding the literature-recommended minimum of 0.50. Thus, the construct validity of the model is confirmed by the obtained data.

Effects of Gender and Age on the TCIA Results

The next step in analyses was to test TCIA measurement invariance according to gender. The fit of consecutive models with increasingly high constraint is presented in **Table 7**. The sample being large, we performed invariance assessment not on the basis of differences in the range of values of chi squared (sensitive to sample size), but by comparing the values of CFI and RMSEA between models. Following the recommendations found in the literature on the subject (Cheung and Rensvold, 2002; Chen, 2007), we consider a model to be invariant if CFI change between consecutive models does not exceed 0.01 and if the change in RMSEA does not exceed 0.02.

Even the most constrained model that tested scalar invariance had a very good fit, and differences in CFI between the models did not exceed 0.01, though comparing more and less constrained models does bring a decline in fit, slightly exceeding the critical values. However, given that the change in RMSEA between the least and the most constrained model is only 0.005, there are significant grounds to consider the models well-fitted and the test itself invariant according to gender.

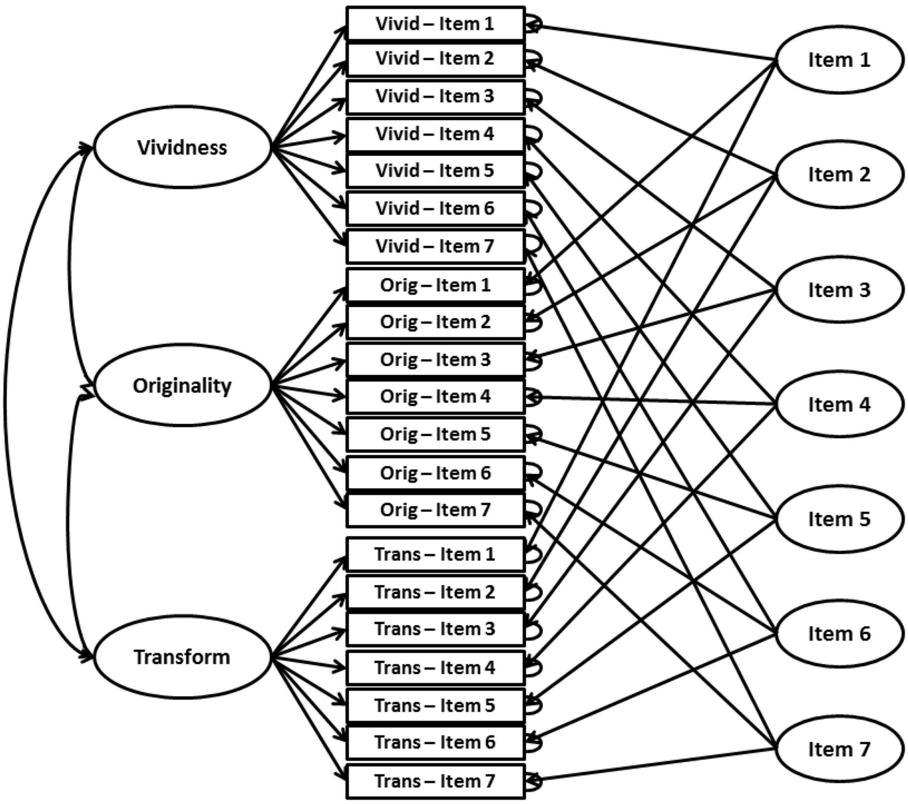

FIGURE 5 | Multi-trait, multi-method confirmatory factor analysis model testing for construct validity of the TCIA.

The next step was to check the existence of gender differences in terms of the characteristics of creative imagination. For this purpose, three latent variables: vividness, originality, and transformativeness were predicted by gender. The model was well fitted to data ($\chi^2/df = 1.42$, $CFI = 0.988$, $RMSEA = 0.018$), and the effect of gender in all three cases turned out to be statistically significant. More specifically, women exhibited a higher level of vividness ($\beta = 0.25$, $p < 0.001$), originality ($\beta = 0.19$; $p < 0.001$), and transformativeness ($\beta = 0.17$, $p < 0.001$).

An analogous model with age as a predictor was also well fitted ($\chi^2/df = 2.36$, $CFI = 0.959$, $RMSEA = 0.032$); age was a statistically significant positive predictor of vividness ($\beta = 0.19$, $p < 0.001$), originality ($\beta = 0.14$, $p < 0.001$), and transformativeness ($\beta = 0.078$, $p < 0.01$).

The analyses presented above confirm the construct validity of TCIA. As assumed, the test has a three factor structure, and the three components of creative imagery are significantly and moderately correlated. At the same time, however, correlations between them are not strong enough to make them indistinguishable from one another. Individual items load on the latent variables strongly enough to justify the conclusion about their criterion validity. These data testify to the good validity of the measure.

We devoted the next three studies (7–9) to assessing the reliability of TCIA. Study 7 concerned testing the consistency between the judges scoring TCIA based on detailed guidelines provided in the manual (Jankowska and Karwowski, 2015). Studies 8 and 9 concerned test-retest reliability. The whole research concludes with a presentation concerning reliability assessed as the test's internal consistency.

Interjudge Reliability (Study 7)

Method

Participants

The participants were four judges (all female, mean age $M = 26$ years) trained in TCIA scoring.

Measures and procedure

All the judges took part in a training devoted to details of TCIA scoring and acquainted themselves with the test manual (Jankowska and Karwowski, 2015). Next, each of them was asked to score 100 test sheets.

Results and Discussion

For each of the three TCIA scoring criteria, we computed intercorrelations between the judges' ratings as well as their consistency using Cronbach's α and the intraclass correlation coefficient (ICC) (**Table 8**).

In all situations, interjudge consistency was very high and comparable between the criteria. In all cases, α was equal to

TABLE 6 | CFA Model Fit Parameters.

Measures	Parameters
$\chi^2(df)$ / χ^2/df	241.55 (165)/1.46
CFI/TLI	0.988/0.983
RMSEA (90% *CI*)	0.019 (0.013, 0.029)
CORRELATIONS BETWEEN LATENT VARIABLES	
Vividness-Originality	0.53***
Vividness-Transformativeness	0.39***
Originality-Transformativeness	0.56***
FACTOR LOADINGS	
Range of loadings on Vividness (mean)	0.60–0.67 (0.64)
Range of loadings on Originality (mean)	0.58–0.71 (0.65)
Range of loadings on Transformativeness (mean)	0.59–0.72 (0.68)
Items loadings (Vividness, Originality, Transformativeness)	
Item 1	0.62, 0.69, 0.70
Item 2	0.66, 0.71, 0.71
Item 3	0.65, 0.58, 0.68
Item 4	0.67, 0.66, 0.59
Item 5	0.65, 0.62, 0.67
Item 6	0.64, 0.59, 0.70
Item 7	0.60, 0.68, 0.71

***$p < 0.001$.

TABLE 7 | Analysis of test equivalence according to gender – invariance analysis (CFA).

Model	χ^2/df	CFI	RMSEA (90% CI)
Configural invariance	1.57	0.978	0.016 (0.014, 0.019)
Metric invariance	1.54	0.978	0.016 (0.013, 0.018)
Scalar invariance	1.71	0.968	0.018 (0.016, 0.021)

TABLE 8 | The reliability of judges scoring 100 randomly selected images generated in TCIA.

Study 7 (*N* = 100 drawings)	Judge 1	Judge 2	Judge 3	Judge 4
Vividness (α = 0.91, ICC = 0.89)				
Judge 1	1			
Judge 2	0.78	1		
Judge 3	0.82	0.76	1	
Judge 4	0.64	0.60	0.67	1
Originality (α = 0.90, ICC = 0.89)				
Judge 1	1			
Judge 2	0.74	1		
Judge 3	0.61	0.67	1	
Judge 4	0.75	0.76	0.69	1
Transformativeness (α = 0.92, ICC = 0.91)				
Judge 1	1			
Judge 2	0.84	1		
Judge 3	0.88	0.84	1	
Judge 4	0.70	0.53	0.68	1

All correlations are statistically significant ($p < 0.001$).

