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What Box?': behavioral, neuro-imaging, and training studies on the development of creative cognition in adolescence

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Sietske W. Kleibeuker



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training studies on the development
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‘What box?’

Behavioral, neuro-imaging, and training studies on the
development of creative cognition in adolescence

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CHAPTER 1

General introduction

‘The Ministry of Education, Science and Culture is working on a creative nation, and recognizes the importance of creative development in education’

Creative thinking has been indicated as ‘the premier 21st century skill’, and not without reason. In our current *knowledge society*, continuous innovation is critical, and information bases rapidly change and grow. Consequently, flexibility and the ability to think out of the box, to think divergently (or to generate and test multiple problem solutions instead of a single one) and to gain insight, are valued more than ever before.

These statements underscore the importance of creative thinking in our society and point toward the particular relevance of creativity development. They also raise important questions, including ‘What does creative thinking mean? Does the ability to think creatively develop across childhood and adolescence, and how? Which neural mechanisms are involved during creative performance and, how (if possible) can creativity be improved?’ Research on creative thinking development in adolescence to adulthood is severely lacking, yet this age group deserves close examination, as they are our future thought leaders.

From studies in related research fields, there is evidence that adolescence is a time period for crucial development of cognitive abilities (Casey, Jones, & Hare, 2008; Steinberg, 2005), and adolescents’ brain demonstrates marked changes in structure and function (Luna, et al., 2010; Giedd and Rapoport, 2010; Shaw et al., 2008). This thesis therefore, focuses on this age group and transition period in order to address the above questions.

To study the mechanisms underlying creative thinking development, the research in this thesis combines behavioral measures with brain activation, as measured with functional magnetic resonance imaging (fMRI), across domains and ages, in both single test and longitudinal training designs. This allowed me to examine both age- and experience-related effects on creative thinking performance during functional brain development. Before describing the performed research and consequent results in Chapters 2 to 6, this chapter will provide an introduction to the theory of

creative thinking, including the theoretical framework that has been incorporated to understand the processes underlying creative thinking. Subsequently, relevant prior research on the neural correlates of creative thinking is discussed. A short introduction of the adolescent period is then given, followed by an overview of prior research on creative thinking training. The introduction chapter finishes by providing the main goal of the thesis and a short overview of the upcoming chapters.

What is creative thinking?

Creativity is commonly referred to as the ability to generate ideas, insights and solutions that are both original and feasible (e.g. Amabile, 1996; Sternberg & Lubart, 1996). As such, creative outcomes should be new and uncommon, yet also potentially useful and relevant; original but infeasible ideas are commonly strange whereas ideas that are feasible but not original are mundane, and in a sense, boring. Creativity is believed to be one of humans' most important and complex behaviors. For example, creative insights solve daily problems, (e.g., use a broom to obtain a toy from under the couch); are requisite for scientific breakthroughs; and creative strategizing allows one to win competitions (De Dreu & Nijstad, 2008). To understand creative performance, the present dissertation builds upon the creative cognition approach which identifies creative success as inherent to normal human cognitive functioning (Ward, Smith, & Finke, 1999), and emphasizes the dependency on fundamental cognitive functions, such as working memory and executive control (Nijstad, De Dreu, Rietzschel, & Baas, 2010; Sowden, Pringle & Gabora, 2014). Accordingly, the development of creative capacities are considered to be related to the development of supporting cognitive functions, and, concurrently, creativity training success is considered to be depended on the trainability of its supporting functions.

Although the exact processes supporting creative outcomes are still under debate, it has become common to describe creative thinking through so called *dual-process models* of creative thinking. In cognitive and social psychology, dual-process models generally include two ways of achieving one's goal: 1) through fast, implicit and associative processing; and 2) through deliberate, effortful and logical processing (Chaiken & Trope, 1999). In the field of creative cognition, dual-process models commonly imply that both types of processing are involved to establish creative solutions that are both imaginative and useful.

A specific type of dual processing model, *The Dual Pathway to Creativity Model* (Baas, De Dreu & Nijstad, 2008; De Dreu, Baas, & Nijstad, 2008; Nijstad et al, 2010; Rietzschel, De

Dreu, & Nijstad, 2007), describes creative outputs as the result of 1) cognitive flexibility, and 2) cognitive persistence. According to the model, cognitive flexibility enables accessibility to multiple and broad cognitive categories; flexible switching between these categories; and a global processing style or broad focus. Cognitive persistence, on the other hand, is associated with focused and systematic effort, in-depth exploration of a relatively small number of cognitive categories, and a local processing style or narrow focus (De Dreu et al., 2008; 2012). Indeed, a vast body of research has shown that creative performance can be achieved through both a flexible and divergent way of thinking (e.g., Duncker, 1945; Oppenheimer, 2008; Simonton, 1997; Winkielman, Schwarz, Fazendeiro, & Reber, 2003), as well as a persistent and systematic way of thinking (Dietrich, 2004; Dietrich & Kanso, 2010; Finke, 1996; Rietzschel, Nijstad, & Stroebe, 2007; Sagiv, Arieli, Goldenberg, & Goldschmidt, 2009; Simonton, 1997). It is commonly assumed, as with other dual-process models, that creative outcomes are the product of both processing types, with different contribution ratios and, dependency on the type of task as well as individual functioning.

To date, creativity research has mainly focused on two types of cognitive functions that represent creative potential: *divergent thinking* and *insight*. Divergent thinking is the most commonly tested function in creativity research, and is considered an important component of the creative process as it captures one's capacity to create novelty (Torrance, 1966). Divergent thinking tasks require the generation of multiple solutions to an open-ended problem (Guilford, 1967) and have been shown to have significant predictive value for creative success (Kim, 2008). Divergent thinking can be measured in different domains. In this thesis, I studied the Alternate Uses Task (AUT) to test divergent thinking in the verbal domain, and the Creativity Ability Test (CAT) and the Matchstick Problem Task (MPT) to test divergent thinking in the visuo-spatial domain. The AUT requires individuals to think of as many unusual uses for a common object, for example, for a *brick*. The CAT and MPT involve pre-described rules that participants must adhere to when instructed to find as many solutions as possible. The CAT consists of squares including figures. Participants are asked to compose triads of squares based on the properties (e.g., number, position) of the figures included. The MPT involves an arrangement of matches that must be reorganized to make other pre-described patterns by removing a number of matchsticks. To solve these kinds of problems (CAT & MPT), one is required to overcome mental fixation. In case of the CAT, mental fixation is created due to one's own (prior) solution. In case of the MPT, fixation is the result of initially presented formation of matchsticks.

Creative performance in divergent thinking tasks is commonly expressed in terms of *fluency*, *flexibility* and *originality* (Guilford, 1967; Torrance, 1966). Fluency refers to the number of ideas, insights, problem solutions, or products that are generated. Larger numbers of ideas are associated with better creative performance under the assumption that quantity breeds quality. Flexibility refers to the generation of different conceptual categories or themes of ideas, and as such, requires overcoming mental fixedness; in case of the AUT *brick*, ‘building’ and ‘weight’ would be two different solution categories - the more different the categories, the more flexible a person is. The third measure of creative performance, originality, refers to the uniqueness or infrequency of solutions and ideas. The originality of an idea or solution is generally expressed in terms of a) ‘uniqueness’ which corresponds to a certain score assigned by an experienced scorer (or set of), or b) ‘infrequency’ as calculated by taking into account the number of appearances of a certain solution across the total of solutions generated by the entire pool of participants. Fluency and originality may be correlated (under the assumption of ‘quantity breeds quality’; Diehl & Stroebe, 1987), but it is not necessary, since one might generate a large number of solutions or ideas without uniqueness or originality (see De Dreu et al., 2008; Förster, Friedman, & Liberman, 2004). Fluency and flexibility are commonly related, at least to a certain degree; generating ideas or solutions in various categories will be associated with more ideas/solutions overall (Nijstad, Stroebe, & Lodewijx, 2002). Flexibility may also be correlated to originality as larger numbers of conceptual categories increase the chance that uncommon categories are used and, consequently, relatively uncommon solutions are generated (Rietzschel et al., 2007). It should be noted that flexibility is not only a measure of creative performance, but refers to a cognitive process where it includes the ability to break set and use flat associative hierarchies of concepts (see above; *The Dual Pathway to Creativity Model*; Baas et al., 2008; De Dreu et al., 2008; Nijstad et al., 2010; Rietzschel et al., 2007).

Insight tasks, in contrast to divergent thinking tasks, have a demonstrable correct solution. This type of task generally requires establishing associations among previously unrelated or weakly related information, and mentally restructuring the problem space (Förster et al., 2004; Smith & Kounios, 1996). Insight solutions differ from non-insight solutions in that 1) solvers experience their solutions as sudden and have an ‘aha!’ experience; 2) prior to producing an insight, solution solvers sometimes come to an impasse, a state of high uncertainty as to how to proceed; and 3) solvers usually cannot report the processing that led them to the solution. Common to divergent thinking tasks, insight tasks also have the pretension to measure creative potential; both types of tasks are associated with creative ability, but address different aspects of

the creative process. Commonly used tasks used in the present thesis include the Gestalt Completion Task (GCT; Eckstrom et al., 1976), the Snowy Picture Task (SPT; Eckstrom et al., 1976) and the Remote Associates Task (RAT; Mednick, 1962). The first two tasks (GCT & SPT) capture insight ability in the visual domain whereas RAT focuses on insight ability in the verbal domain. The GCT consists of fragmented pictures and requires one to imaginatively complete them. In the SPT, participants are presented with a series of images of familiar objects hidden within visual noise. Participants need to disregard misleading interpretations that are rendered by the context to identify the objects. The RAT consists of triads of words and requires one to find a fourth, related word. As such, these insight tasks involve unifying complex or remotely associated information to find a single optimum solution that is retrieved from memory. To gain insight into the development of the complex construct of creative cognition, the current thesis includes a broad set of tasks capturing insight and divergent thinking in the verbal and visual domain.

Neural correlates of creativity

Neuroimaging is a useful method for gaining insight in the processes underlying creative success. In the current thesis, I have used fMRI for studying creative thinking in the visuospatial (Chapter 3) and verbal domain (Chapters 4 & 6). fMRI is a method that utilizes the Blood Oxygenation Level Dependent (BOLD) signal and examines which brain regions are activated during task performance. In recent years, several researchers have investigated creative cognition using lesion studies and neuroimaging techniques, including fMRI. Results are, however, not yet conclusive about the neural underpinnings of this complex construct (Arden, Chavez, Grazioplene, & Jung 2010; Dietrich & Kanso, 2010), and differences between study outcomes are likely related to the various designs capturing different aspects of creative thinking. Despite this, there is consensus that the (lateral parts of) the prefrontal cortex (PFC) plays a role in creative success. This brain region is generally associated with cognitive control functioning and coordinating lower level (associative) brain regions (e.g., Miller & Cohen, 2001), and is involved in both insight and divergent thinking tasks (see e.g., Arden et al., 2010; Dietrich & Kanso, 2010).

Matchstick Problem Tasks (MPT; Guilford, 1967) have previously been used to shed light on the processes underlying creative problem solving. Using MPT and related tasks, neuropsychological and brain imaging studies revealed the involvement of the lateral PFC in creative problem solving. For example, comparison of healthy controls to patients with lesions in different brain regions showed that patients with (right) frontal lesions were impaired in solving

creative problems. Performances were most significantly impaired when strategy switches were required, indicating a role for lateral PFC regions particular in flexibility. Accordingly, an fMRI study in healthy adults demonstrated increased activation in bilateral ventral and dorsal PFC while solving matchstick problems, compared to brain activity while verifying a given solution to a matchstick problem (Goel & Vartanian, 2005). Furthermore, activation in the right dorsolateral PFC (DLPFC) correlated with the percentage of traced solutions, indicating that this region contributes to exploratory success.

The AUT and adapted versions of this verbal divergent thinking task are also commonly applied to gain insight into the underpinnings of creative cognition. Although there are differences between outcomes for these tasks, a relatively consistent finding is the involvement of (left) temporo-parietal regions, including the angular gyrus (AG) and the supramarginal gyrus (SMG) (Arden et al., 2010; Dietrich & Kanso, 2010). For example, Fink et al. (2009, 2010) compared brain activations for generating alternative uses (AU) with activations for retrieving ordinary characteristics (OC) to capture brain regions involved in creative idea generation. Their results revealed increased activity in left angular gyrus (AG) and supramarginal gyrus (SMG). Other researchers utilizing (verbal) divergent thinking paradigms relatively consistently found activations of the PFC (e.g., Abraham et al., 2012; Carlsson, Wendt, & Risberg, 2000; Chavez-Eakle et al., 2007; Folley & Park, 2005; Howard-Jones, et al., 2005; Mashal, Faust, Hendler, & Jung-Beeman, 2007). Notably, a substantial part of these studies revealed positive relations between PFC activations and creative performances (e.g., Carlsson et al., 2000; Chavez et al., 2004; Chavez-Eakle et al., 2007; Gibson, Folley, & Park, 2009). Together, these findings indicate that temporo-parietal regions are involved in divergent thinking processes in general, whereas the ability to recruit PFC successfully might be discriminative for creative capacities. In the current thesis we applied adapted versions of the MPT (Chapter 3) and AUT (Chapter 4) while scanning to examine how creative thinking develops from adolescence to adulthood.

Adolescence

As described above, we focus on creative thinking in adolescence. The particular interest for in this period between childhood and adulthood is related to the characteristics of this period. The onset of adolescence is determined by biological processes as it is characterized by the start of pubertal maturation. The onset typically takes place between 9 and 12 years of age (usually 1 to 2 years later in boys than in girls). The end of adolescence is less explicitly determined as it is partly

culturally defined. Adolescence typically extends into the early 20s when major physical changes have occurred and individual independence in society attained (Crone en Dahl, 2012; Lerner & Steinberg, 2004).

Adolescence is a developmental stage characterized by transformations toward life independency, a period in which individuals come to terms with themselves and their environment. Successful development toward mature adult functioning is associated with creativity and related functions such as exploration and cognitive flexibility. Indeed explorative behavior is essential to develop one's identity, and adolescence has a natural time of learning and adjustment and requires flexibility in thought and action. Hence, adolescence is expected to involve important changes in creative capacities.

Research on creative thinking development throughout adolescence is scarce. Prior research mainly focused on divergent thinking in elementary grades, and only few have investigated development beyond age 12. These studies indicate that performances improve with age from childhood throughout adolescence (e.g., Runco and Bahleda, 1986; Lau and Cheung, 2010), but that performance slumps may occur at different stages in adolescence (Claxton, Pannels & Roads, 2005; Lau and Cheung, 2010). Studies including comparisons between adolescents and adults are also lacking. In one study where early adolescents were compared to adults on divergent thinking fluency and flexibility, no age effects were observed (Wu et al., 2005). The question of how creativity develops between late childhood and adulthood for the broader domain of creativity still remains.

Adolescence is also a time period with crucial development of many cognitive abilities (see e.g., Casey et al., 2008; Steinberg, 2005), especially of PFC functioning-related abilities including working memory and cognitive control. Since these functions are assumed to be related to creative cognition, an interesting question addressed in this thesis is how adolescent-specific changes in PFC functioning relate to creative success.

Previous studies demonstrate that adolescent brains are capable of changing, both structurally and functionally (Luna, et al., 2010; Giedd and Rapoport, 2010; Shaw et al., 2008). Early studies of post-mortem brain tissue reported that the PFC displays great changes well into the adolescent period and are revealed by marked reorganizations of synapses in this region (Huttenlocher, 1979). It is well known, today, that PFC regions are upon the last to mature. Additionally, large-scale longitudinal brain imaging studies identified significant changes during adolescence in gray matter volume. More specifically, these studies revealed that lateral PFC

matures throughout adolescence, following an inverted U-shaped pattern with a peak in early adolescence (Gogtay et al., 2004); they also demonstrated varying developmental trajectories of gray matter for different regions within the PFC (Gogtay & Thompson, 2010). Moreover, functional neuroimaging studies indicate age-related changes of PFC activations for several cognitive functions including working memory, interference control and task-switching (for a review, see Bunge and Wright, 2007).

There is, however, inconsistency among reports of age-related changes in developmental trajectories. Functional neuroimaging studies have reported different developmental trajectories showing that prefrontal cortex is both *more* activated (e.g., Adleman et al., 2002; Crone et al., 2006c), and *less* activated with increasing age (e.g., Durston, et al., 2006; Morton et al., 2009). Age-related increases are commonly interpreted as an increase of the ability to recruit referred brain regions, whereas age-related decreases are often interpreted as increasing efficiency of referred brain regions. Intriguingly, some studies reported a specific peak in lateral PFC activation in middle adolescents (e.g., Crone, et al., 2006a; Dumontheil, et al., 2010). These studies, therefore, appear to challenge the above-mentioned relative simplistic maturational interpretations.

Adolescence is also associated with elevated levels of dopamine in the PFC (see Casey et al., 2008; Spear, 2000). These elevated levels have been shown to induce broadened attention toward externally presented stimuli and explorative behavior (Grey, Buhusi & Scmajuk, 1997). Taken together, PFC function during this transitional phase may not only be associated with limitations in cognitive control-related functions, but may also be tuned specifically toward exploration and adaptive flexibility (Crone & Dahl, 2012; Dahl, 2008; Johnsson & Willbrecht, 2012). Since both cognitive control and explorative behavior have been associated with creative success, the current thesis aims to gain insight into adolescent PFC functioning during different aspects of creative cognition, including creative problem solving and verbal divergent thinking.

Creative thinking training

To extend investigations into the development of creative ideation, this thesis includes creative thinking training effects on adolescents' performances and brain functions utilizing simple practice paradigms. Various studies have already demonstrated the effectiveness of training paradigms in improving creativity in both adults (Glover, 1980; Bott et al., 2014; Kienitz et al., 2014) and children (Torrance, 1972; Cliatt et al., 1980). However, relatively little is known about how malleable creative thinking is in adolescence. Training studies in other higher cognitive skills

include working memory (Klingberg, 2010; Jolles et al., 2012), executive control (Karch and Kray, 2009; Zinke et al., 2012), relational reasoning (Dumontheil et al., 2010), and algebraic equation solving (Qin et al., 2004), and emphasize the training susceptibility regarding performance and brain function during adolescence. In the current thesis we aim to gain insight into the malleability of the adolescent brain with regard to the development of creative thinking skills.

Numerous studies have examined creative thinking training effects on the behavioral level, yet relatively little research has focused on neuronal level. One AUT training study using EEG showed higher synchronization in frontal alpha activity after two weeks of AUT training (Fink et al., 2006), but it is not yet known how this relates to neural activation changes in the different brain regions involved in divergent thinking. A more commonly used approach to enhance creative performance in neuroimaging research involves cognitive stimulation by providing (moderately) creative ideas. Several studies have found this approach to be effective and training has been associated with functional changes of the (left) temporo-parietal, including the left MTG and PFC regions. An important question addressed in the current thesis concerns how activity in these regions changes through creative thinking training in adolescence. This will allow us to have a better understanding of how training-related changes in adolescents take place.

The current thesis

The main goal of this thesis is to gain insight into the development of creative thinking across adolescence and into adulthood. To this end, we utilized a range of creativity tasks, both with and without an fMRI scanner, and before and after training paradigms. This approach allowed me to examine 1) the differential developmental trajectories of various aspects of creative thinking; 2) the development of related neural processes; and 3) the potential toward creative thinking in adolescence.

In Chapter 2, I examined developmental trajectories of creative cognition across development. To this end, participants in four age groups (12-13 yrs, 14-15 yrs, 15-16 yrs, and 25-30 yrs) were subjected to a battery of tasks including the SPT, GCT and RAT to examine insight performance in the visual and verbal domains, and the CAT and the AUT to examine divergent thinking performance in the visuo-spatial and verbal domains, respectively.

The second empirical study, described in Chapter 3, examined behavioral and neural differences for creative problem solving in middle-adolescents (15-17 yrs) and adults (25-30 yrs). Performances and neural activations were measured while performing a matchstick problem Task (MPT) in the fMRI scanner. In addition, performances for the CAT were obtained outside the scanner and related to neural activations during the MPT. Chapter 4 examined the neural correlates of divergent thinking in adults (25-30 yrs) and adolescents (15-17 yrs). To this end, participants generated alternative uses (AU) or ordinary characteristics (OC) for common objects while brain activity was assessed using fMRI. Chapter 5 focused on whether performance could be improved by practicing alternative uses generation. The effectiveness of creative ideation training was examined in adolescents (13-16 yrs) and adults (23-30 yrs) measuring creative ideation performances on two versions of the AUT. Participants followed one of three training types, each comprising eight 20-minute sessions within 2 weeks time: 1) alternative uses generation (experimental condition); 2) object characteristic naming (control condition); or 3) rule-switching (control condition).

In Chapter 6, we tested the benefits of training creativity in adolescents. To this end, behavior and neural activity in 15-16-year-old adolescents performing an AUT task in the scanner were compared before and after two weeks of divergent thinking training, and we compared this to AUT activity in an active control group who performed a task-switching training program. Finally, Chapter 7 summarizes the main results of the empirical studies presented in this thesis. Here, implications of the results are discussed and suggestions for future research are presented.

CHAPTER 2

The development of creative cognition across adolescence: distinct trajectories for insight and divergent thinking

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Abstract

We examined developmental trajectories of creative cognition across adolescence. Participants ($N = 98$), divided into four age groups (12/13 years, 15/16 years, 18/19 years, and 25-30 years), were subjected to a battery of tasks gauging creative insight (visual; verbal) and divergent thinking (verbal; visuo-spatial). The two older age groups outperformed the two younger age groups on insight tasks. The 25-30-year olds outperformed the two youngest age groups on the *originality* measure of verbal divergent thinking. No age-group differences were observed for verbal divergent thinking *fluency* and *flexibility*. On divergent thinking in the visuo-spatial domain, however, only 15/16-year-olds outperformed 12/13-year-olds; a model with peak performance for 15/16-year-olds showed the best fit. The results for the different creativity processes are discussed in relation to cognitive and related neurobiological models. We conclude that middle adolescence is a period of not only immaturities but also of creative potentials in the visuo-spatial domain, possibly related to developing control functions and explorative behavior.

Introduction

Creativity is considered a cornerstone of human society. Creativity is defined as the ability to generate ideas and problem solutions that are both novel and appropriate (Amabile, 1996; Sternberg & Lubart, 1996), and is a prerequisite for human survival and prosperity (Runco, 2004). For example, creative insights solve daily problems (Runco, 2004), artistic creativity promotes mate attraction (Griskevicius, Cialdini, & Kenrick, 2006; Miller, 2000), and creative strategizing allows one to win competition and conflicts (De Dreu & Nijstad, 2008). These and related insights suggest that creativity provides fitness and functionality, in that individuals with creative ability have higher probability of surviving and prospering than those lacking creative abilities.

Across human development, adolescence is an age period characterized by transformations toward life independency (Collins, Gleason, & Sesma, 1997; Hill & Holmbeck, 1986), and is a crucial phase for the development of many cognitive abilities (see e.g., Casey, Jones, & Hare, 2008; Steinberg, 2005). It has been argued that creative problem solving abilities are necessary and important skills facilitating the advancement toward mature adult functioning (Jaquish & Ripple, 1980). Hence, adolescence is expected to involve important changes in creative abilities. The aim of the current study was therefore to examine creative abilities across this transitional age period measuring two cognitive functions that represent creative potential: *insight* and *divergent thinking*.

Creative insight and divergent thinking

Insight tasks are commonly used to understand performance in creative problem solving situations (e.g., De Dreu, Baas, & Nijstad, 2008; Friedman & Förster, 2001; Harkins, 2006; Kounios & Beeman, 2009). Insight tasks typically require establishing associations among previously unrelated or weakly related information, and mental restructuring the problem space; processes which have a central role in creative cognition (Förster, Friedman, Liberman, 2004; Smith & Kounios, 1996). There is widespread agreement that insight solutions differ from non-insight solutions in that: 1) solvers experience their solutions as sudden and obviously correct; 2) prior to producing an insight solution solvers sometimes come to an impasse, no longer progressing toward a solution; 3) solvers usually cannot report the processing that enables them to overcome an impasse and reach a solution.

The second type of task, divergent thinking, is commonly used to verify creative potential and captures the extent to which individuals create novelty (Torrance, 1966). Divergent thinking

tasks generally require participants to generate multiple solutions to an open ended problem (Guilford, 1967). The rationale behind these tasks is that creative success is assumed to be related to; a) one's ability to generate many responses (fluency), under the assumption that quantity breeds quality; b) the ability to generate responses in many different conceptual categories (flexibility); and c) the ability to generate unusual or infrequently generated responses (originality) (Guilford, 1950, 1967). Insight and divergent thinking are both associated with the ability to be creative, yet represent different aspects of the creative process.

It is important to distinguish divergent thinking from convergent thinking, as both have been associated with creative cognition (Cropley, 2006; Guilford 1950, 1967; DeYoung et al., 2008). As summarized above, divergent thinking refers to the ability to generate multiple associations to an idea in a random, unorganized way (Baas, De Dreu, & Nijstad, 2008; Friedman & Förster, 2000; Isen & Daubman, 1984; Martindale, Hines, Mitchell, & Covello, 1984). Convergent thinking, however, refers to an analytical and evaluative thinking mode, associated with discovering relations among information, and represents the capacity to quickly focus on the one best solution to a problem (Guilford, 1967; Gaborra, 2010; Runco, 2004). Consequently, convergent thinking has previously been related to cognitive control functioning and general intelligence (De Haan, 2009; Runco, 2004).

Prior research on creativity development mainly focused on divergent thinking but most authors documented divergent thinking only in elementary grades, and few have investigated development beyond age 12. For example Claxton, Pannels, and Rhoads (2005) performed a longitudinal study on figural divergent thinking, examining participant from 4th, 6th and 9th grade. Few age differences were apparent, although they observed a slump in originality for 6th graders. Jacquish and Ripple applied a verbal task in which participants had to respond to presented sounds. Comparisons between pre-adolescents ($M_{age} = 10.8$ years) and adolescents ($M_{age} = 16.4$ years) showed increased fluency and flexibility for the adolescents, but no changes in originality. Runco and Bachleda (1987) used a different and extensive set of divergent thinking tasks across 5th to 8th graders. Performance on the measures of verbal divergent thinking changed as a linear function of age. Lau and Cheung (2010) applied a similar set of tests to 4th to 9th graders, but showed that changes may be non-linear. They observed increased performances from 4th to 5th grade, a decrease to 7th graders, and then an increase in divergent thinking in 9th graders. Studies including comparisons between adolescents and adults are scarce. In one study, where participants had to come up with unusual uses for a common object, comparing 6th graders with university

students revealed no age related changes for verbal divergent thinking (Wu, Cheng, Ip, McBride-Chang, 2010). This set of findings indicates that developmental changes differ between study methods, even within one type of creative cognition task such as divergent thinking. Moreover, this review of findings sets out the lack of research on development of creativity throughout the period of adolescence. In all, it leads to the question how creativity develops between late childhood, adolescence and adulthood for the broader domain of creativity, assessing divergent thinking and creative insight within the same individuals. The broader assessment in the same individuals is needed to unravel whether there are different developmental patterns for different aspects of creative cognition, and to understand how these aspects are related. To our knowledge the current study is the first to assess both insight and divergent thinking capacities from adolescence to adulthood.

The current study

A set of creativity tasks was administered to early (12/13 years), middle (15/16 years) and late adolescents (18/19 years) as well as adults (25-30 years). The battery included three creative insight tasks: the Gestalt Completion Test (GCT; De Dreu, Baas & Nijstad, 2008; Eckstrom, French, Harman, & Demen, 1976), the Snowy Picture Test (SPT; Baas, De Dreu, & Nijstad, 2011; Friedman & Förster, 2000, 2001; Eckstrom et al., 1976) and the Remote Associates Test (RAT; Mednick 1962), and two tasks gauging divergent thinking: the Alternate Uses Test (AUT; Torrance, 1966) and the Creative Ability Test (CAT, Van Dam & Van Wesel, 2006).

The three insight tasks all tap into insight but for different domains; visual or verbal. The GCT consists of fragments of pictures, the SPT consists of pictures blurred through complex patterns of visual noise, and the RAT consists of triads of words and requires participants to find a fourth related word. All insight tasks involve restructuring and unifying complex or remotely associated information to find a single optimum solution that is retrieved from memory. As such, these tasks require divergent but also convergent thinking (Guilford, 1950) as well as general knowledge, for which we expected to find age related increases.