TABLE 9 | Test–retest reliability and internal consistency of TCIA.

	Vividness	Originality	Transformativeness
Study 8 (test–retest, 3 weeks) *N* = 86	0.89***	0.91***	0.98***
Study 9 (A-B, 5 weeks), *N* = 39	0.63***	0.55***	0.43***
Studies 1–9 (internal consistency)			
Cronbach's α	0.83	0.84	0.86
H (CFA)	0.83	0.84	0.87

***$p < 0.001$.

or higher than 0.90 (originality α = 0.90, vividness α = 0.91, and transformativeness α = 0.92), with slightly lower but still acceptable ICC values (vividness and originality ICC = 0.89, transformativeness ICC = 0.91).

The fact that briefly trained judges equipped with example assessments of TCIA products are capable of scoring the products of this test very similarly testifies to its good reliability. High consistency is a precondition of precise measurement. It is worth noting that the values we obtained are similar to those usually obtained in the case of other creativity tests, for example TCT-DP (Kālis et al., 2014) or TTCT (Dziedziewicz et al., 2013). This makes it legitimate to believe that even though TCIA scoring is a multifaceted and seemingly complex and difficult process, following our recommendations and using the examples provided does in fact make it possible to obtain highly reliable data. In the next two studies, we tested the reliability of TCIA in time: in Study 8 we used the same version of the test twice, whereas in Study 9 we used version B. In the final step, using aggregated data from all the studies described in this paper, we present data on the internal consistency of TCIA.

Test–retest Reliability (Studies 8–9)

Method

Participants

Study 8. The participants in Study 8 were 86 people (43 women) aged 13 to 15 years ($M = 14.02$, $SD = 0.84$). They were high-school students from a large city in central Poland.

Study 9. The participants in Study 8 were 39 people (29 women) aged 13 to 14 years ($M = 13.75$, $SD = 0.47$). They were middle-school students from a big city in central Poland.

Measures and procedure

In Study 8, TCIA version A was used twice with a 3-week interval. In Study 9, there were 5 weeks between the measurement sessions using versions A and B of TCIA.

Results and Discussion

Test-retest correlations between measurement using the same version of the test with an interval of 3 weeks were very high ($r = 0.89$ for vividness, $r = 0.91$ for originality, and $r = 0.98$ for transformativeness, all p's < 0.001), testifying to very high measurement reliability (**Table 9**).

In the case of studies using versions A and B of the test, with an interval of 5 weeks between measurements, correlations were still fairly high—they ranged from $r = 0.43$ for transformativeness, through $r = 0.55$ for originality, and $r = 0.63$ for vividness (all p's < 0.001).

The high values of test-retest correlations, especially those from Study 8, combined with the high interjudge consistency presented earlier, testify to the good reliability of TCIA measurement. The final step of our analyses was to test the internal consistency of each scale of TCIA. For this purpose, we used aggregated data from all the studies presented in this paper.

Internal Consistency (Studies 1–9 Aggregated)

Method

Participants

The analysis covered data collected from 1740 people at different ages—the participants in Studies 1–9. In total, the sample consisted of 1200 women (69%) and 540 men (31%); 42 people did not give their gender. The participants' age ranged from 10 to 55 years ($M = 16.33$, $SD = 4.72$); most of them were students or university students taking part in various research projects using TCIA.

Measures and procedure

All the participants solved TCIA, sometimes together with other tests and self-report measures and sometimes as the only test.

Results and Discussion

We assessed internal consistency using the values of Cronbach's α and the H coefficient—composite reliability specific to confirmatory factor analysis (Hancock and Mueller, 2001). The scale on which the criteria were measured being short (0-1-2 in the case of each criterion and each individual item), we computed internal consistency on the basis of the matrix of polychoric correlations estimated in Mplus 7.1 (Muthén and Muthén, 2015).

The two methods yield very similar estimations of internal consistency. In the case of vividness and originality, the internal consistency indices have very similar values (0.83 for vividness and 0.84 for originality), whereas in the case of transformativeness internal consistency is $\alpha = 0.86$ and $H = 0.87$.

These values demonstrate the good reliability of the test, especially as both coefficients applied depend on the number of items in a scale, and each scale of TCIA consists of a relatively small number of items (7). Internal consistency exceeding 0.80 may be regarded as highly acceptable and testifying to the good quality of TCIA measurement.

GENERAL DISCUSSION

Creative functioning requires different abilities that very likely also include visual creative imagination. According to the conjunctional model of creative imaging ability (Dziedziewicz and Karwowski, 2015), the key abilities are those of visualizing, transforming, and enriching imagery, as well as combining them into new wholes. It must be stressed that this is not only the domain of children with vivid imagination or artists, but the quality of every person's mind, which facilitates visualizing problems and looking at them in new ways, leading to original solutions being generated more easily. This is what makes it so important to have valid and reliable tests of creative imagination. The existing instruments for measuring visual creative imagination have many shortcomings; for example, they have unclear theoretical roots, copy the scoring standards of divergent thinking tests, or measure only selected elements of imagery abilities, mainly vividness and originality. The detailed analysis of problems connected with measuring creative imagination, described in this paper, constituted the basis for the assumptions adopted in the construction of TCIA.

The aim of the presented research was to document the quality of measurement using TCIA. Four issues must be stressed in this conclusion. First, the results of correlational studies using other measures of creative imagination and creative thinking confirm the criterion validity of the test (Studies 1–5). Second, the study of creative imagination using TCIA combined with the measurement of intelligence and school achievement provided sufficient evidence for the discriminant validity of the new instrument (Study 6). Third, aggregated data from all studies subjected to confirmatory factor analysis provided arguments in favor of the test's construct validity—its three-factor structure was confirmed. Finally, both versions of the test as a whole are reliable, and this also applies to each of their scales (Studies 7–9).

We have demonstrated the measurement invariance of TCIA in case of gender. It allowed us to test for gender differences in the latent means of TCIA scales. Although the differences were small in terms of the effect size, females outperformed males in vividness, originality and transformativeness. Similarly, there was small, but positive effect of age, with older participants achieving higher results in the TCIA. Gender differences obtained in our studies fit well with previous studies and show that not only women usually obtain higher scores than men in self-assessed imaginative abilities (mainly vividness) (Harshman and Paivio, 1987; Narchal and Broota, 1988), but they also do in terms of imaginative abilities (Karwowski, 2009; Lau and Cheung, 2010). These differences may be due to girls' engaging more in role-playing or personal fantasy plays than boys during preschool years (Werebe and Baudonniere, 1991). Furthermore, girls around 4 to 5 years of age have been observed to engage in role-playing and in personal play fantasy twice as often as the boys of a similar age group (Jones and Glenn, 1991). One of the most widely replicated findings in the research on imaginary companions is that girls are more likely to have them than boys (Singer and Singer, 1992; Carlson and Taylor, 2005).

Summing up, it should be said that TCIA is characterized by high validity and reliability in measuring visual creative imagination. Moreover, several findings presented in this paper may be interesting not only as confirmations of the quality of the test. The generally weak association between creative imagination and divergent thinking or intelligence we have obtained replicates previous findings that generally show low correlations between imagination and creativity (Schmeidler, 1965). Although generally those correlations are statistically significant and positive, they rarely exceed the value of $r = 0.30$, hence providing good arguments that these constructs are relatively independent aspects of creative abilities (see e.g., Rhodes, 1981; Russ and Grossman-McKee, 1990; Dziedziewicz et al., 2013). Usually, correlations between divergent thinking and vividness of imagery are higher than those with transformativeness (LeBoutillier and Marks, 2003). Similarly, usually creative imagination is more strongly related to originality than to fluency of thinking (Dziedziewicz et al., 2013, 2014).