The two divergent thinking tasks also focused on different domains, verbal and visuo-spatial. The Alternate Uses Test (AUT, Torrance, 1966) requires participants to specify as many original uses for a well-known object (e.g., brick) as they can; these are assessed in terms of fluency, flexibility and originality. Based on prior research using similar tests (Wu et al, 2010), we did not expect performance differences between the younger and older age groups. The second test, the CAT, is a visuo-spatial task in which participants are instructed to find as many matching

figures as possible according to prespecified rules. To find correct solutions to the CAT, relations among objects have to be retrieved based on corresponding features. The CAT requires some degree of convergent thinking as participants need to incorporate provided rules. It shows some similarities with relational reasoning tasks and tasks that test for frontal lobe functioning in terms of cognitive flexibility, e.g., the Wisconsin Card-Sorting Test (WCST; Myake et al., 2000). The nature of the CAT is, however, divergent rather than convergent, as rules are not provided about *where* solutions might be found or *what* solutions might look like. As such, the task differs from relational reasoning and cognitive flexibility tasks. We expected performance increases across the younger age groups, but we did not expect this task to be related to insight tasks.

Methods

Participants

Ninety-eight participants were divided into four age groups: 25 12/13-year-olds ($M = 13.10$ years, $SD = .47$, 13 male), 30 15/16-year-olds ($M = 16.07$ years, $SD = .48$, 13 male), 25 18/19-year-olds ($M = 19.12$ years, $SD = .50$, eight male), and 18 25-30-year-olds ($M = 27.03$, $SD = 1.81$, eight male). Gender distributions did not significantly differ across age groups ($\chi^2(3, N = 98) = 2.13, p = .55$). Participants were recruited from local schools (early and middle adolescents), from Leiden University (late adolescents and adults), and through local advertisements. All participants provided informed consent. In the case of minors, consent was also obtained from primary caregivers. To screen for behavioral problems participants from all age groups filled out the self-report version of the Strengths and Difficulties Questionnaire (SDQ; Goodman, 1997). Total scores for the two youngest age groups fell in the non-clinical range. No standard scores were available for ages >18 years, but scores from the older age groups did not differ significantly from the younger age groups. Depending on age and testing location, participants received a fixed payment, course credits, or a present.

Cognitive and behavioral assessment

Creativity has been associated with intelligence (Furnham & Bachtiar, 2008; Batey, Furnham, & Safiullina, 2010), working memory (De Dreu, Nijstad, Baas, Wolsink & Roskes, in press; Oberauer, Sü, Wilhelm & Wittmann, 2008; Vandervert, Schimpf & Hesheng, 2007), and verbal fluency (Gilhooly, Fioratou, Anthony & Wynn, 2007). To control for age-effects related to these concepts, standard scores were obtained from the WISC or WAIS subtests Similarities

(verbal IQ) and Digit Span (DS; working memory)(Wechsler, 1991, 1997), and the Groninger Intelligence Test subtest Verbal Fluency (VF) (GIT; Luteijn & van der Ploeg, 1983). Eighty-four participants completed the Similarities subtest, 82 participants completed DS subtest, and 87 participants completed the VF subtest. One-way ANOVAs performed on these three measures revealed no significant age group effects (Similarities: $F(3,83) = 1.08, p = .36$; DS: $F(3,81) = 1.83, p = .15$; VF: $F(3,86) = .750, p = .53$). This renders alternative explanations for age-related differences in terms of verbal intelligence, working memory or verbal fluency unlikely.

Materials

Insight tasks

Three insight tasks were included: the *Gestalt Completion Test*, the *Snowy Picture Test* and the *Remote Associates Test*. Both the Gestalt Completion Test (GCT, Eckstrom et al., 1976) and the Snowy Picture Test (SPT, Eckstrom et al., 1976) measure visual insight (Förster et al., 2004; Eckstrom et al., 1976). In the GCT, participants view a series of fragmented pictures of familiar objects and indicate what they see. Successful identification of the objects requires processing relations among elements and integrating the fragments into a coherent ‘Gestalt’. This process of *restructuring a stimulus set* is commonly considered a basic process of creative cognition (Schooler & Melcher, 1995). In the current study, we used a computerized version comprising 10 fragmented pictures (De Dreu, Baas, & Nijstad, 2008). The test items were preceded by two examples. Participants could type their answers or skip the question. By clicking a button the participants proceeded to the next picture. Response time was not restricted. Responses were coded as correct or incorrect (including skipped items).

In the SPT participants are presented with a series of images of familiar objects hidden within visual noise. To identify the hidden objects participants need to disregard misleading interpretations rendered by the context. The computerized version, used in this study, contained the first 12 pictures from the original SPT set (Baas, De Dreu, & Nijstad, 2011). Test items were presented in random order and were preceded by two examples. Answers could be typed during an unlimited response time, and responses were coded as correct or incorrect (including skipped items). The next picture was presented upon a button click.

The Remote Associates Test (RAT; Mednick, 1962) is a measure of verbal insight. Participants are presented with three words (e.g., envy, golf, beans) and are instructed to generate the one word that relates to all of these three words (i.e., green). To come up with the correct

solution, participants need to identify relations among the three stimulus words. These relations are generally not the most obvious. In the current study, we used a computerized version of the RAT comprising 30 triads of Dutch words (De Dreu et al., 2011; Baas et al., 2011). Test items were presented in a random order, preceded by two example items. Participants were instructed to type their answers or skip if no solution was found and click a button to go to the next item. The response time was unlimited. Responses were coded as correct or incorrect (including skipped items).

Divergent thinking tasks

To gauge divergent thinking, we used the *Alternate Uses Test* (AUT, Guilford, 1967), and the *Creative Ability Test* (CAT, Van Dam & Van Wesel, 2006). The AUT measures divergent thinking in the verbal domain in terms of *fluency*, *flexibility*, and *originality*. Participants are given the name of an object and asked to generate as many alternative uses for the object as possible. In the current computerized version, participants were instructed to generate alternative uses for a *brick* (e.g., Baas et al., 2011; Friedman & Forster, 2001). Solutions can be unusual but must be appropriate. Answers could be typed for a fixed length of 4 minutes. Participants were instructed to press ENTER after each answer typed to submit the answer. Concurrently, the response field was cleared and the next answer could be given. *Fluency* scores were computed by counting the number of correct solutions provided. *Originality* was determined as follows. For each solution, frequency of occurrence across the total of solutions (provided by all participants) was determined. Since frequency distributions were positively skewed, frequency scores were log-transformed before averages were computed (similar effects were found with non-log-transformed frequency scores). Then, average frequency scores were computed for each participant. *Flexibility* was measured by the number of solution-categories. A trained rater assigned each solution to one of 35 solution-categories (e.g., building aspect; load; toy). Then, the number of applied solution-categories was counted for each participant individually.

The CAT measures *fluency* and *originality* of divergent thinking in the visuo-spatial domain. The test problem consists of nine squares including figures. Participants are asked to compose triads of squares based on the properties (e.g., number, position) of the figures included. These squares must be similar concerning a particular figure property (or properties) and therefore differ from the other six squares. Fluency scores were computed by counting participants' number of correct answers. Originality was computed by summing the uniqueness scores (1 = 'common' to 5 = 'very unique') of correct answers. Uniqueness scores were based on occurrence of solutions

in previous validity studies (Van Dam & Van Wesel, 2006). Higher scores corresponded to lower frequency of occurrence. Participants were instructed to write down as many triads as they could. Response time was limited to 10 minutes. Prior to the test, participants were presented with an example emphasizing the variety of possible solutions (Van Wesel, 2006).

Procedure

Participants were invited to participate in a study about general problem solving. They were tested individually either in a classroom or in a separate room at Leiden University. Test administration was divided into three parts: 1) computerized versions of the GCT, SPT, RAT and AUT, for which participants were seated in front of a 15 inch laptop; 2) Similarities, DS and VF, which were administered orally; and 3) a paper and pencil version of the CAT. Duration of the three test parts was approximately 30, 15 and 15 minutes respectively including instructions. Participants were encouraged to ask for help if any ambiguity concerning a test remained after reading the instructions. In between tasks participants were given a break, and upon completion of the entire experiment, participants were debriefed and received their compensation.

Due to practical limitations, only 89 of the total of 98 participants completed all the computerized test ($N_{12/13 \text{ yrs}} = 25$; $N_{15/16 \text{ yrs}} = 23$; $N_{18/19 \text{ yrs}} = 25$; $N_{25-30 \text{ yrs}} = 16$), and 95 participants completed the CAT ($N_{12/13 \text{ yrs}} = 24$; $N_{15/16 \text{ yrs}} = 30$; $N_{18/19 \text{ yrs}} = 20$; $N_{25-30 \text{ yrs}} = 17$).

Results

First, we tested for age differences on insight and divergent thinking measures using analyses of variance (ANOVAs) with age as between-subjects factor. Significance thresholds were set to $p < .05$. All significant effects survived Greenhouse–Geisser correction. For all ANOVAs, Levene's test of homogeneity of variances was applied. Tukey HSD tests when variances were homogeneous, or Games–Howell tests when variances were non-homogeneous, were applied for post hoc analysis of between-group comparisons. Means and standard deviations of insight and divergent thinking measures are presented in Table 2-1. In addition, we conducted Principal Component Analyses (PCA) and correlations among task performances to identify relations between the different types of creativity measures.

Table 2-1. Means and standard deviations for performance parameter for insight and divergent thinking tasks by age group

		12/13 yrs		15/16 yrs		18/19 yrs		25-30 yrs	
		<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Insight									
<i>Visual</i>	GCT ^a	5.36	1.87	5.65	1.43	6.92	1.04	7.44	1.36
	SPT ^a	5.89	1.83	6.00	2.20	7.56	2.04	7.82	1.74
<i>Verbal</i>	RAT ^a	7.32	3.24	9.57	3.26	12.44	3.49	13.06	2.95
Original Ideation									
<i>verbal</i>	AUTfluency ^a	10.76	5.72	9.70	4.88	11.12	5.92	10.13	4.59
	AUTflexibility ^a	6.80	3.08	5.96	2.44	7.36	2.69	7.19	3.06
	AUToriginality ^a	0.85	0.13	0.87	0.19	0.81	0.12	0.73	0.10
<i>Visuo-spatial</i>	CATfluency ^b	7.17	3.19	9.17	2.39	8.35	2.29	8.28	2.22
	CAToriginality ^b	10.58	6.79	13.53	5.26	11.48	4.71	12.22	4.80

Note. ^a 12/13 yrs, *n*=25; 15/16 yrs, *n*=23; 18/19 yrs, *n*=25; 25-30 yrs, *n*=16; ^b 12/13 yrs, *n*=24; 15/16 yrs, *n*=30; 18/19 yrs, *n*=20; 25-30 yrs, *n*=17; GCT = Gestalt Completion Test; SPT = Snowy Picture Test; RAT = Remote Association Test; AUT = Alternate Uses Test; CAT = Creative Ability Test.

Task performances

Insight tasks

Performances for the insight tests were examined in terms of accuracy (quantified as the number of correct solutions).

Visual insight: GCT and SPT

Participants' number of correct insights performances were submitted to a multivariate ANOVA with age group (12/13 yrs, 15/16 yrs, 18/19 yrs, 25-30 yrs) as between-subject variable. A multivariate main effect of age group ($F(6,170) = 5.36$; $p < .001$; $\eta^2 = .25$) was found. Univariate ANOVAs were used to further examine the data. Both tasks revealed univariate main effects of age group. On the GCT, $F(3,85) = 9.58$; $p < .001$; $\eta^2 = .25$, post hoc Games-Howell comparisons (Levene's test $F(3,85) = 3.17$; $p = .03$) showed that participants from the two older age groups out-performed participants from the two younger age groups (12/13 yrs < 18/19 yrs, $p = .001$; 15/16 yrs < 18/19 yrs, $p = .002$; 12/13 yrs < 25-30 yrs, $p = .004$ and 15/16 yrs < 25-30 yrs,

$p = .006$; see Figure 2-1a). The univariate ANOVA for the SPT also resulted in a main effect of age, ($F(3,85) = 5.80$; $p = .002$; $\eta^2 = .16$), and again, the age group effect was driven by significant differences between participants of the two younger age groups on the one hand and participants from the two older age groups on the other hand; better performance was achieved by older participants. Post hoc Tukey HSD (Levene's test: $p > .5$) revealed significant effects for contrasts 12/13 yrs < 18/19 yrs, $p = .02$; 15/16 yrs < 18/19 yrs, $p = .04$; 12/13 yrs < 25-30 yrs, $p = .02$; and 15/16 yrs < 25-30 yrs, $p = .04$, see Figure 2-1b).

Verbal insight: RAT

Performance scores were entered into an ANOVA with age group (12/13 yrs, 15/16 yrs, 18/19 yrs, and 25-30 yrs) as between-subjects variable. Performance differed across age groups $F(3,85) = 14.68$; $p < .001$; $\eta^2 = .34$. Tukey HSD post hoc analysis (Levene's test: $p > .5$) showed that accuracy for participants from the two older age groups was significantly better compared to participants from the two younger age groups; 12/13 yrs < 18/19 yrs, $p < .001$; 15/16 yrs < 18/19 yrs, $p = .016$; 12/13 yrs < 25-30 yrs, $p < .001$ and 15/16 yrs < 25-30 yrs, $p = .008$, see Figure 2-1c).

In all, the developmental trajectories of the creative insight tasks seemed to follow stepwise rather than linear or curvilinear patterns, generally observed for development of cognitive control (e.g., Huizenga et al., 2006). Post hoc model analyses using linear regression analyses confirmed that SPT and GCT results fitted stepwise patterns (contrast: -1, -1, 1, 1; for 12/13 yrs, 15/16 yrs, 18/19 yrs, 25-30 yrs age groups) better than linear (modeling results as a linear function of age) or curvilinear models (modeling results as log-transformed or quadratic functions of age), SPT: $F(1, 87) = 16.56$, $R = .37$, $p < .001$; GCT: $F(1, 87) = 27.15$, $R = .49$, $p < .001$. RAT results revealed best fit with the log-transformed curvilinear model: $F(1, 87) = 39.30$, $R = .56$, $p < .001$.