Limitations and Future Directions

The research presented here had a correlational character. Experimental research would make it possible to check, in a controlled way, whether the complexity of different imagery transformations was reflected in the Transformativeness scale. Further research should capture the dynamics of the process of image transformation, as has been done in the analysis of reaching solutions in creativity tests (Beaty et al., 2014). Perhaps it is even worth attempting to combine the testing of creative imagination with neuropsychological methods such as EEG or MRI (Fink and Benedek, 2012).

What seems very promising is the profile-based approach in the measurement of creative imagination, which shows the complex and multifaceted nature of this disposition. In the future, using the experience gathered when classifying the profiles of other multiscale tests and questionnaires, it is worth developing an objective and reliable system of defining profiles of creative imagery abilities by means of statistical procedures. Its usefulness for scientific purposes, but above all in individual assessment and in choosing the type of stimulatory interventions, will be invaluable.

The results presented in this paper focused especially on the version of TCIA that is intended for group research. Another paper devoted to a version developed for individual studies that includes the study of children aged 4 and older is in preparation.

At present, plans also exist to perform a cultural adaptation of TCIA in order for the instrument to be successfully used in other countries (outside Poland), in research on imagination—its nature, development, and determinants, in comparative cross-cultural studies.

CONCLUSION

The results of our studies to date on the validity and reliability of the TCIA make it legitimate to say that TCIA is a measure with good—or even very good—psychometric properties and a clear theoretical basis.

What makes it valuable is, above all, the emphasis it gives to the complexity and multidimensionality of visual creative imagination, in which it stands out favorably against other tests measuring this disposition. This test enables a systematic analysis of all the three components important to the functioning of creative imagination while remaining relatively independent of creative thinking. Due to the possible application of the instrument in assessment and intervention practice—in measuring the effectiveness of stimulatory interventions—the fact that that TCIA exists in two versions is also of significance.

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Disentangling the Impact of Artistic Creativity on Creative Thinking, Working Memory, Attention, and Intelligence: Evidence for Domain-Specific Relationships with a New Self-Report Questionnaire

*Katrin Lunke and Beat Meier**

Institute of Psychology and Center for Cognition, Learning and Memory, University of Bern, Bern, Switzerland

The goal of the present study was to take a new look at the relationship between creativity and cognitive functioning. Based on models that have postulated domain- and sub-domain-structures for different forms of creativity, like scientific, technical or artistic creativity with cognitive functions as important basis, we developed a new questionnaire. The Artistic Creativity Domains Compendium (ACDC) assesses interest, ability and performance in a distinct way for different domains of artistic creativity. We present the data of 270 adults tested with the ACDC, standard tests of divergent and convergent thinking, and tests of cognitive functions. We present fine-grained analyses on the internal and external validity of the ACDC and on the relationships between creativity, working memory, attention, and intelligence. Our results indicate domain-specific associations between creativity and attention as well as working memory. We conclude that the ACDC is a valid instrument to assess artistic creativity and that a fine-grained analysis reveals distinct patterns of relationships between separate domains of creativity and cognition.

Keywords: artistic creativity, divergent thinking, convergent thinking, creativity questionnaire, intelligence

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Massimiliano Palmiero, Università degli Studi dell'Aquila, Italy

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Barbara Colombo, Champlain College, USA
Snehlata Jaswal, Indian Institute of Technology Jodhpur, India

Correspondence:
Beat Meier
beat.meier@psy.unibe.ch

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INTRODUCTION

"Creativity is intelligence having fun" says a quote alleged to Albert Einstein, suggesting that creativity and cognition are closely linked together. Often in contemporary research, however, the relationship between creativity and intelligence has been discussed controversially. While some researchers have distinguished the constructs from each other, others have described them as complements (Guilford, 1959; Wallach and Kogan, 1965; Hocevar, 1980; Runco and Chand, 1995; Sternberg and Lubart, 1999; Kaufman and Baer, 2005; Kaufman, 2012). Different domains and sub-domains of creativity and different levels of involvement into creative activities can be distinguished. Here, we introduce the *Artistic Creativity Domains Compendium* (ACDC), a new self-report-measure for artistic creativity. It separately assesses the four domains *visual arts*, *literature*, *music* and *performing arts* and 18 according sub-domains such as *painting*, *ballet-dancing* or *acting* on three levels of involvement, that is, *interest*, *ability,* and *performance*. We present data of a norm-sample of 270 adults and relate artistic creativity to measures of divergent and convergent thinking, working memory, attention, and intelligence.

Creativity can be defined as the ability to generate new and adaptive ideas or novel solutions to problems and it is thus considered as fundamental for human civilization (Sternberg and Lubart, 1999; Takeuchi et al., 2011). It can be divided into divergent and convergent thinking and is usually tested by verbal or figural output (e.g., Mednick and Mednick, 1971; Goff and Torrance, 2002). Divergent thinking is characterized by the production of many different original solutions – rather than only one; convergent thinking is characterized by finding the one and only correct solution for a given problem. Additionally, self-report and third-person-questionnaires can be used to assess creativity in terms of creative operations, achievements, and creative activities (e.g., Hocevar, 1980; Carson et al., 2005; Antonietti et al., 2011; Kaufman, 2012).

Beyond the general definition, creativity is a versatile construct that can be expressed in many forms, domains and facets. Artistic, scientific, and technical creativity have been proposed as specific forms in previous research (Stein, 1953; Davis et al., 2011; Kaufman, 2012; Kozhevnikov et al., 2013). Moreover, each different form of creativity includes different domains and these yet sub-domains, such as design, scriptwriting and crafting (e.g., Carson et al., 2005; Kaufman, 2012; Glaveanu et al., 2013). Due to the complexity of specific forms of creativity, the definition what a new and adaptive product should be like and how it is created has to be further specified. Next, we describe three key points determining artistic creativity (independence of time pressure, domain-width, and levels of involvement) and how we propose to assess them.

First, as the process of artistic creativity is likely to be more time-consuming than stimulus triggered divergent or convergent thinking due to domain specific stages, self-report questionnaires provide the opportunity to report past achievements specific for artistic creativity, instead of pressing the participants to produce creative solutions under non-ecological time pressure. Thus, we decided to develop a questionnaire that protocols artistic creativity completely independent of time pressure.

Second, artistic creative thinking is not limited to figural and verbal modes of expression. While painting, sculpting and designing can be easily described as figural expressions, and writing certainly is a verbal form of expression, singing, dancing, and acting cannot be sufficiently characterized by only these two modes. Thus, it is important to cover a wide range of different domains and sub-domains as proposed by Carson et al. (2005) and Kaufman and Baer (2005). This offers a better perspective on different modes of artistic expression and also enables the analysis of specific relationships between different domains of artistic creativity and constructs of cognitive functioning (Davis et al., 2011; Kaufman, 2012). Moreover, different forms and domains of creativity are linked to different thinking styles and even different characteristics of intelligence (Carson et al., 2005; cf. Kaufman, 2012).

To take this into account, the ACDC addresses the four main artistic domains of *visual arts*, *literature*, *music* and *performing arts* separately. Moreover, for each domain related sub-domains are included. For *visual arts,* they include *painting*, *sculpting*, *photography,* and *graphic design*; for *literature*, they include *fictional writing*, *poetry*, *play writing,* and *journalism*; for *music* they include, *classical music*, *jazz music*, *rock music,* and *folk music* and for *performing arts*, they include *dancing, ballet,* and *acting in movies, theaters* and *musicals*. Thus, it is possible to investigate the relationships among the several domains, sub-domains and their superordinate modes of creative expression and differences in their relationships to cognitive functions with the ACDC.