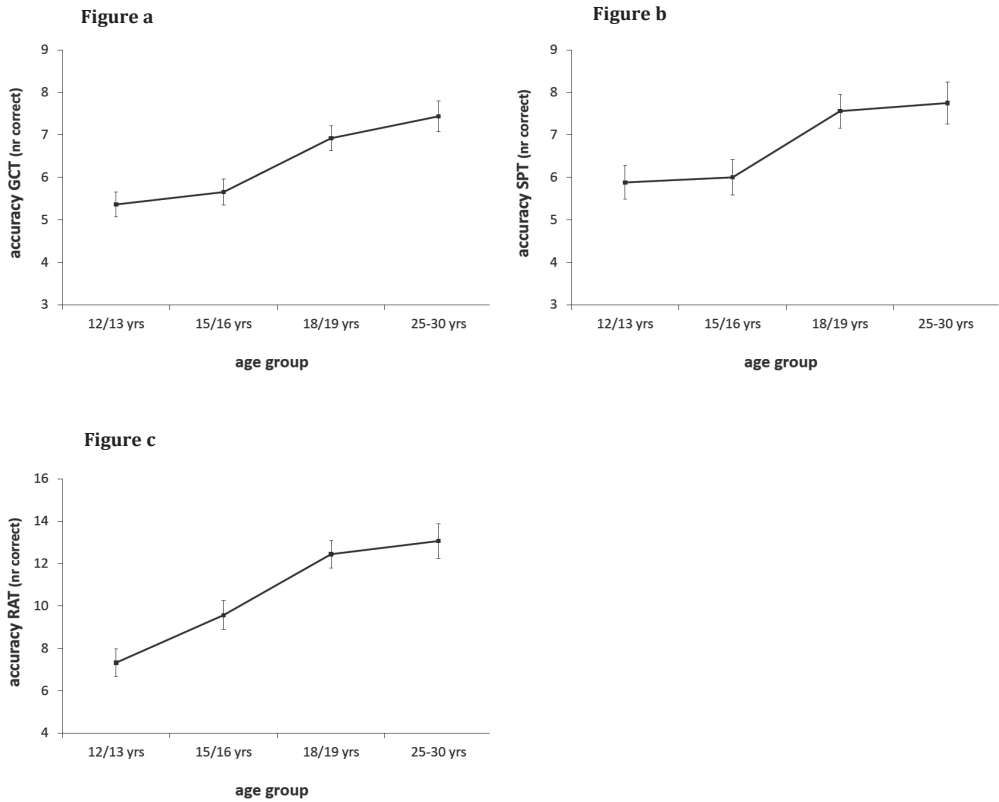


Figure 2-1. Insight performances

Mean $\pm$ 1 standard error (SEM) of the number of correct solutions for each group for the Gestalt Completion Test (a), Snowy Picture Test (b), and Remote Association Test (c).

Divergent thinking

Verbal divergent thinking: AUT

Performance was measured in terms of *fluency*, *flexibility* and *originality*. Univariate ANOVAs for the fluency and flexibility measures with age group (12/13 yrs, 15/16 yrs, 18/19 yrs, 25-30 yrs) as between subject variable showed no age group differences ($p > .05$). A univariate ANOVA on originality, represented by the mean frequency of solutions, yielded a significant age group effect ($F(3,85) = 3.79$, $p = .01$; $\eta^2 = .12$). Post hoc Tukey HSD analyses (Levene's test: $p > .5$) showed that the two younger age groups had higher frequency scores (i.e., were *less* original) compared to the oldest age group (12/13 yrs $<$ 25-30 yrs, $p = .03$ and 15/16 yrs $<$ 25-30 yrs, $p = .02$). The 18/19 yrs group took an intermediate position and did not significantly differ from the

other three groups. Accordingly, age group related changes of AUT originality, displayed in Figure 2-2, were best described by a linear model, $F(1, 87) = 11.37$, $R = .34$, $p = .001$.

Response times (time between entering consecutive solutions) showed large intra-subject variability, rendering it unlikely that participants typing speed, rather than the time for generating correct solutions was the main factor responsible for the observed inter-subject differences.

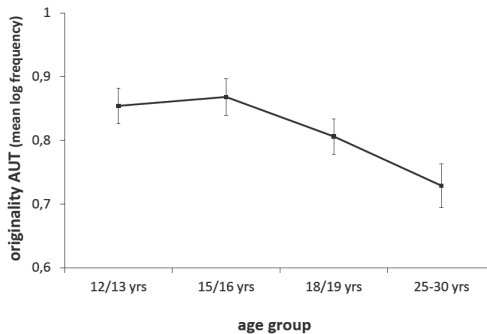


Figure 2-2. Verbal Divergent Thinking *originality*

Mean $\pm$ 1 standard error (SEM) of average log-transformed frequencies of ideas generated in the Alternate Uses Test for each age group.

Visuo-spatial divergent thinking: CAT

Performance was measured in terms of *fluency* and *originality*. Univariate ANOVAs with age group (12/13 yrs, 15/16 yrs, 18/19 yrs, 25-30 yrs) as between subject variable resulted in significant age group effects for fluency ($F(3,91) = 2.71$, $p < 0.05$; $\eta^2 = .08$) but not for originality ($F(3,91) = 1.39$, $p = .25$; $\eta^2 = .04$). Post hoc Tukey HSD analyses (Levene's test of equality: $p > .5$) showed that 15/16 years olds gave significantly more correct answers than 12/13 yrs olds ($p = .03$). The two adult groups did not significantly differ from each other or from the two younger age groups (all p 's $> .05$). As such, the results, presented in Figure 2-3, showed a complex pattern that did not fit significantly with linear, stepwise, or curvilinear models. Alternative model analyses regarding peak performance for middle adolescents (contrast: -1 3 -1 -1 ; for 12/13 yrs, 15/16 yrs, 18/9 yrs, and 25-30 yrs respectively) revealed significant fit ($F(3,91) = 5.01$, $p = .028$).

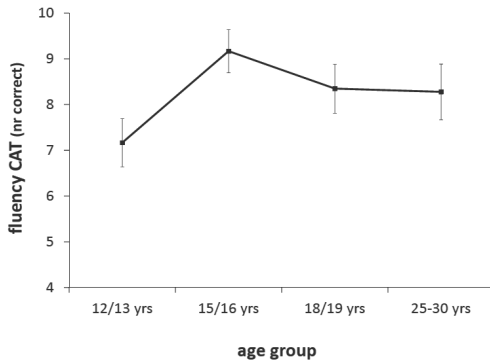


Figure 2-3. Visuo-Spatial Divergent Thinking *fluency*
Mean $\pm$ 1 standard error (SEM) of the number of correct solutions on the Creative Ability Test for each age group.

Principal Component Analyses

Principal Component analyses were performed on GCT, SPT and RAT performances, AUT fluency, AUT flexibility, AUT originality, CAT fluency and CAT originality scores ($N_{12/13 \text{ yrs}} = 25$; $N_{15/16 \text{ yrs}} = 23$; $N_{18/19 \text{ yrs}} = 25$; $N_{25-30 \text{ yrs}} = 16$) followed by Varimax Rotations. This approach was chosen to maximize the distinctions among aspects. The threshold for retained Eigenvalues was set to at 1.0 and only variables with loadings of at least .5 are interpreted as significant. The analysis revealed three factors, which accounted for 70% of the common variance. Table 2-2 shows that these factors reflect the trichotomy of developmental patterns observed with previous analyses. The first factor loaded with performances on the insight tasks and, marginally significantly, with AUT originality. The second factor loaded with AUT fluency, and AUT flexibility, and the third factor with CAT performances.

Chapter 2 Creative cognition across adolescence

Table 2-2. Varimax rotated exploratory factor model

	Factor 1	Factor 2	Factor 3
GCT	.77	.08	-.01
SPT	.68	-.13	-.06
RAT	.76	-.10	-.01
AUTfluency	-.03	.94	-.00
AUTflexibility	.03	.93	.03
AUToriginality	-.49	-.26	-.10
CATfluency	.04	-.01	.96
CAToriginality	-.04	.04	.97

Note. $N = 86$; GCT = Gestalt Completion Test; SPT = Snowy Picture Test; RAT = Remote Association Test; AUT = Alternate Uses Test; CAT = Creative Ability Test. Loadings $\geq .50$ are in given in boldface.

Correlations

Bivariate correlations: Table 2-3 shows the correlations between creative task performances over all participants. As predicted, significant correlations are observed between measures of insight, between measures of verbal divergent thinking, and between measures of visuo-spatial divergent thinking. Additional correlations are observed between AU originality and insight performance, but only the correlation with GCT was statistically significant. Correlations between AU originality and SPT and RAT respectively were only marginally significant. Notice that AU originality scores are based on frequency scores, so that negative correlations indicate positive relations between originality and insight. In all, these correlations are in congruence with the extracted factors in the PCA.

Table 2-3. Bivariate correlations for performance parameters for Insight and Divergent Thinking tasks

	Insight		Divergent Thinking				
	SPT	RAT	AUT fluency	AUT flexibility	AUT originality	CAT fluency	CAT originality
GCT	.320 *	.453 **	.064	.078	-.275 *	-.002	-.003
SPT		.334 **	-.073	-.056	-.201	.019	-.099
RAT			-.115	.001	-.183	.063	-.072
AUTfluency				.791 **	-.152	-.002	.041
AUTflexibility					.142	.044	.046
AUToriginality						-.014	-.105
CATfluency							.870 **

Note. $N = 89$ except for following correlations: Insight-CPT ($N = 86$); AUT-CPT ($N = 86$); CPT-CPT ($N = 95$). GCT = Gestalt Completion Test; SPT = Snowy Picture Test; RAT = Remote Association Test; AUT = Alternate Uses Test; CAT = Creative Ability Test. * $p < .01$, two-tailed; ** $p \leq .001$, two-tailed.

Partial correlations: Only correlations between GCT and RAT ($r = .24, p = .026$), AU fluency and AU flexibility ($r = .79, p < .001$), and CAT fluency and CAT originality ($r = .87, p < .001$) remained significant after controlling for age group means. The disappearances and strong decreases of correlations between insight and divergent thinking after correction for age group effects indicate that the initial bivariate correlations between these constructs are likely driven by developmental differences.

Discussion

The aim of this study was to augment understanding of the development of creativity across adolescence. Using a range of creativity tests, we found distinct developmental patterns indicating that: 1) creative insight and the qualitative measure of verbal divergent thinking, originality, continue to develop into late adolescence; 2) the two quantitative measures of verbal divergent thinking, fluency and flexibility, reach adult level early in adolescence and; 3) visuo-spatial divergent thinking shows a non-linear developmental pattern with best performance at age 15-16. This trichotomy was supported by factor reduction and correlation analyses. In all, these data support the distinctiveness of creativity aspects. Mechanisms that may underlie these trajectories are discussed in the following paragraphs.

Creative insight

Creative insight showed increased performance with age continuing into late adolescence on both visual and verbal problems. Our results therefore indicate that the ability to successfully restructure and unify complex or remotely associated information is not fully developed until late adolescence.

A first factor that might have contributed to these developmental differences is the increasing amount of knowledge and experience gained with increasing age; both forms of insight require retrieval of stored knowledge and associations. Second, age related increases might be related to development of cognition control functioning. Creative insight performance has been shown to benefit from deliberate, focused, and structured exploration of cognitive categories or perspectives (De Dreu, Nijstad, & Baas, 2008; Finke, 1996; Schooler, Ohlsson, & Brooks, 1993; Simonton, 1999) and incremental search processes (Boden, 1998; Newell & Simon, 1972). In addition, neuroimaging studies indicate the importance of the prefrontal cortex for successful creative insight (Kounios et al., 2006; Razumnikova, 2007). It is now well documented that cognitive control functions, and associated prefrontal cortex areas, develop across childhood and adolescence (see e.g., Casey, Jones, & Hare, 2008; Crone, 2009). Specifically, cognitive control functions such as working memory, inhibition, monitoring, and mental switching, show protracted developmental trajectories throughout adolescence (Huizinga et al., 2006; Luna, Garver, Urban, Lazar & Sweeny, 2004). Accordingly, immature cognitive control functioning for the two youngest age groups in our study likely explains, at least to some degree, the observed age related differences.

Visual Insight

The developmental pattern for visual insight was best described by a model that tested for a performance-step between middle and late adolescence, rather than a linear age change. Non-linear developmental patterns with relative poor performance in middle adolescence are not uncommon in literature on visual cognition. For example, Uhlhaas and colleagues (2009) found sudden interruptions in Gestalt perception development during adolescence. Neurophysiologic measures indicate that these developmental interruptions are related to reorganizations of functional neural networks, which is compatible with functional and structural non-linear trajectories of cortical networks during this period as seen in imaging studies (Ashtari et al., 2007; Gogtay et al., 2004; Luna, 2010). Accordingly, we might expect functional changes toward more

adult-like coordination of visual information processing to induce developmental stagnation of visual insight performance, as observed in our study.

Verbal divergent thinking

For verbal divergent thinking we found different developmental patterns for the three divergent thinking measures. Fluency and flexibility performances did not change throughout the age range. These results are in congruence with previous findings on verbal ideation for 6th graders and university students (Wu et al., 2010) and indicate that the capacity to generate numerous ideas from different categories is already fully developed in early adolescence. For the third measure of ideation, originality, which was not reported separately in the Wu et al (2010) study, marked increases were found after middle adolescence. Thus, although adolescents as young as 12 years old are able to produce adult-level numbers of solutions, the quality of solutions still develops.

Common to insight development, a first factor that might (partially) account for the developmental changes in originality performance concerns knowledge and experiences (Weisberg, 1999). Individual lifestyles of adults and late adolescents generally involve larger inter-individual variance of experiences and knowledge compared to younger groups. Consequently, older age-groups might create relatively infrequent associations and ideas. A second possible explanation for the age group differences concerns developmental changes in other cognitive processes. Successful creative thinking is associated with flexible coordination between analytic and associative processing (Christoff, Gordon & Smith, 2009a, 2009b; Martindale, 1999; Martindale & Hasenflus, 1978). Both associative and analytic processing is believed to lead to numerous ideas (De Dreu et al., 2012, Nijstad et al., 2010). However, the quality of generated ideas seems related to the coordination between them (e.g. Martindale, 1999), an ability that is associated with functioning of late developing prefrontal brain regions (Kerns, 2006; Kerns et al., 2004). Thus, for early and middle adolescents the ability to successfully shift between the two types of processing might not be fully developed (Smolucha & Smolucha, 1986; see also Runco, 2007). To test these hypotheses on the combined influence of associative, and analytical of processing, future research might relate creative thinking across age groups to activation in prefrontal cortex (e.g. see Fink et al., 2009).

Visuo-spatial divergent thinking

The participants' performance on the CAT showed marked increases from early to middle adolescence, whereas early adolescents' performance did not differ from late adolescents' or

adults'. These results suggest an advantage for middle adolescents on this aspect of creativity. It should be noted that the middle adolescents did not differ significantly from the older age groups in performance, but the model which tested for a middle adolescent peak provided significant fit.

Success on this type of task is relatively independent of knowledge but requires shifting between representations of visual information provided, applying a set of rules, and monitoring behavior; cognitive functions that are still developing during young adolescence (Huizinga et al., 2006). It seems logical that the above-mentioned factors relate to the increase for middle compared to early adolescents. However, as mentioned, the youngest group did not differ significantly from the oldest two age groups, suggesting a relative advantage for the middle adolescents. The divergent character of the task introduces benefits for widely focused exploration of the externally presented information. Both animal and human studies indicate that explorative behavior is characteristic for adolescents (Dahl, 2011; Johnson & Wilbrecht, 2011), and that this behavior is likely associated with increased levels of dopamine in prefrontal cortex during this age period (see Casey et al, 2008; Spear, 2000). For middle adolescents, the required cognitive control functions are expected to be sufficiently developed. Combining these prerequisites with broadened attention toward externally presented stimuli (e.g., Gray, Buhusi & Schmajuk, 1997), provides an explanation for the observed developmental pattern with advantages for middle adolescents. This hypothesis needs to be tested more elaborately in future research.

To summarize, several cognitive and related neurobiological aspects are likely to contribute to the distinct developmental patterns for insight and divergent thinking, including knowledge and experience, coordination between information processes, reorganizations of functional networks, and widely focused explorative behavior during adolescence. There are, however, some limitations of the current study that should be taken into account when drawing conclusions about developmental changes; a) the current study included a relatively small sample size ($n=19$ to $n=30$ per age group) and therefore future studies should replicate results to validate our findings; b) the study design was cross-sectional rather than longitudinal, which limits the reliability of the revealed age differences; c) the gaps between age groups may hide short-term changes in performance; and d) because of practical limitations, there were some differences present between the younger and older participants in test administration (see Methods section). However, a lack of significant age group differences with regard to norm scores on measures of general cognitive abilities render it unlikely that the observed developmental patterns were merely the consequence of cohort effects. Thus, we believe the current study provides meaningful insights

into the creative abilities and constraints across adolescent development and provides interesting hypotheses that need to be tested in future research.

Conclusions

To our knowledge the current study is the first to examine the development of diverse aspects of creativity across adolescent development. The findings demonstrated distinct developmental trajectories with marked discrepancies between divergent thinking and creative insight. These results could be related to age-related differences of knowledge and experiences only to some degree, and are likely related to the protracted development of cognitive control functioning and the relatively wide and explorative focusing style characteristic for middle adolescents. Similar conclusions have been suggested by animal research showing that adolescent mice show relatively greater flexibility for learning than more mature mice (Johnson & Wilbrecht, 2011). We hypothesize that these developmental changes are related to reorganizations of functional networks, which is in line with the developmental theory of interactive specialization (Johnson, 2011).

In future studies, it will be of interest to relate creative thinking to activation in the prefrontal cortex, to examine the combined influence of associative, automatic, and analytical, deliberate types of processing (e.g. see Fink et al., 2009). As individuals enter adolescence, this confronts them with multiple possibilities for learning and adaptation, possibly guided by increased capacity for widely focused processing, giving them opportunities for exploration. In sum, the current results indicate that adolescent development is not only a time of immaturity but also of flexibility and potential for creativity.

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CHAPTER 3

Prefrontal cortex involvement in creative problem solving in middle adolescence and adulthood

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Abstract

Creative cognition, defined as the generation of new yet appropriate ideas and solutions, serves important adaptive purposes. Here, we tested whether and how middle adolescence, characterized by transformations toward life independency and individuality, is a more profitable phase than adulthood for creative cognition. Behavioral and neural differences for creative problem solving in adolescents (15-17years) and adults (25-30 years) were measured while performing a matchstick problem task (MPT) in the scanner and the creative ability test (CAT), a visuo-spatial divergent thinking task, outside the scanner. Overall performances were comparable, although MPT performance indicated an advantage for adolescents in creative problem solving. In addition, adolescents showed more activation in lateral prefrontal cortex (PFC) (ventral and dorsal) during creative problem solving compared to adults. These areas correlated with performances on the MPT and the CAT performance. We discuss that extended PFC activation in adolescence is important for exploration and aids in creative cognition.

Introduction

The human capacity for creative problem solving is of unparalleled quality. Defined as the generation of new yet appropriate ideas, insights, and solutions (Sternberg & Lubart, 1996), creative cognition has been critical throughout human evolution and serves important adaptive purposes (Runco, 2004). It is well known that adolescence is a period characterized by transformations toward life independency and individuality (Collins et al., 1997), and a crucial phase for the development of many cognitive abilities (e.g., Casey et al., 2008; Steinberg, 2005). Yet, relatively little is known about whether and how this age period is important for *creative* cognition. It has been argued that creative problem solving abilities are important skills facilitating the advancement toward mature adult functioning; a transformational trajectory that requires adaptive skills (e.g., Jaquish & Ripple, 1980). Hence, adolescence is expected to be an age period of enhanced creative abilities (Kleibeuker, De Dreu & Crone, 2013).

Creative problem solving typically requires divergent thinking (generating ideas by exploring many possible solutions), and flexibility in terms of restructuring and manipulating problem information. Consider, for example, the matchstick problem (Guilford, 1967) where a spatial composition including several matchsticks has to be restructured so as to form a new pre-described composition. Using these and related tasks, neuropsychological and brain imaging studies uncovered the importance of the lateral prefrontal cortex (PFC) in creative problem solving. Miller and Tipett (1996) compared healthy controls to patients with lesions in different brain regions, and found that patients with (right) frontal lesions showed impaired creative problem solving. Performances were most significantly impaired when flexibility in terms of strategy switches was required. Another study, in healthy adults, showed increased activation in bilateral ventral and dorsal prefrontal cortex when solving matchstick problems compared to verifying a given solution to a matchstick problem (Goel and Vartanian, 2005). Furthermore, activation in the right dorsolateral PFC (DLPFC) correlated with the percentage of traced solutions, indicating that this region contributes to exploratory success.

Whereas the role of the prefrontal cortex in the development of creative problem solving is largely unexplored, large scale longitudinal brain imaging studies showed profound changes during adolescence: gray matter volume in lateral PFC matures throughout adolescence, following an inverted U-shaped pattern with a peak in early adolescence (Gogtay et al., 2004). In addition, functional brain-imaging studies have reported different developmental trajectories showing that prefrontal cortex is both *more* activated (e.g., Adleman et al., 2002; Crone et al., 2006c), and *less*

activated with increasing age (e.g., Durston, et al., 2006; Morton et al., 2009). These age-related changes are sometimes interpreted as an increase of the ability to recruit referred brain regions, and other times as increasing efficiency of referred brain regions. Intriguingly, some studies reported a middle adolescent specific peak in activation in lateral prefrontal cortex (e.g., Crone, et al., 2006a; Dumontheil, et al., 2010) and thereby challenge the abovementioned relative simplistic maturational interpretations. An alternative possibility is that prefrontal cortex function during this transitional phase may be tuned specifically toward exploration and adaptive flexibility (Crone & Dahl, 2012; Dahl, 2008; Johnsson & Willbrecht, 2012), which in turn may be specifically beneficial for creative problem solving. Recent behavioral research on creative cognition, including early-, middle-, and late-adolescents and young adults revealed a peak for visuo-spatial divergent thinking for middle-adolescents (Kleibeuker et al., 2012). These results provide initial support for an alternative maturational view, indicating increased exploratory success for middle-adolescents compared to younger and older age groups.

Here we tested the alternative maturational possibility by examining (i) how creative problem solving performance develops from adolescence to adulthood, and (ii) how adolescent specific changes in PFC functioning relate to creative problem solving.

We tested middle adolescents versus adults applying a matchstick problem task (MPT) to assess visuo-spatial creative problem solving (inside the scanner), and the creative ability test (CAT; Van Dam & Van Wesel, 2006) to assess visuo-spatial divergent thinking (outside the scanner). We obtained this latter measure to reveal individual differences in brain activations during creative problem solving related to divergent thinking capacity. We focused on visuo-spatial tasks because performance is relatively independent of conceptual development and knowledge, both which differ substantially between age groups (Kavac, et al. 2010).

Based on the results obtained by Goel and Vartanian (2005), we anticipated bilateral PFC activation during creative problem solving, and predicted that activation of these regions would correlate with creative problem solving performance, as measured with MPT, and with divergent thinking capacity, as measured with CAT. Based on the hypothesis that middle adolescence is a time window of enhanced neural activity in lateral prefrontal cortex, advantageous for exploration and adaptive flexibility (Luna et al., 2010; Dahl, 2011), we predicted that adolescents would show more activation in task-relevant prefrontal cortex areas than adults, and that this activation would be associated with better creative performance.

Methods

Participants

Forty-two participants with no history of neurological or psychiatric disorders participated in the present study, divided across two age-groups: 25 adolescents (15–17-year-olds) and 17 adults (25–30-year-olds). The final analyses involved thirty-six participants; 20 adolescents ($M_{age} = 16.07$ years, $SD = .48$, 11 male), and 16 adults ($M_{age} = 27.03$ years, $SD = 1.81$, 7 male). Two participants were excluded from the analysis due to technical failures. Four adolescents with lowest IQ-scores were excluded to avoid significant differences between age groups. Gender distributions did not differ between age-groups ($\chi^2(1) = .44, p = .51$).

Participants were recruited from local schools and through local advertisements. All participants provided informed consent. In the case of minors, consent was also obtained from primary caregivers. Participation was compensated with either money or course credits. All procedures were approved by the Medical Ethics Committee of Leiden University Medical Center (LUMC).

To obtain an estimate of intelligence we included two subscales of the Wechsler Adult Intelligence Scale (Digit Span and Similarities; Wechsler, 1991, 1997; see Soveri, Laine, Hämäläinen & Hugdahl, 2011). The estimated IQ scores did not differ between age groups ($M_{adolescents} = 24.79$, $SD_{adolescents} = 2.25$; $M_{adults} = 27.00$, $SD_{adults} = 3.41$; $t(34) = 1.64, p = .12$, corrected for unequal variances (Levene's test for equality of variances: $p < .05$).

Creative Problem Solving Tasks

Matchstick problem task

Participants were presented with a computerized MPT inside the scanner, consisting of a total of 48 matchstick problems (28 experimental, 20 control). Problems contained 22-match formations that consisted of eight fully formed squares (Figure 3-1; Goel & Vartanian, 2005). Underneath the matchsticks, a caption instructed participants to remove a specified number of matchsticks in order to generate a specified number of fully formed squares. On experimental trials participants had to determine whether the problem was solvable (18 out of 28 problems were solvable). These problems required divergent thinking and set-breaking (shifting between representations of the problem space) as well as convergent thinking (to verify the correctness of a possible solution). On control trials, a certain number of matches were already crossed out.

Participants had to determine whether the provided solution was correct (10 out of 20 control trials were correct). Figure 1 shows a visual display of events captioned by the time line. Each trial started with a 4-second-presentation of one of two questions: ‘Is there a solution for the following problem’ (experimental problems) or; ‘Is the following solution correct’ (control problems). Next, an experimental or control matchstick problem was presented for 15 seconds. Participants could respond by pressing a button with the right index finger (for ‘no’) or with the right middle finger (for ‘yes’). A red border appeared after 12 seconds to indicate that there were 3 seconds left to respond. A fixation cross was presented in between trials with randomly varied duration (0 - 7.7 seconds, jitter). Experimental and control problems were presented in random order over three blocks (18 trials per block); there was no repetition of matchstick problems within or between experimental and control trials.

The dependent variables were the percentages correct responses for experimental and control trials. In addition, we distinguished between trials that were solvable and trials that were not solvable.

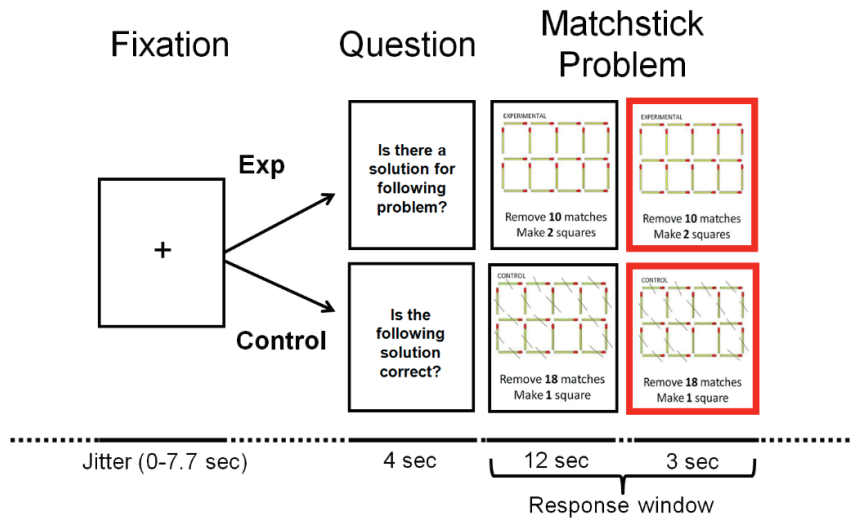


Figure 3-1. Time-line of a Match Problem Task trial (see text for explanation)

Creative ability test

To assess divergent thinking in the visuo-spatial domain, we used a pencil and paper version of the Creative Ability Test (CAT; Van Dam & Van Wesel, 2006), which was administered outside the scanner. This task consists of nine squares that include one to five open

and/or filled circles. Participants were asked to search for triads of squares with corresponding properties (i.e., same number of circles, same position of circles), such that the other six squares would not correspond on this property. A valid solution would, for example, be the notation of three squares that included exactly four circles, whereas the other six included either more or less than four circles. There was a time limit of 10 minutes during which participants were requested to find as many triads as possible. The dependent variable was the number of correct solutions. One adolescent was not given the CAT because of logistical reasons.