Third, one can be interested in different domains, in each domain the level of ability can vary, and making the creative achievement available for others reflects creative performance. That is, the quality of artistic creative products is influenced by knowledge and technical expertise. Beyond coming up with creative ideas, creativity also involves the creation of an artistic output expressed in a specific domain. The individual either has the aim and ability to do so or not. If the ability is present, the production on a subsequent level can be more or less skilled. Ideally, it will then be judged in an appropriate frame of reference (Stein, 1953; Mulvenna, 2013). Levels of involvement in different creative domains have already been addressed in the Creative Achievements Questionnaire (CAQ; Carson et al., 2005), which includes several hierarchically organized levels of involvement. They presume that scores on lower levels are required to score on higher levels of achievement. In contrast, we suggest that the levels of involvement are not necessarily dependent and participants can score in any pattern. Therefore, the ACDC is organized in three levels of involvement: *interest*, *ability,* and *performance.* These can be assessed independently. The first level refers to the mere interest in a domain and sub-domain. The second level refers to past completion of creative accomplishments. The third level refers to publication of completed artworks. This differentiation of levels of involvement enables to assess the specificity of a certain degree of involvement for each (sub-) domain separately. It also provides for the possibility to assess the development of creative profiles over time. This may be particularly useful to assess progresses in development, to test the effectiveness of creativity training, and for the assessment of pathological changes related to neurodegenerative and/or psychological disorders (Flaherty, 2005; Inzelberg, 2013; see **Image 1** in the Supplementary Materials for a specific example of a personal profile). In sum, the ACDC is a self-report questionnaire to assess artistic creativity with its domains and subdomains on three levels of involvement (for the full questionnaire see **Table S1** in the Supplementary Materials).

In differentiating several forms and levels of involvement of artistic creativity, it is an interesting question how they further relate to cognitive functions. For divergent and convergent creativity, contradictory results between creativity and cognitive functioning have been found which have been explained as a function of overlaps in the assessment of the different constructs (Hocevar, 1980; Batey and Furnham, 2006). Kaufman and Baer (2005) explain creativity as a result of motivation and cognitive functioning, thus implying that different abilities may cause creativity in different domains. Similarly, Damasio (2001) proposed that different cognitive abilities relate to different forms, domains and sub-domains of creativity.

Several studies support this position. For example, Hocevar (1980) found that verbal intelligence was the best predictor of creativity in the literature-domain. Kaufman and Baer (2004) showed that different cognitive characteristics were related to different forms of creativity. Specifically, creativity in communication and writing correlated positively with verbal SAT scores whereas creativity in math correlated positively with mathematical SAT scores. Furnham and Crump (2013) found that art students scored higher on vigilance and in a verbal abstract reasoning task. Moreover, science students scored higher on an intelligence test as well as on a logical reasoning task and a numerical reasoning task. In addition, several studies found that physical activity had a positive influence on executive functioning such as attention and working memory (Best, 2010). As some domains and sub-domains of creativity include more or less physical activity, different relations for different domains are plausible. We consider it important to further specify the relationship between cognitive functioning and specific domains and sub-domains of artistic creativity and to compare the results with different behavioral creativity measures.

The first goal of this study was to validate a new self-report-questionnaire that assesses artistic creativity. The ACDC covers *interest*, *ability,* and *performance* in artistic domains and sub-domains of different modes of creative expression. The second goal was to test the relationship between artistic creativity and common tests of figural and verbal, divergent and convergent thinking, in order to test the external validity of the ACDC. The third goal was to relate artistic creativity and divergent and convergent thinking to cognitive functions such as working memory, attention, and intelligence. This enables us to generate new insights into the relationships between domain-specific artistic creativity, typical measures of creativity (such as convergent and divergent thinking) and cognitive functions more generally.

In line with the suggestion that creativity is domain-specific (e.g., Kaufman and Baer, 2005), we expected specific relationships between divergent and convergent creativity and the ACDC for figural and verbal domains of artistic creativity, such as painting or writing. Moreover, in line with the suggestion that overlap in processing requirements determines the relationship between creativity and cognitive functions (e.g., Hocevar, 1980), we expected that cognitive functions would be associated differently for the different domains, sub-domains and levels of involvement of artistic creativity.

MATERIALS AND METHODS

Scale Construction of the ACDC

The ACDC includes *literature*, *visual arts*, *performing arts*, and *music* as separate domains. For each domain, it includes three levels of involvement as described above (*interest, ability, performance*). For each sub-domain four questions were constructed. The first two questions refer to interest in a certain sub-domain. For example, for the "painting" sub-domain, "I have a strong interest in painting" and "I visit painting exhibitions." The third question refers to ability, for example, "I paint pictures," and the forth question refers to performance, for example, "I have already exhibited my pictures publicly" (see **Table S1** in the Supplementary Materials).

For each scale mean scores were computed to provide a profile of the four domain-scales visual arts, literature, music and performing arts, the three levels of involvement and further the 12 scales of domain differentiated by level of involvement *interest* in *visual arts*/*literature*/*music*/*performing arts*, *ability* in *visual arts*/*literature*/*music*/*performing arts* and *performance* in *visual arts*/*literature*/*music*/*performing arts* (see **Table S1** in the Supplementary Materials). **Figure 1** shows the hypothesized scale structure.

Participants

A total of 320 German speaking, healthy participants, 160 women and 160 men, aged 18–53 years ($M = 26.19$, $SD = 8.52$) were recruited from the general public. Approximately half of them were students, the other half had already completed their professional education. The study was approved by the institutional ethical review committee of the University of Bern. Participants signed written informed consent before data collection. They did not receive a reward for participation. Due to missing data, we had to eliminate 50 data sets. Thus, the final sample consisted of 270 participants.

Materials

Artistic Creativity

The ACDC consists of 72 questions about interest, ability and performance in four artistic domains (visual arts, literature, music and performing arts) and 18 corresponding sub-domains (painting, sculpting, photography, graphic design, fictional-writing, poetry, play-writing, journalism, classical music, jazz music, rock music, folk music, movie-acting, theater-acting, dancing, ballet-dancing, musical performance). The full questionnaire is presented in **Table S1** in the Supplementary Materials. In this study we used a computerized version. For analysis, mean-scores were computed overall, across domains (*visual arts, literature, music* and *performing arts*), across levels of involvement (*interest, ability,* and *performance*), and across both domains and levels of involvement (*interest* in *visual arts*, *ability* in *visual arts*, *performance* in *visual arts*; *interest* in *literature*, *ability* in *literature*, *performance* in *literature*; *interest* in *music, ability* in *music*, *performance* in *music*; *interest* in *performing arts, ability* in *performing arts, performance* in *performing arts).* It is available in German and in English, the present study was conducted with the German version.

Convergent Thinking

The *Remote Associates Test* (RAT) by Mednick and Mednick (1971) was used to assess convergent thinking (translated into German by Bolte et al., 2003). Thirty word triads were taken from the modified version. Triads consisted of nouns only. A total sum-score of all correct answers was calculated.

Divergent Thinking

In order to assess divergent thinking, the *Abbreviated Torrance Test for Adults* translated to German (ATTA, Goff and Torrance,

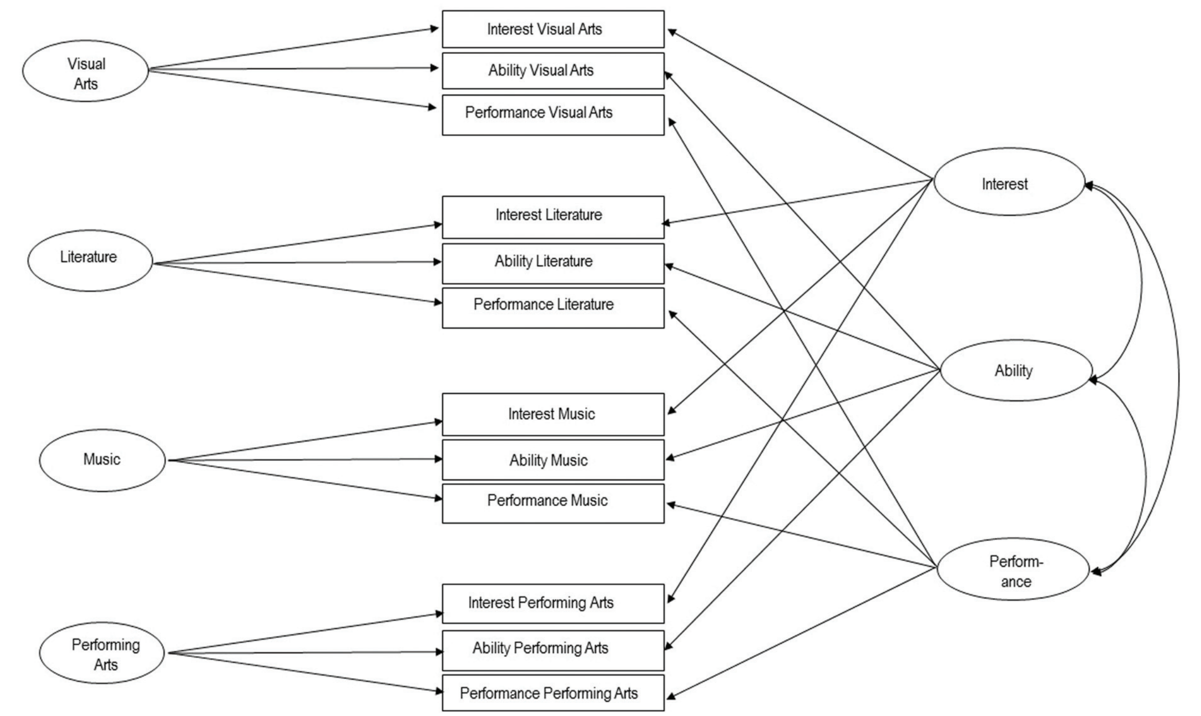

FIGURE 1 | Scale-structure of the Artistic Creativity Domains Compendium (ACDC).

2002) and the *Sentence Construction* sub-test of the German *Analyse des Schlussfolgernden und Kreativen Denkens* (ASK, Schuler and Hell, 2005) were used.

The ATTA consists of one verbal and two figural tasks. In the verbal task, a fictional scenario is presented. Participants are instructed to imagine as many problems as possible that might occur in this situation. In the two figural tasks, the participants are presented with incomplete figures provided on a test sheet. They are instructed to complete them and to give a title for each picture. Two independent raters scored the tasks according to the manual (i.e., Fluency, Originality, Richness and Colourfulness of Imagery, Emotion/Feelings, Future Orientation, Humor and Provocativeness for the verbal task and Elaboration, Flexibility, Openness, Unusual Visualization, Movement/Sound, Richness and Colorfulness of Imagery, Abstractness of Titles, Articulateness, Combination of Figures, Internal Visual Perspective, Emotion and Fantasy for the figural task). Interrater-reliability for the present sample was $r = 0.91$. We computed a mean score of both ratings.

The ASK, consists of the presentation of four capital letters. Participants are instructed to construct four-word sentences with these letters as the initial letters. A sum score of all countable sentences in both trials was calculated and ranked according to the manual.

A *figural divergent thinking score* was calculated as the mean of all figural scales of the ATTA and a *verbal divergent thinking* score was calculated as the mean of all verbal scales of the ATTA and the sum score of the ASK.

Intelligence

The *Wortschatztest* (WST), a German vocabulary test was used to assess verbal intelligence (Schmidt and Metzler, 1992). The test consists of 42 words and 210 pseudo-words. Each trial consists of one word and five pseudo-words. The intelligence score was calculated as the total number of correct minus incorrect responses.

Attention

To measure attention, the D2-R was used (Brickenkamp et al., 2010). It consists of a sheet of paper that contains the letters *d* and *p* which are combined with different numbers of apostrophes. Participants have to find the letters *d* with two apostrophes and circle them as fast as possible. The number of correct detections per line were summarized, excluding the first and the last line, and false positives were subtracted. The results are used to calculate a sum score which is then transformed according to age norms.

Working Memory

Working memory was tested with a German version of the *Reading Span Task* (RST; Daneman and Carpenter, 1980, cf. Jaeggi et al., 2010). It consists of 100 unrelated sentences. Half of them make sense semantically and half do not but all are syntactically correct. Each sentence contains 6–15 words (*M*: 10.05; *SD*: 1.98) with a mean word length of 6.25 (*SD*: 0.81). Reading-span is scored as the set-size of the block in which all words of at least three sets can be remembered correctly or the block in which at least two sets were remembered minus 0.5.

Procedure

After signing written informed consent, participants were tested individually. The study consisted of the ACDC, tests of divergent and convergent thinking, intelligence, working memory, and attention. The ordering of the tests is displayed in **Table 1**.

For the D2-R (Brickenkamp et al., 2010) participants were given a paper and pencil and were instructed to cross out all *d*-target-stimuli combined with two dashes, distributed in an exercise-line including 26 target-stimuli and 31 distractor-stimuli. The test consisted of 14 lines, which had to be filled out successively without break. Participants had to start a new line every 20 s. Next, the *RAT* was administered. Participants were instructed to find the single fourth word that could possibly connect the three former unrelated words of each triad. They solved the 30 word triads of the *RAT*, presented on one sheet, within 5 min (Bolte et al., 2003). Afterward, the *RST* was conducted (Daneman and Carpenter, 1980). Subjects were asked to read sentences aloud that were presented on a computer screen, decide whether they made sense or not and to memorize each last word of the sentence. Set-size ranged from two sentences to six sentences in a non-random order with increasing difficulty. The sentences were presented in the center of a white screen and participants pressed 1 if the sentence made sense and 0 if not. At the end of each set the instruction to recall the final words of each previously read-out sentence in the correct order appeared on a white screen. Responses were collected by the investigator. Five blocks of five sets each were presented consecutively.

Next, the divergent thinking tests were administered. In the verbal task of the ATTA (Goff and Torrance, 2002), participants were presented the situation that they are able to fly, on a sheet. They had 3 min to write down as many problems they thought could occur in this situation. In the figural task of the ATTA, participants received sheets with incomplete figures they had to turn into interesting drawings for which titles had to be invented. The participants had 3 min to complete each of the three tasks, starting with the verbal one, followed by the two figural tasks. Next, the ASK (Schuler and Hell, 2005) was administered as a further measure of verbal divergent thinking. Participants were twice presented four capital letters on a sheet and instructed to invent as many four-word-sentences as possible. They had three trials for both combinations. Then the WST (Schmidt and Metzler, 1992) was administered to test verbal intelligence. In 42 trials the participants were asked to each time choose the one existing word beside five distractor-pseudo-words. Words were presented in a 16-point font with an associated number between 1 and 6 each. Participants were instructed not to guess, but to press 0 if they did not know the answer. Answers could be given with the keyboard. As a last test, the ACDC was conducted on the computer. Participants answered the 72 questions with the keyboard on a four point Likert-Scale ranging from 1 = strongly disagree/never over 2 = disagree/rarely and 3 = agree/sometimes to 4 = strongly agree/frequently.

TABLE 1 | Procedure: ordering of tasks.

Construct	Test	Time (minutes)
Attention	D2-R	8
Convergent thinking	RAT	6
Working memory	RST	25
Divergent figural thinking	ATTA	10
Divergent verbal thinking	ASK	7
Verbal intelligence	WST	13
Artistic creativity	ACDC	10

For abbreviations see text.

Statistical Analysis

Analysis of the Structure of the ACDC

To analyze the scale-structure of the ACDC we used a *Multi-Trait-Multi-Methods-Model* (MTMM). This allows investigating artistic creativity from two view-points, the four different domains and the three different levels of involvement (Nussbeck et al., 2012). The sub-domain-scales – divided on levels of involvement – could thereby be explained by (besides the error components) the domains and the level of involvement (Eid, 2000). For robust results and in order to keep a minimum of 200 cases per analysis we applied bootstrapping. The MTMM was calculated with AMOS using asymptotically distribution free estimation to control for skewed distributions.

TABLE 2 | Mean values and standard deviations for Artistic Creativity Domains Compendium scores, creativity tests, and cognitive tests.