Procedure

Outside the scanner, participants received instructions and completed a four-trial practice session of the MPT. Then they were acclimated to the MRI environment in a mock scanner. After completion of the scanning phase (during which they performed the MPT), they completed the WAIS subtests Digit Span and Similarities, as well as the CAT.

MRI data acquisition

Scanning was performed with a standard whole-head coil on a 3-Tesla Philips Achieva MRI system (Best, The Netherlands) in the Leiden University Medical Center. Three runs of 167 T2*-weighted whole-brain EPIs, preceded by two dummy scans to allow for equilibration of T1 saturation effects, were subsequently acquired (TR = 2.2 s; TE = 30 ms, flip angle = 80 degrees, 38 transverse slices, 2.75 x 2.75 x 2.75 mm (+ 10% inter-slice gap). Stimuli were presented running E-prime software (version 1.2, Psychology Tools Inc.) and projected onto a screen at the head of the scanner bore. Participants viewed the stimuli by means of a mirror mounted on the head coil assembly. Head motion was restricted by using pillow and foam inserts that surrounded the head. The maximum movement parameters were below 3 mm and the maximum rotation was below 0.5 degrees for all participants and all scans. In accordance with Leiden University Medical Center policy, all anatomical scans were reviewed and cleared by a radiologist from the Radiology department.

MRI data analysis

SPM5 software (Wellcome Department of Cognitive Neurology, London, UK, <http://www.fil.ion.ucl.ac.uk>) was used for image preprocessing and analyses. Images were corrected for slice-time differences, followed by rigid body motion correction. Functional volumes were spatially normalized to EPI templates based on MNI305 stereotaxic space (Cocosco et al.,

1997) using a 12-parameter affine transformation together with a nonlinear transformation involving cosine basis functions. Data were resampled to 3 mm cubic voxels. Functional volumes were smoothed using an 8 mm full-width half-maximum 3D Gaussian kernel. For each participant, the functional time series were modeled by a series of events convolved with a canonical hemodynamic response function (HRF). Matchstick problems were modeled separately based on condition (experimental or control), solvability (solvable or unsolvable), and performance (correct or incorrect), with the time point of presentation as onset and response-time as duration, and entered in a general linear model along with a basic set of cosine functions to high-pass filter the data, and a covariate for run effects. In addition, the questions preceding the experimental and control trials were modeled as covariates of no interest (onset: presentation onset; duration: 4000 ms). Only correct trials were included in higher level analyses (number of trials: experimental solvable: $M_{\text{adolescents}} = 4.20$, 0-9; $M_{\text{adults}} = 2.81$, 0-6; Experimental unsolvable: $M_{\text{adolescents}} = 15.93$, 7-10; $M_{\text{adults}} = 15.19$, 6-10; Control solvable: $M_{\text{adolescents}} = 9.25$, 7-10; $M_{\text{adults}} = 9.25$, 7-10; control unsolvable: $M_{\text{adolescents}} = 8.85$, 7-10; $M_{\text{adults}} = 8.69$, 6-10). The least square parameter estimates of height of best fitting canonical HRF for each condition were used in pair wise contrasts (experimental > fixation; control > fixation; experimental > control). The resulting first level contrast images, computed on a subject-by-subject basis, were submitted to group analyses. At the group level, we performed one-tailed t-tests on these three contrasts, treating participants as a random effect, and two-sample t-tests to compare age groups.

We further conducted whole-brain regression analyses on the contrasts experimental > control and experimental > fixation to test for brain behavior relations using mean performance on experimental trials and performance on the CAT respectively. Whole brain fMRI analyses were FDR corrected for multiple comparisons (Genovese et al., 2002), with $p < .05$ and with at least 10 contiguous voxels. For whole-brain regression analyses and age group (2) x condition (2) analyses we applied both FDR correction (voxel level) and the commonly used threshold of $p < .001$ uncorrected with at least 10 contiguous voxels. Results are reported in the MNI305 stereotaxic space.

Region-of-interest (ROI) analyses

ROI analyses were performed to illustrate creative problem solving differences in lateral PFC between the age-groups. ROIs were derived from the whole brain contrast experimental > control, including inferior frontal gyrus triangularis (IFG-tri) and dorsolateral prefrontal cortex

(DLPFC). Analyses were performed using the MarsBaR toolbox in SPM5 (Brett et al., 2002), averaging signals across the voxels that make up an ROI.

Results

Matchstick Problem Task

Performances

To test for age differences in problem solving performance we conducted a 2 (condition) x 2 (solvability) x 2 (age group) mixed ANOVA. Results, which are presented in Table 3-1 and Figure 3-2, showed three significant effects: a main effect of condition with more correct answers for control problems than experimental problems ($F(1,34) = 620.52, p < .001; \eta^2 = .94$), a main effect of solvability with more correct answers for unsolvable than solvable problems ($F(1,34) = 314.64, p < .001; \eta^2 = .89$), and an interaction effect between solvability and condition ($F(1,34) = 510.86, p < .001; \eta^2 = .93$). As can be seen in Figure 3-2 (left panel), the differences in accuracy for the control versus experimental conditions were present for solvable problems but not significant for unsolvable problems (solvable: $F(1,34) = 951.69, p < .001; \eta^2 = .97$; unsolvable: $F(1,34) = .37, p > .5; \eta^2 = .01$).

There were no significant overall effects including age group (all p 's $> .05$). However, our main interest was in solvable experimental problems because these problems especially represented creative problems, requiring generation of new, appropriate representations of the problem space. Analysis on accuracy for solvable experimental problems, applying an independent t-test, revealed a significant age-group effect showing better performance for adolescents than adults ($t(34) = 2.08; p = .047$; corrected for unequal variances).

Table 3-1. Means and standard deviations for MPT and CAT performances

		15-17 yrs		25-30 yrs	
		<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
MPT^a (% correct)					
<i>experimental</i>	solvable	23.33	14.60	15.63	7.09
	unsolvable	88.50	8.75	84.38	14.59
<i>control</i>	solvable	92.50	7.86	92.50	8.56
	unsolvable	88.50	8.13	86.88	11.95
MPT^b (RT in ms)					
<i>experimental</i>	solvable	9918.24	2106.05	10163.39	2265.33
	unsolvable	10555.35	1047.51	10179.91	1892.62
<i>control</i>	solvable	8474.22	1747.87	8399.39	1939.51
	unsolvable	7973.13	2095.15	7623.33	1967.50
CAT^c (nr correct)		10.21	2.44	8.81	2.78

Note. ^a 15-17 yrs, *n*=20; 25-30 yrs, *n*=16; ^b 15-17 yrs, *n*=18; 25-30 yrs, *n*=15; ^c 15-17 yrs, *n*=19; 25-30 yrs, *n*=16;

MPT = matchstick problem task; CAT = creative ability test.

Response times

Response times for correct trials are shown in Table 3-1 and Figure 3-2 (right panel). One adult and two adolescents were not included in the analysis because they did not have observations for correct solvable experimental trials. A 2 (condition) x 2 (solvability) x 2 (age group) mixed-model ANOVA on response times revealed a significant main effect of condition ($F(1,31) = 61.30, p < .001; \eta^2 = .67$) with longer response times for experimental trials, and a condition x solvability interaction effect ($F(1,31) = 6.58, p = .015; \eta^2 = .18$). The interaction effect was determined by larger RT differences for unsolvable trials ($F(1,31) = 80.44, p < .001; \eta^2 = .72$) relative to solvable trials ($F(1,31) = 19.66, p .001; \eta^2 = .39$). No age groups effects were revealed (all p 's $> .05$), rendering it unlikely that age group effects for fMRI results were related to response time differences.

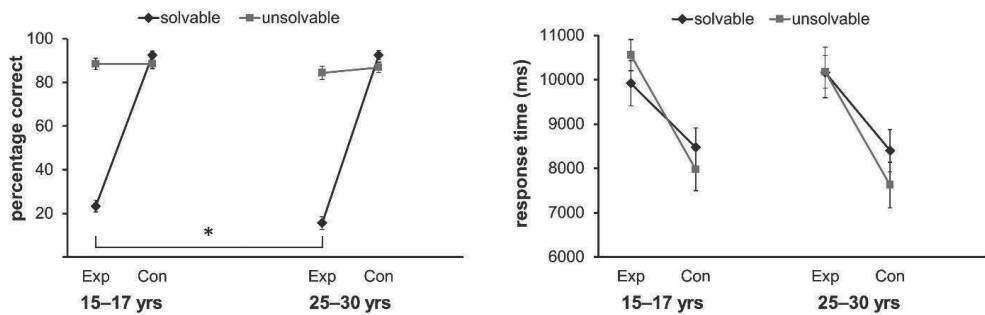


Figure 3-2. Performance on the match problem task. Accuracy measures (% correct) are presented left, response times (ms) are presented right. * $p < .05$

Creative ability test

Results for the CAT are displayed in Table 3-1. Even though the mean number of correct solutions for the adolescent-group was higher than that for the adult-group, the group difference for visuo-spatial creative fluency was not significant ($F(1,34) = 2.51, p = .12; \eta^2 = .07$).

fMRI results

Whole-brain comparisons

To extract the activation patterns related to creative problem solving we conducted whole-brain voxel-wise t-tests on activation levels for the contrast correctly solved experimental (E) problems > correctly solved control (C) problems ($E > C$) across all participants ($N = 36$). These analyses were performed collapsed across solvable and unsolvable *conditions* because these conditions resulted in similar activation patterns (see ROI analyses below for an exception). Results revealed a number of significantly activated regions, which are presented in Figure 3-3a and Table 3-2, including left inferior frontal gyrus (IFG) and left middle frontal gyrus (MFG) (FDR corrected, $p < .05$).

Table 3-2. Neural activations for the contrast experimental > control for all participants

Brain regions	L/R	K	Z-value peak voxel	MNI coordinates		
				x	y	z
Inferior frontal gyrus (tri), medial frontal gyrus	L	159	5.22	-45	36	24
Middle cingulate cortex, superior medial gyrus	L	22	4.09	-12	27	33
			3.55	-9	24	42
Inferior parietal lobule	L	11	4.01	-30	-60	39

Note. $N = 36$; L/R = left or right hemisphere; K = cluster size (nr of voxels); MNI = Montreal Neurological Institute.

Significance threshold set at $p < .05$, FDR corrected; > 10 contiguous voxels.

To test for developmental differences, a two-sample t-test (adolescents versus adults) was conducted on the contrast $E > C$. The contrast adults > adolescents revealed no significant results. The reversed contrast adolescents > adults, however, resulted in increased activation in left IFG and MFG, left inferior parietal lobule, and right DLPFC (uncorrected, $p < .001$, > 10 voxels; see Figure 3-3b and Table 3-3). The regions in left IFG and MFG overlapped with the area within the left IFG identified in the main contrast $E > C$ across participants. Moreover, the right DLPFC region overlapped with a region previously associated with an increasing numbers of correct solutions for the matchstick problems (Goel & Vartanian, 2005). Notably, left IFG and right DLPFC remained significant in the two-sample t-test when applying false discovery rate (FDR) correction ($p < .05$; > 10 contiguous voxels; see Table 3-3).

Chapter 3 Prefrontal cortex involvement in creative problem solving

Table 3-3. Neural activations for adolescents > adults for the contrast experimental > control

Brain regions		L/R	K	Z-value peak voxel	MNI coordinates		
					x	y	z
Frontal lobe	Inferior frontal gyrus (tri), middle frontal gyrus (DLPFC)	R	77	4.73	33	24	15 *
				4.16	39	33	18 *
				3.53	48	42	24
	Middle orbital gyrus	L	32	4.17	-27	45	-9 *
				3.44	-18	-54	-9
	Precentral gyrus	L	67	4.08	-45	3	42 *
				3.48	-36	-3	36
	Inferior frontal gyrus (tri)	L	58	3.87	-51	27	27 *
				3.53	-39	24	27
	Precentral gyrus, postcentral gyrus ¹	R	20	3.78	54	-18	45
				3.18	45	-12	45
	Inferior frontal gyrus (tri)	L	10	3.65	-39	24	15
	Inferior frontal gyrus (tri), middle frontal gyrus	L	41	3.48	-36	42	12
				3.37	-48	42	9
				3.15	-33	42	21
Parietal lobe	Supra marginal area	L	10	3.48	-6	21	45
	Inferior parietal lobule	L	48	3.61	-36	-54	45
				3.30	-36	-66	51
Temporal lobe	Superior temporal gyrus	R	44	4.43	60	-27	9 *
	Middle temporal gyrus	L	11	3.18	-48	-6	-15
Occipital lobe	Superior occipital gyrus	R	27	3.99	24	-78	36 *
	Cuneus	R	13	3.53	21	-87	9
	Middle occipital gyrus	L	12	3.61	42	-78	3
	Inferior occipital gyrus	L	25	3.41	-33	-78	-9
				3.36	-45	-75	-12
Basal ganglia	Caudate nucleus	L	15	4.22	-18	3	18
	Pallidum	L	12	3.48	-15	-6	-3
Cerebellum		R/L	314	4.31	6	-66	-27 *
				3.99	-9	-69	-30 *
				3.88	-9	-75	-15

Note. $N_{adults} = 16$, $N_{adolescents} = 20$; L/R = left or right hemisphere; K = cluster size (nr of voxels); DLPFC = dorsolateral prefrontal cortex; MNI = Montreal Neurological Institute.

*regions that are significant with the stricter significance threshold of $p < .05$, FDR correction, > 10 voxels.