Test-score	*M*	*SD*
ACDC total	1.71	0.30
Visual arts	1.90	0.47
Literature	1.51	0.32
Music	1.70	0.38
Performing arts	1.73	0.41
ACDC interest	2.14	0.44
ACDC ability	1.57	0.34
ACDC performance	1.16	0.18
Interest in visual arts	2.20	0.61
Ability in visual arts	2.03	0.62
Performance in visual arts	1.18	0.34
Interest in literature	1.98	0.55
Ability in literature	1.21	0.31
Performance in literature	1.08	0.16
Interest in music	2.17	0.49
Ability in music	1.47	0.54
Performance in music	1.15	0.26
Interest in performing arts	2.18	0.58
Ability in performing arts	1.62	0.52
Performance in performing arts	1.22	0.30
ASK	100.99	9.93
ATTA mean verbal score 1	1.58	1.32
ATTA mean figural score 1	6.29	2.73
ATTA mean verbal score 2	11.07	5.07
ATTA mean figural score 2	23.24	6.88
RAT	5.01	2.34
Verbal intelligence	31.16	3.69
Attention	105.69	9.57
Working memory	2.79	1.13

External Validity

Correlations were analyzed in SPSS with z-transformed data. Significance level was set to $\alpha = 0.05$.

RESULTS

Mean and standard deviation for all variables are displayed in **Table 2**.

Structure of the ACDC

We generated an MTMM-model with 200 bootstraps according to the structure of the ACDC, that is, 72 items in four domains separated by level of involvement (interest, ability and performance in visual arts, literature, music and performing arts). The fit was good with $\chi^2(39) = 55.75$, $p < 0.05$, *Comparative Fit Index* (CFI) = 0.96, *Tucker Lewis Coefficient* (TLI) = 0.94, and a *root mean square error* (RMSEA) of 0.04. The indicator-reliabilities of the domains by levels of involvement were all above

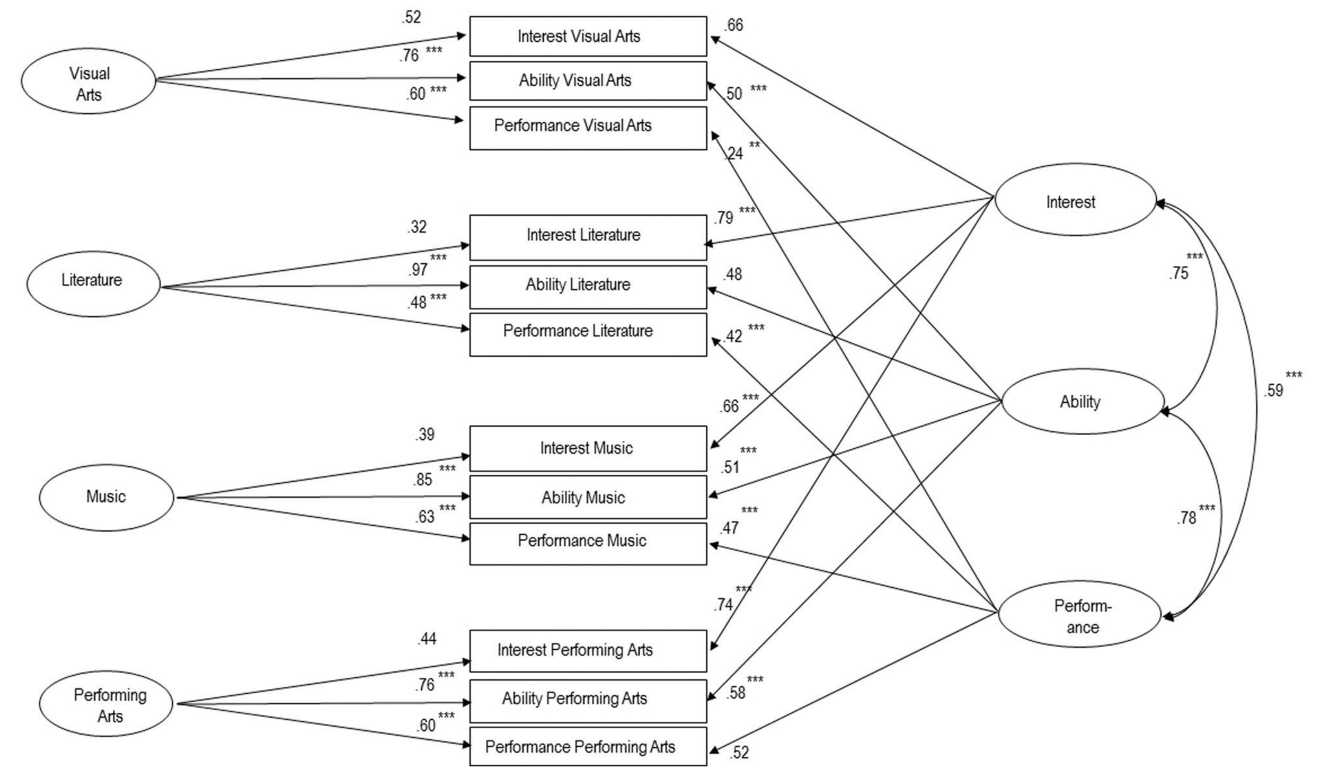

FIGURE 2 | Multi-Trait-Multi-Methods-Model (MTMM) of the Artistic-Creativity-Domains-Compendium (ACDC), standardized solution. One-sided arrows: factor-loadings; two-sided arrows: correlations. $**p < 0.01$, $***p < 0.001$. Factor-loadings without asterisk have been set to 1 prior to estimation (unstandardized solution).

TABLE 3 | Correlations between the overall ACDC-Score, ACDC-levels, ACDC-domains and divergent and convergent thinking scores.

	ACDC T	ACDC I	ACDC A	ACDC S	ACDC VA	ACDC L	ACDC M	ACDC PA	DF	DV	CV
ACDC total	1										
ACDC interest	0.95**	1									
ACDC ability	0.86**	0.69**	1								
ACDC performance	0.70**	0.49**	0.70**	1							
Visual arts	0.74**	0.71**	0.63**	0.48**	1						
Literature	0.76**	0.76**	0.62**	0.46**	0.43**	1					
Music	0.74**	0.68**	0.72**	0.51**	0.37**	0.48**	1				
Performing arts	0.79**	0.74**	0.65**	0.64**	0.41**	0.53**	0.38**	1			
Divergent (Figural)	0.17**	0.16**	0.15*	0.12*	0.15*	0.07	0.05	0.22**	1		
Divergent (Verbal)	0.33**	0.27**	0.38**	0.25**	0.25**	0.30**	0.19**	0.28**	0.26**	1	
Convergent	−0.04	−0.05	−0.01	0.00	−0.02	−0.02	−0.02	−0.04	−0.01	0.06	1

*ACDC, Artistic Creativity Domains Compendium, *p < 0.05, **p < 0.01.*

0.4, indicating good convergent validity and implying that all 12 scales can be maintained as constructed. The complete model with standardized correlations and factor-loadings is presented in **Figure 2**.

Internal Consistency of the ACDC

Internal consistency was high, with Cronbach's alpha of $\alpha = 0.93$ for the 72 items as a whole. For the four domains, internal reliability was $\alpha = 0.88$ for *visual arts*, $\alpha = 0.80$ for *literature*, $\alpha = 0.84$ for *music* and $\alpha = 0.87$ for *performing arts*.

For the levels of involvement resulted $\alpha = 0.91$ for *interest*, $\alpha = 0.77$ for *ability* and $\alpha = 0.68$ for *performance*. Further differentiation of levels of involvement for each domain resulted in $\alpha = 0.84$ for *interest* in *visual arts*, $\alpha = 0.71$ for *ability* in *visual arts*, $\alpha = 0.57$ for *performance* in *visual arts*. For *literature* resulted $\alpha = 0.77$ for *interest*, $\alpha = 0.37$ for *ability* and $\alpha = 0.25$ for *performance*. For *interest* in *music* $\alpha = 0.75$ was obtained, for *ability* in *music* resulted $\alpha = 0.75$ and for *performance* in *music* $\alpha = 0.31$. For *performing arts* resulted $\alpha = 0.83$ for *interest*, $\alpha = 0.52$ for *ability* and $\alpha = 0.59$ for *performance*.