¹cluster also includes parietal lobe structures (postcentral gyrus)

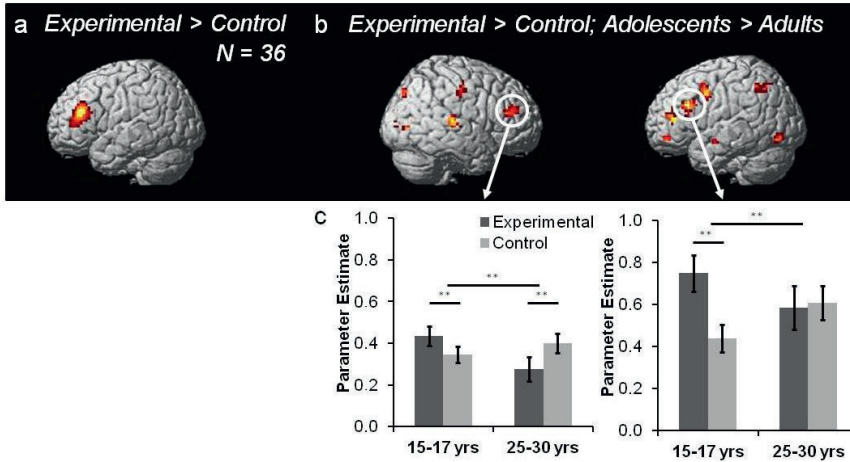


Figure 3-3. Whole brain activations for a) the contrast experimental > control overall ($N = 36$; $p < .05$, FDR corrected, > 10 contiguous voxels), and b) adolescents > adults for the contrast experimental > control (significance threshold set at $p < .001$, uncorrected)

ROI analyses

To inspect the patterns revealed in the age group analyses visually, post-hoc ROI analyses of variances were conducted on regions within the left IFG and right DLPFC identified in the two-sample t-test for the contrast $E > C$ ($p < .001$, uncorrected; similar results were obtained for $p < .05$, FDR corrected). Results are displayed in Figure 3-3c, which shows that adolescents but not adults recruited left IFG more for experimental compared to control matchstick problems (condition effect_{adults}: $F(1,15) = .47$, $p > .10$; condition effect_{adolescents}: $F(1,19) = 34.46$, $p < .001$). A largely similar pattern is observed for the right DLPFC, with more activation during experimental relative to control problems for adolescents ($F(1,19) = 13.91$, $p = .001$), but an opposite effect ($C > E$) for adults ($F(1,15) = 27.52$, $p < .001$).

Additional analyses of variances on solvability effects, applying 2 (condition) $\times$ 2 (solvability) $\times$ 2 (age group) mixed ANOVAs, revealed a significant main effect of solvability for

left IFG ($F(1,31) = 4.41, p = .044$), but none of the interaction effects was significant (all p 's $> .1$). However, there was a significant condition $\times$ solvability $\times$ age group interaction ($F(1,31) = 14.97, p = .001$) for the right DLPFC. The condition $\times$ age group interaction effect for the right DLPFC was larger for the solvable problems ($F(1,31) = 39.71, p < .001$) than for unsolvable problems ($F(1,31) = 4.32, p = .05$). These findings suggest that the condition $\times$ age group effect for activation in the right DLPFC region mainly relies on *creative* success for matchstick problems.

Individual differences

To test for brain areas directly related to creative problem solving performance, we conducted whole-brain voxel-wise regression analyses on the contrast $E > C$ (significance threshold $p < .001$, uncorrected) with performance on experimental trials (E-correct) as covariate of interest. Results showed significant activation in a region in the left IFG directly adjacent to the abovementioned IFG region observed for the contrast adolescents $>$ adults in the whole-brain $E > C$ analysis (see Figure 3-4; ROI-peak-Z-value = 3.68 at MNI coordinates -48 12 27, 34 contiguous voxels). Notably, the correlation between the contrast $E > C$ and E-correct was significant after controlling for age group ($r_{\text{partial}}(33) = .46, p = .005$, confirming that this region is involved in successful task performance independent of age.

Regression: $E > C$ with performance on experimental Matchstick problems

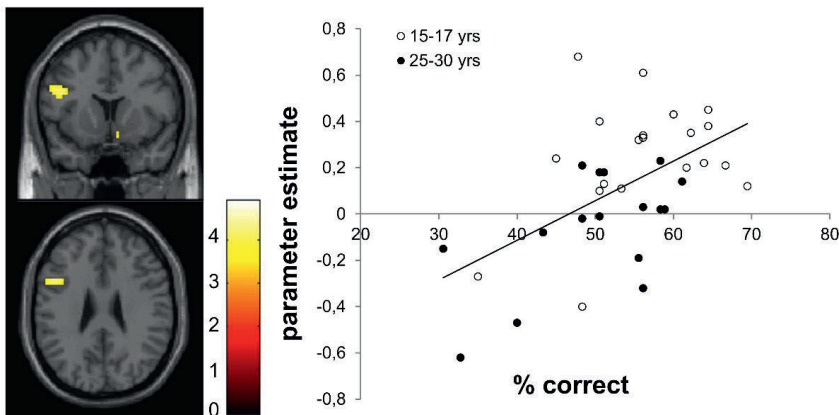


Figure 3-4. Left: whole brain activations for the regression on the contrast experimental $>$ control with performance on experimental matchstick problems (% correct) ($p < .001$, uncorrected; > 10 contiguous voxels; section coordinates: $Y = 12, Z = 27$). Right: correl

Next, we performed whole-brain voxel-wise regression analyses with post-scanning CAT performance (number of correct solutions) to gain knowledge on brain activations related to visuo-spatial creative cognition in general ($p < .001$, uncorrected). No significant relations were observed for the contrast $E > C$. However, a regression analysis on $E > \text{fixation}$ revealed a positive relation between activation right DLPFC and CAT performance (see Figure 3-5; ROI-peak-Z-value = 3.64 at MNI coordinates 39 33 27, 14 contiguous voxels). This region was in close proximity with the right DLPFC area showing a significant condition $\times$ age group interaction effect for the contrast $E > C$.

Regression: $E > \text{fixation}$ with CAT performance

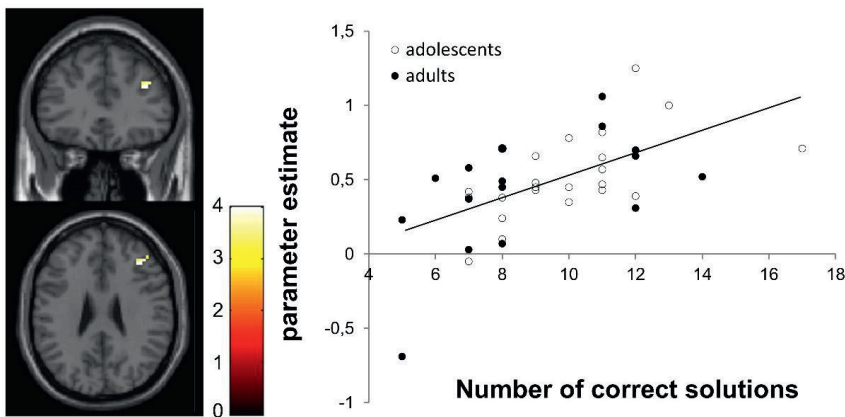


Figure 3-5. Left: whole brain activations for the regression on the contrast experimental $>$ fixation with performance on the CAT (number of correct solutions) ($p < .001$, uncorrected; > 10 contiguous voxels: section coordinates: $Y = 33$, $Z = 27$). Right: correlation

Discussion

In the present study, we examined developmental differences in creative problem solving capabilities and related these to brain activation patterns during a matchstick problems task. We hypothesized that adolescence is a period of enhanced PFC activation for exploration and adaptive purposes. The behavioral results showed that creative problem solving is already well developed in middle adolescents. Overall performance on creative problem solving did not differ between adolescents and adults, but age groups differences of solvable experimental problems of the MPT indicate better creative problem solving capacities for the middle adolescents.

The second part of our research goal concerned the question whether there were developmental differences in the underlying brain regions that support creative cognition. Brain imaging data yielded three main results: 1) Consistent with prior studies, we found increased activation of left lateral PFC during successful creative problem solving. 2) A direct comparison between age groups revealed increased activation in left IFG and right DLPFC during successful creative problem solving for adolescents compared to adults. 3) Individual differences analyses revealed that activation in left IFG and right DLPFC during successful creative problem solving was correlated with performance on experimental matchstick problems and on a visuo-spatial divergent thinking task that was administered outside the scanner, respectively. These results imply that adolescents, relative to adults, have a tendency to recruit relevant prefrontal brain areas during creative problem solving and show activity patterns common to persons with high divergent thinking capacities. Below, possible mechanisms underlying the observed results are discussed in further detail.

Lateral PFC and representation selection

Consistent with prior studies using a matchstick problems task (Goel & Vartanian, 2005), and a different visuo-spatial creative thinking task (Aziz-Zadeh, Liew & Dandehar, in press), we found that left lateral PFC was significantly more active during experimental relative to control problems. These findings underscore the importance of left lateral PFC areas in thinking and problem solving (e.g., Gazzangia, 2000). More specifically, these processes might comprise generating and choosing among various representations of the problem space and processing conflicting representations. Indeed, previous studies have shown left IFG involvement during both verbal (Thompson-Schill et al, 2002) and non-verbal (Brandon et al., 2004) tasks that require overriding a highly activated representation or selecting among weakly activated, incompatible representations (Hirshorn & Thompson-Schill, 2006). These two forms of conflict create demands for cognitive control and indicate a specific role of the left IFG for switching between representations (see also Crone et al., 2006b).

Besides the left IFG, adolescents also showed activation in the right DLPFC during experimental matchstick problems. Goel and Vartanian (2005) reported that this region was specifically important for finding more solutions for experimental matchstick problems. Interestingly, in the current study this area was also positively correlated with performance on a separate creativity task (CAT), *measuring visuo-spatial divergent thinking*, that was taken outside

the scanner. These results suggest that persons with high exploratory capacities have tendency to recruit right DLPFC to a relative large extent during successful creative problem solving.

Right DLPFC activations have previously been implicated in working memory processes (Crone et al., 2006; Curtis & d'Esposito 2003; Jolles et al., 2011), which fits with recent results showing a positive correlation between working memory and creative cognition (De Dreu, et al., 2012). Other studies indicated the importance of right DLPFC in higher level cognitive control functions such as monitoring behavior in accordance with task goals (Shallice, 2004), and planning and manipulating internal representations of problem information (Ruh et al., 2012). Impaired right DLPFC functioning, on the other hand, has been associated with impulsive behavior (Ridderinkhof et al., 2011).

These prior findings, together with our present neuroimaging results, suggest a controlled though flexible manner of processing, especially in middle adolescents, that is successful for creative problem solving.

Developmental differences

A direct comparison of activation demonstrated that these task-relevant areas in PFC, IFG and DLPFC, are more engaged in adolescents than in adults. This finding is consistent with prior studies that reported increased activation in lateral PFC in middle adolescents (see Crone & Dahl, 2012 for an overview). Such age-related decreases are generally ascribed to less efficiency of functional networks including the referred brain regions, whereas age-related increases are commonly interpreted as insufficient recruitment of late-developing brain regions (reviewed in Crone & Ridderinkhof, 2011). However, these maturational interpretations might be too simplistic. Indeed, several studies found adolescent specific peaks in prefrontal regions for working memory tasks, inhibition tasks, relational reasoning tasks, and task shifting (e.g., Crone, et al., 2006a; Dumontheil et al., 2010; Geier et al., 2009; Velanova et al., 2009).

An alternative hypothesis *considered here* is that increased activation in PFC during middle adolescence is important for this developmental period and provides advantages for this phase in life. For example, the road toward adult individuality includes leaving parental custody and building one's own life in a world full of opportunities as well as uncertainties. To achieve these goals, it is presumably beneficial to be tuned toward exploration and adaptive flexibility (Dahl, 2011; Crone & Dahl, 2012), which in turn may be associated with better, rather than less developed creative problem solving abilities (Kleibeuker et al., 2013; see also De Dreu et al.,

2011). This hypothesis finds support in a recent animal study (Johnson & Willbrecht, 2011) that found that explorative learning is more adaptive in adolescent than adult mice. In agreement with these findings, analyses of the behavioral patterns in the current fMRI study indicated a slight advantage for adolescents relative to adults on problems that required creative cognition most evidently (solvable experimental matchstick problems). The current neuroimaging data provide additional evidence into the direction of the alternative maturational hypothesis by showing that adolescence recruit brain regions in a way common to persons with high divergent thinking and creative problem solving capacities.

This hypothesis should be tested in more detail in future research, but provides important implications putting forward that middle adolescence is an essential phase in cognitive development.

Limitations of the current study include the use of a cross-sectional rather than a longitudinal design. Interpretations of developmental changes from adolescence toward adulthood made in this study are consequently merely suggestive and require confirmation from analyses of creative cognition over time. Inclusion of an additional age group of younger participants in future studies would make it possible to explicitly test the hypothesis that adolescence is a period of a peak in effective increased prefrontal activations. Another issue to be considered for future research is the use of tasks from other domains. Creativity is a general concept that covers outcomes from a wide range of fields. It would be interesting to investigate whether the observed age-related differences are specific to the visuo-spatial requirements of the current tasks, or more general effects existing across creativity domains.

Conclusion

Taken together, we showed that middle adolescents reveal high levels of creative problem solving. To the best of our knowledge, this study was the first to demonstrate that adolescents show more activation in PFC than adults in a manner which is task relevant, and, thereby, contrasts with a simplistic maturational view of functional brain development (Johnson, 2011). We suggest an alternative hypothesis arguing that increased activation in PFC is adaptive for creative problem solving during a phase in life that is tuned toward exploration and developing individuality.

Acknowledgements

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Supplement

Results for $N = 40$ (including 4 adolescents with lowest IQ scores)

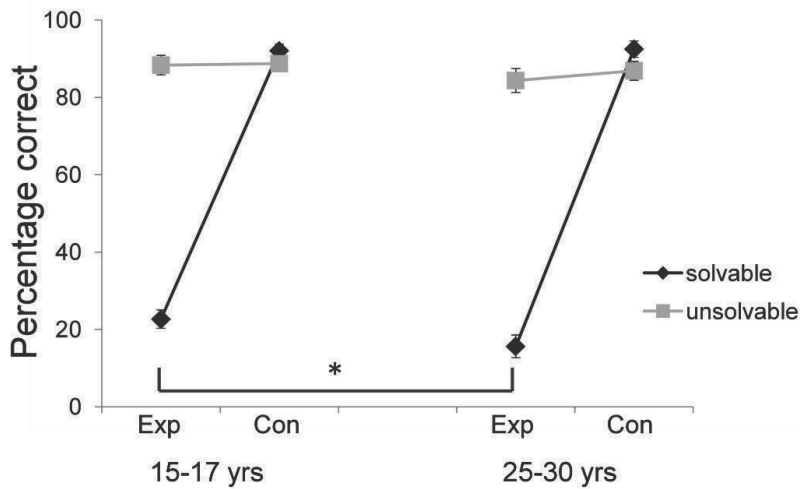


Figure 3-S1a. Performance on the Match Problem Task: accuracy measures (% correct) * $p < .05$; $N_{\text{adolescents}} = 24$, $N_{\text{adults}} = 16$.