External Validity

In order to test the external validity of the ACDC, we assessed its relation to divergent and convergent thinking. The *figural divergent thinking* was computed as a mean from the scores ATTA Mean Figural 1 and 2, and *verbal divergent thinking* was computed from ATTA Mean Verbal Score 1 and 2 and ASK (cf. **Table 2**). The mean score of the ACDC correlated significantly with the *figural divergent thinking* score and the *verbal divergent thinking* score. The correlation with the *convergent thinking* score was not significant.

On the level of *involvement in art*, the *figural divergent thinking* score correlated with *interest*, *ability*, and *performance*. The *verbal divergent thinking* score also correlated significantly with *interest*, *ability*, and *performance*. Results for the *convergent* score of the RAT were not significant. These correlations are presented in **Table 3**.

On the level of *art domains*, the *divergent figural* mean-score was significantly correlated with *visual arts* and *performing arts*. The *divergent verbal* mean-score correlated significantly with *visual arts*, *literature*, *music* and *performing arts*. The *convergent* score of the RAT correlated with none of the domain scores of the ACDC. These correlations are likewise presented in **Table 3**.

The correlations between artistic domains divided further by levels of involvement are presented in **Table 4**. They showed a significant correlation for the *figural divergent thinking* score with *interest* in *visual arts, ability* in *visual arts*, *interest* in *performing arts*, *ability* in *performing arts*, and *performance* in *performing arts*. The *verbal divergent* thinking score correlated significantly with *interest* in *visual arts, ability* in *visual arts*, *interest* in *literature*, *ability* in *literature*, *performance* in *literature*, *ability* in *music*, *interest* in *performing arts*, *ability* in *performing arts*, and *performance* in *performing arts*. Convergent thinking correlated with none of the domain scores divided by levels of involvement of the ACDC.

TABLE 4 | Correlations between ACDC domains divided by levels of involvement, divergent, and convergent thinking scores.

	I VA	A VA	P VA	I L	A L	P L	I M	A M	P M	I PA	A PA	P PA	DF	DV	CV
Interest in visual arts	1														
Ability in visual arts	0.64**	1													
Performance in visual arts	0.40**	0.54**	1												
Interest in literature	0.50**	0.30**	0.11	1											
Ability in literature	0.27**	0.29**	0.13*	0.63**	1										
Performance in literature	0.17**	0.22**	0.16**	0.40**	0.67**	1									
Interest in music	0.45**	0.25**	0.10	0.50**	0.25**	0.20**	1								
Ability in music	0.21**	0.25**	0.19**	0.39**	0.31**	0.26**	0.56**	1							
Performance in music	0.14*	0.18*	0.24**	0.25**	0.20**	0.19**	0.41**	0.72**	1						
Interest in performing arts	0.47**	0.32**	0.10	0.59**	0.33**	0.30**	0.42**	0.27**	0.23**	1					
Ability in performing arts	0.26**	0.28**	0.07	0.32**	0.25**	0.28**	0.21**	0.25**	0.18**	0.69**	1				
Performance in performing arts	0.24**	0.23**	0.21**	0.29**	0.29**	0.37**	0.18**	0.25**	0.31**	0.52**	0.67**	1			
Divergent (Figural)	0.15*	0.14**	0.05	0.06	0.05	0.07	0.06	0.03	0.02	0.21**	0.21**	0.15**	1		
Divergent (Verbal)	0.21*	0.27**	0.11	0.28**	0.23**	0.20**	0.12	0.25**	0.11	0.24**	0.27**	0.23**	0.26**	1	
Convergent	−0.04	0.09	0.02	−0.01	−0.05	0.00	−0.06	0.02	0.02	−0.04	−0.04	−0.02	−0.01	0.06	1

ACDC, Artistic Creativity Domains Compendium, $^{*}p < 0.05$, $^{**}p < 0.01$.

ACDC and Cognition

The total score of the ACDC correlated with *verbal intelligence*. On level of involvement, *verbal intelligence* correlated with *interest*, and *ability*. *Attention* and *working memory* did not correlate with any of the levels of involvement. Correlations are presented in **Table 5**.

We also explored the relation between specific artistic domains and intelligence, attention, and working memory. On level of domains, *verbal intelligence* correlated with *visual arts, literature*, *music* and *performing arts*. *Attention* correlated with *performing arts*. *Working memory* did correlate with *literature*. All correlations are likewise shown in **Table 5**.

Further, for the artistic domains of the ACDC divided by levels of involvement *Ability* in *performing arts* correlated positively with *attention*. *Interest* in *visual arts, interest* in *literature, interest* in *music, interest* in *performance* and *ability* in *literature, ability* in *music* and *performance* in *music* correlated with *verbal intelligence*. *Interest* in *literature* and *ability* in *literature* and *performance* in *music* correlated with *working memory*. **Table 6** shows all correlations.

Finally, we also analyzed the relationship between *divergent* and *convergent thinking*, *verbal intelligence*, *attention*, and *working memory*. The *figural divergent thinking* score correlated with *attention*. The *verbal divergent thinking* score correlated with *verbal intelligence* and *working memory*. The *convergent thinking* score correlated significantly with *verbal intelligence*. These correlations are shown in **Table 7**.

DISCUSSION

We present the ACDC, a new questionnaire that covers artistic creativity in different domains (*visual arts*, *literature*, *music* and *performing arts)* on different levels of involvement (*interest in*, *ability to,* and *performance)*. We used the ACDC to investigate the relation between domains, sub-domains and levels of involvement and cognitive functions in a differentiated way. Internal consistency among the four domains as well as the levels of involvement was very good. The MTMM-model that was used to separate the domains and levels of involvement showed a good fit. It supports a model of artistic creativity that differentiates levels of involvement for each sub-domain. Moreover, the good fit of the model structure with uncorrelated domains of artistic creativity suggests a clear specificity of the scales. The indicator-reliabilities of the sub-scales were high and the factor loadings for subordinate scales were mostly high, supporting the scale-construction of the questionnaire. However, lower loadings on some sub-scales in the domains of literature and music, for instance, may reflect the skewed distribution that is typical for this kind of non-expert population (Silvia et al., 2012). In another population, for instance for a sample of authors or musicians, these items might be more selective. These results together with a good internal consistency of each of the domain scales and the total score support the necessity to assess them separately. Low factor loadings, for example in the domain *literature* are supposedly due to low variance in that particular scale. The correlations between levels of involvement are very high. However, the by far lowest correlation between interest and performance still supports our suggestion to observe the scales separately.

In the external validation of the ACDC the correlations support the hypothesis that it indeed measures forms of divergent creativity. The non-significant correlation between the ACDC and convergent thinking might suggest that artistic creativity is rather related to divergent than to convergent thinking. In future studies, tests of figural convergent creativity should be included to see if the results are similar.

On the level of artistic domains, *visual arts* and *performing arts* correlate significantly with the *divergent figural* mean-score whereas *music* and *literature* did not. These results demonstrate that the ACDC does not only assess general divergent thinking but also shows differences between the domains. Moreover, the higher correlation with *performing arts* indicates that this domain shares a higher portion of divergent figural creativity. This complements earlier findings in which physical activity was strongly correlated with higher divergent creativity (Best, 2010). To exclude the possibility that the higher correlation is due to higher physical activity in people who practice *performing arts*, it is therefore important to control for an influence of general physical activity.

TABLE 5 | Correlations between the overall ACDC-Score, ACDC-levels, ACDC-domains and cognitive functions.

	ACDC T	ACDC I	ACDC A	ACDC S	ACDC VA	ACDC L	ACDC M	ACDC PA	VI	A	WM
ACDC total	1										
ACDC interest	0.95**	1									
ACDC ability	0.86**	0.69**	1								
ACDC performance	0.70**	0.49**	0.70**	1							
Visual arts	0.74**	0.71**	0.63**	0.48**	1						
Literature	0.76**	0.76**	0.62**	0.46**	0.43**	1					
Music	0.74**	0.68**	0.72**	0.51**	0.37**	0.48**	1				
Performing arts	0.79**	0.74**	0.65**	0.64**	0.41**	0.53**	0.38**	1			
Verbal intelligence	0.25**	0.27**	0.19**	0.09	0.15*	0.27**	0.23**	0.13*	1		
Attention	−0.00	−0.03	0.04	0.01	−0.11	−0.06	−0.04	0.16**	0.15*	1	
Working memory	0.03	−0.02	0.11	0.08	−0.04	0.14**	0.02	0.02	0.22**	0.10	1

*ACDC, Artistic Creativity Domains Compendium, *p < 0.05, **p < 0.01.*

TABLE 6 | Correlations between ACDC domains divided by levels of involvement, divergent, and convergent thinking scores.

	I VA	A VA	P VA	I L	A L	P L	I M	A M	P M	I PA	A PA	P PA	VI	A	WM
Interest in visual arts	1														
Ability in visual arts	0.64**	1													
Performance in visual arts	0.40**	0.54**	1												
Interest in literature	0.50**	0.30**	0.11	1											
Ability in literature	0.27**	0.29**	0.13*	0.63**	1										
Performance in literature	0.17**	0.22**	0.16**	0.40**	0.67**	1									
Interest in music	0.45**	0.25**	0.10	0.50**	0.25**	0.20**	1								
Ability in music	0.21**	0.25**	0.19**	0.39**	0.31**	0.26**	0.56**	1							
Performance in music	0.14*	0.18*	0.24**	0.25**	0.20**	0.19**	0.41**	0.72**	1						
Interest in performing arts	0.47**	0.32**	0.10	0.59**	0.33**	0.30**	0.42**	0.27**	0.23**	1					
Ability in performing arts	0.26**	0.28**	0.07	0.32**	0.25**	0.28**	0.21**	0.25**	0.18**	0.69**	1				
Performance in performing arts	0.24**	0.23**	0.21**	0.29**	0.29**	0.37**	0.18**	0.25**	0.31**	0.52**	0.67**	1			
Verbal intelligence	0.21**	0.05	−0.01	0.30**	0.14*	0.08	0.19**	0.22**	0.15*	0.15*	0.09	0.05	1		
Attention	−0.12	−0.06	−0.07	−0.05	−0.10	−0.01	−0.06	0.01	−0.06	0.12	0.22**	0.11	0.15*	1	
Working memory	−0.08	0.04	−0.01	0.12*	0.17**	0.04	−0.08	0.11	0.15*	−0.00	0.03	0.04	0.22**	0.10	1

*ACDC, Artistic Creativity Domains Compendium, *$p < 0.05$, **$p < 0.01$.*

TABLE 7 | Correlations between divergent and convergent thinking, intelligence, attention, and working memory.

	DF	DV	CV	Intelligence	Attention	WM
Divergent (Figural)	1					
Divergent (Verbal)	0.26**	1				
Convergent	−0.01	0.06	1			
Verbal intelligence	0.07	0.32**	0.20**	1		
Attention	0.13*	0.12	0.01	0.15*	1	
Working memory	0.05	0.19**	0.06	0.22**	0.10	1

*$p < 0.05$, **$p < 0.01$.

The significant correlation between each of the domains *visual arts, music, literature,* and *performing arts* of the ACDC and the *divergent verbal* mean-score, with *literature* correlating highest, suggests that the domain *literature* might share the highest portion of verbal divergent thinking. On level of involvement, the ACDC levels *interest, ability,* and *performance* correlated significantly with *figural* and *verbal divergent thinking.* For verbal divergent thinking, *ability,* as assessed with the ACDC, showed a higher correlation. This result indicates that the divergent verbal tests represent divergent creative thinking best on the medium level of involvement.

In sum, the external validation of the ACDC with divergent and convergent tests indicates that the questionnaire measures the construct "artistic creativity" that correlates with divergent creativity and does not overlap with convergent creativity. Moreover, the differing results among domains and levels of involvement concerning figural and verbal scores support the expected separation of domains and levels of involvement.

Further, the analysis of the correlations between the ACDC, intelligence, attention and working memory also showed interesting results. Only *verbal intelligence* correlated significantly with the ACDC sum score together with all four domains *visual arts, literature*, *music* and *performing arts* on domain-level. These results indicate a relation between artistic creativity and intelligence that is not domain specific. A relationship between musicality and intelligence has been investigated by previous studies (Schellenberg, 2004; Moreno et al., 2011). The division of domains by level of involvement shows that on level of *ability* or *performance* only *ability* in *music* and *literature* and *performance* in *music* correlate significantly with *verbal intelligence*. On level of involvement *interest* and *ability* correlated significantly with the *verbal intelligence*, with *interest* correlating higher than *ability.* On level of *interest*, *interest* in *visual arts, literature, music* and *performing arts* correlated with *verbal intelligence*. These results, showing that interest in several domains is related to *verbal intelligence*, complement findings that people scoring high on openness to experience also show higher intelligence scores (Silvia and Sanders, 2010).

Attention correlated significantly positive with *performing arts* overall as well as *ability* in *performing arts.* This indicates the importance of a differentiated assessment of forms, domains and sub-domains of creativity and anticipate different processes for them. The fact that *ability* in *performing arts* correlated significantly with attention gives interesting insights into potential mechanisms of this domain. Here, action taking might be important. Attention could play a crucial role in the execution of *performing arts* like dance and play. It remains to clarify if the effects arise from a higher proportion of physical activity in general as described before concerning *performing arts* and divergent creativity (Best, 2010). Future studies should control with questions about weekly physical activity. The negative correlation of *visual arts* with attention sheds further light on the differing former results concerning its relation with divergent verbal and figural and artistic thinking.

Working memory correlated with *literature* overall and with *interest* and *ability* in *literature.* As the RST is a verbal working memory task future studies should relate the ACDC to non-verbal tests of working memory.

To further analyze the correlations between artistic creativity and cognitive functioning we compared them to the correlations obtained between divergent and convergent tests and cognitive functioning. The divergent figural creative test correlated positively with attention whereas the verbal test did not. The fact that both parties also significantly correlate with *performing arts,* lead to hypothesize a domain specific positive relation between divergent figural creativity and attention, specifically triggered by *performing arts.* Only the divergent verbal task on the other hand, correlated with *verbal intelligence* and the working memory task. This seems to provide evidence that divergent verbal and figural creative tasks and the different ACDC scales do not exclusively measure the same share of creativity. Moreover, it leads to the question if other forms of creativity, for example scientific creativity, would correlate differently with measures of working memory. Future studies that aim to investigate other forms of creativity could shed light on this question. A*s* the RST is a verbal measurement of working memory, a different pattern of relationships may emerge for figural or numerical working memory tasks. Same applies for measures of intelligence. In future studies, figural intelligence tests could also be included to clarify if the relation between artistic creativity and intelligence is specific for *verbal intelligence*.

CONCLUSION

The ACDC is a new easy to use questionnaire that enables to assess artistic creativity in several domains and sub-domains. It provides separate scales for interest, ability, and performance, providing for fine-grained results. Moreover, the ACDC offers the possibility to study changes across development, in training studies, or to follow up on pathological changes. It also gives the opportunity to investigate relationships between different aspects of artistic creativity and personality traits, affective, or cognitive style in a straight-forward way. Further, our results show that relationships between creativity and cognitive functioning are most pronounced within domains and at the level of interest and ability. They show that different domains and sub-domains build on different cognitive functions. Interestingly all four domains of artistic creativity, on a level of interest, rather relate to more complex cognitive functions like *verbal intelligence*, than to basic cognitive functions like attention. This is important for future research in order to disentangle the relationships between different domains of creativity and general aspects of cognition.

AUTHOR CONTRIBUTIONS

All authors listed, have made substantial, direct and intellectual contribution to the work, and approved it for publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2016.01089

TABLE S1 | Artistic Creativity Domains Compendium (ACDC).

IMAGE 1 | ACDC-Profile.

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