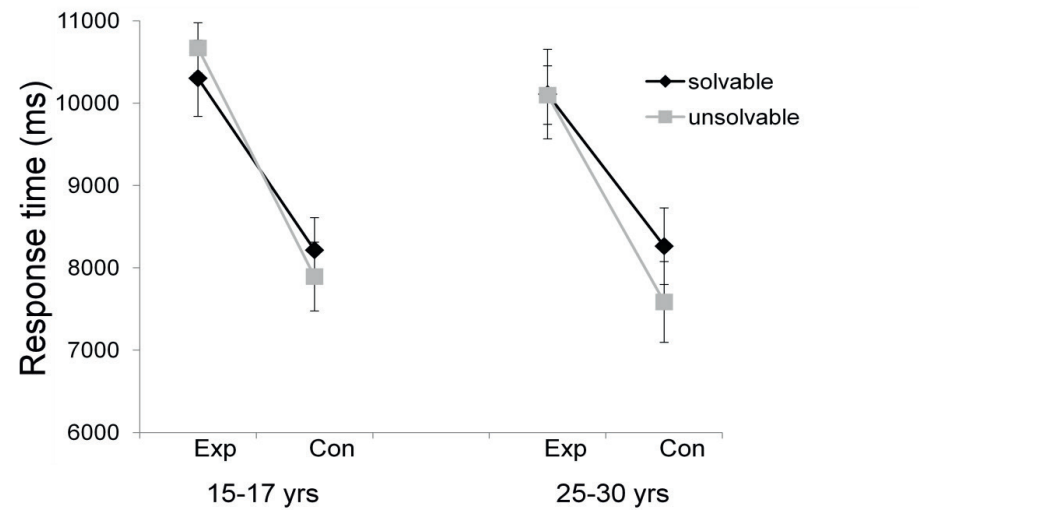


Figure 3-S1b. Performance on the Match Problem Task: response times (ms) for correctly solved problems. $N_{\text{adolescents}} = 22$, $N_{\text{adults}} = 16$.

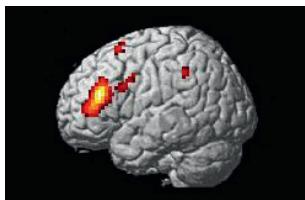


Figure 3-S2. Whole brain activations for the contrast experimental > control overall ($N = 40$; $p < .05$, FDR corrected, > 10 contiguous voxels).

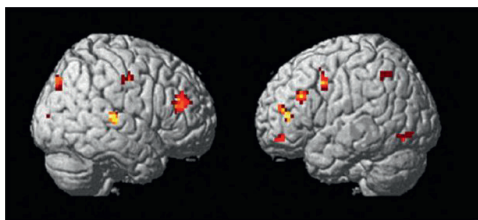


Figure 3-S3. Developmental differences: adolescents > adults for the contrast experimental > control (significance threshold set at $p < .001$, uncorrected, > 10 contiguous voxels; $N_{\text{adolescents}} = 24$, $N_{\text{adults}} = 16$).

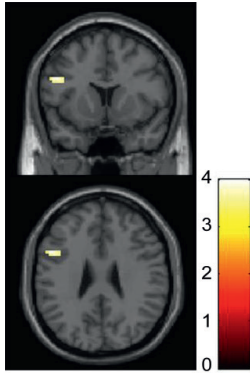


Figure 3-S4. Whole brain activations for the regression on the contrast experimental > control with performance on the experimental Matchstick Problems (% correct) ($p < .001$, uncorrected; > 10 contiguous voxels; section coordinates: $Y = 12$, $Z = 27$).

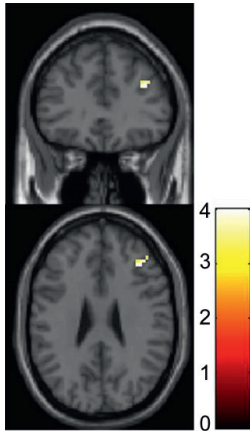


Figure 3-S5. Whole brain activations for the regression on the contrast experimental > fixation with performance on the CAT (number of correct solutions) ($p < .001$, uncorrected; > 10 contiguous voxels: section coordinates: $Y = 33$, $Z = 27$).

CHAPTER 4

The neural coding of creative idea generation across adolescence and early adulthood

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Abstract

Creativity is considered key to human prosperity, yet the neurocognitive principles underlying creative performance, and their development, are still poorly understood. To fill this void, we examined the neural correlates of divergent thinking in adults (25-30 years) and adolescents (15-17 years). Participants generated alternative uses (AU) or ordinary characteristics (OC) for common objects while brain activity was assessed using fMRI. Adults outperformed adolescents on the number of solutions for AU and OC trials. Contrasting neural activity for AU with OC trials revealed increased recruitment of left angular gyrus, left supramarginal gyrus, and bilateral middle temporal gyrus in both adults and adolescents. When only trials with *multiple* AU were included in the analysis, participants showed additional left inferior frontal gyrus (IFG)/middle frontal gyrus (MFG) activation for AU compared to OC trials. Correspondingly, individual difference analyses showed a positive correlation between activations for AU relative to OC trials in left IFG/MFG and divergent thinking performance and activations were more pronounced in adults than in adolescents. Taken together, the results of this study demonstrated that creative idea generation involves recruitment of mainly left lateralized parietal and temporal brain regions. Generating multiple creative ideas, a hallmark of divergent thinking, shows additional lateral PFC activation that is not yet optimized in adolescence.

Introduction

Creative performance – generating ideas, solutions, and insights that are both novel and useful (Sternberg and Lubert, 1996) – is key to human survival and prosperity. For example, creativity predicts success in conflict situations (De Dreu & Nijstad, 2008), academic success (Furnham & Bachtiar, 2008) and serves important adaptive purposes (Runco, 2004). However, despite its importance for an extensive range of domains of life, the neurocognitive foundations of creative performance are still poorly understood. Furthermore, we know exceedingly little about the developmental trajectories in creative performance. Accordingly, the present study examined neural correlates of divergent thinking performance – a critical ingredient of creative performance (Baas, De Dreu & Nijstad, 2008) with significant predictive value for creative success (e.g. Kim, 2008) – in adolescents and adults.

Creativity research distinguishes a variety of approaches, associated with different views concerning the components underlying creative success. Creativity is sometimes considered to be an attribute of a few brilliant minds, and a result of deviant brain functioning. In contrast, the *creative cognition* approach emphasizes that creative capacity is inherent to normative human cognitive functioning and that relevant processes are open to investigation. Our exceptional flexible use of language, our ability to create and use new mental categories to organize our experiences, and our ability to mentally manipulate objects are only some examples of mundane forms of creativity that support the creative cognition approach (Ward, Smith, & Finke, 1999). These creative outcomes are a function of a variety of cognitive and motivational processes.

De Dreu and colleagues distinguished two pathways of processes that breed creative outcomes: *flexible processing* and *perseverance*, which are summarized in the Dual Pathway to Creativity Model (DPCM) (Baas, De Dreu, & Nijstad, 2008; Nijstad, De Dreu, Rietzschel, & Baas, 2010). Here, creative performance including the generation of original ideas and creative insights are related to flexible, divergent thinking on the one hand and persistent, bottom-up processing on the other. The *flexibility pathway* involves the generation of novel ideas and creative insights through the use of extensive cognitive categories, flexible switching between categories and strategies, and the use of distant (rather than close) associations (e.g., Amabile, 1983; Eysenck, 1993; Mednick, 1962; Koestler, 1964; Simonton, 1999). Indeed, creativity is often associated with deviating from traditional procedures or ‘breaking set’, and with overcoming cognitive biases or ‘functional fixedness’ (e.g., Duncker, 1945; Smith & Blankenship, 1991;

Wertheimer, 1945). The *persistence pathway* encompasses the processes that lead to creative ideas, insights and problem solutions through systematic and effortful exploration of possibilities within only a few categories or perspectives (Boden, 1998; Dietrich, 2004; Finke, 1996; Newell & Simon, 1972; Simonton, 1997). For example, De Dreu et al. (2012; also see Oberauer, Suss, Wilhelm & Wittmann, 2008) showed that working memory capacity predicted creative performance when time-on-task was long rather than short, because working memory capacity enabled individuals to persist and persevere in generating ideas and creative insights.

Although DPCM identifies creative processes at a cognitive level, the neural processes and developmental trajectories are still poorly understood. Here we explore neural correlates of performing a widely used creativity task- the Alternative Uses Test (AUT) (Guilford, 1967). The AUT asks people to generate as many as possible alternative uses (AU) for a common object (e.g., a brick; with an alternative usage being, e.g., making music). Ideas generated during such a divergent thinking task are commonly coded for originality (the less frequent the idea being mentioned, the more original it is), flexibility (the more uses from different semantic categories, the more flexible someone is), and fluency (the more ideas, the more fluent). Neuroimaging research on creative cognition research in general and divergent thinking in particular has revealed varied results. The most consistent finding across verbal divergent thinking paradigms is the involvement of (left) temporo-parietal regions, including angular gyrus (AG) and supramarginal gyrus (SMG) (Arden, Chavez, Grazioplene, & Jung, 2010; Dietrich & Kanso, 2010). Activity changes of these brain areas have for example been observed during tasks that require linking incoherent sentences (Sieborger, Ferstl, & von Cramo, 2007) or words (Bechtevera et al., 2004, Starchenko, Bechtevera, Pakhomov, & Medvedev, 2003) into a coherent story, creating metaphors and analogies (Hansen, Azzopardi, Matthews, & Geake, 2008), or thinking of AU for common objects (Abraham et al., 2012; Fink et al., 2009, 2010). Fink et al. (2009, 2010) compared activity during the generation of AU with activity during the retrieval of ordinary characteristics (OC), which is thought to be more related to intelligence in general. Results showed increased activity in left angular gyrus (AG) and supramarginal gyrus (SMG), and decreased activity in right AG for generating AU relative to retrieving OC. Another finding that is relatively consistent across various divergent thinking studies concerns the involvement of prefrontal cortex (PFC) (e.g., Abraham et al., 2012; Carlsson, Wendt, & Risberg, 2000; Chavez-Eakle et al., 2007; Folley & Park, 2005; Howard-Jones, et al., 2005; Mashal, Faust, Hendler, & Jung-Beeman, 2007), a brain region that is generally associated with cognitive control functioning and coordinating lower level (associative) brain regions (e.g., Miller & Cohen, 2001). Notably, a substantial part of the studies

that put forward the significance of prefrontal recruitment revealed positive relations between PFC activations and creative performances (e.g., Carlsson et al., 2000; Chavez et al., 2004; Chavez-Eakle et al., 2007; Gibson, Folley, & Park, 2009). In all, these results indicate that temporo-parietal regions are involved in divergent thinking processes in general whereas the ability to recruit PFC successfully might be discriminative concerning creative capacities.

Interestingly, in a prior behavioral study we showed that adults were more successful than adolescents in generating original ideas, although there were no age differences in fluency and flexibility (Kleibeuker, De Dreu, & Crone, 2013). One hypothesis is that these age differences are associated with immature cognitive control processes and related prefrontal brain functioning. PFC regions are upon the latest to mature; structural (gray and white matter) and functional changes have been observed throughout adolescence and into adulthood (Luna, et al., 2010; Giedd and Rapoport, 2010; Shaw et al., 2008). Age related changes of PFC activations have been observed for several cognitive functions including working memory, interference control and task-switching (for a review, see Bunge and Wright, 2007). Therefore, we differentiated in our analyses between adolescents and adults in order to understand how possible developmental differences in divergent thinking are associated with neural activity in the prefrontal cortex and, possibly, temporo-parietal regions including left AG and SMG. Specifically, we conducted an fMRI study in which adults and adolescents were asked to provide AU or ordinary characteristics (OC) for common objects (Fink et al., 2009; Fink et al. 2010). To reveal brain regions involved in creative cognition, activity for AU generation was contrasted with activity for ordinary characteristics retrieval. According to previous studies, we expected to find activation in left AG and left SMG for alternative generation relative to ordinary characteristic retrieval. To better understand the processes underlying the *divergent* aspect of creative idea generation, we investigated activation patterns for the generation of *multiple* creative ideas, which specifically requires switching between solutions. Based on prior research results, we anticipated lateral PFC activations to be positively associated with divergent thinking performance in both adults and adolescents and to be larger in adults than in adolescents.

Methods

Participants

Forty-five right-handed participants with no self-reported history of neurological or psychiatric disorders participated in the present study, divided across two age groups: 25 adolescents (15–17-year-olds) and 20 adults (25–30-year-olds). Analyses involved forty-three participants; 24 adolescents ($M_{age} = 16.89$ yrs, $SD = .63$, 12 male), and 19 adults ($M_{age} = 26.83$ yrs, $SD = 1.37$, 9 male). One adolescent was excluded from the analysis due to technical failures, and one adult was excluded because of excessive head motion (> 1.75 mm). Gender distributions did not differ between age groups ($\chi^2(1) = .03, p = .86$).

Participants were recruited from local schools and through local advertisements. All participants provided informed consent. In case of minors, consent was also obtained from primary caregivers. Participation was compensated with either money or course credits. All procedures were approved by the Internal Review Board of Leiden University Medical Center (LUMC).

To obtain an estimate of intelligence we included two subscales of the Wechsler Adult Intelligence Scale (Digit Span and Similarities; Wechsler, 1991, 1997, see Soveri et al., 2011). The scaled intelligence scores did not differ between age groups (Adolescents: $M = 24.54$, $SD = 2.32$; Adults: $M = 25.89$, $SD = 4.16$; $t(41) = 1.27, p = .22$, corrected for unequal variances) or gender (Males: $M = 25.48$, $SD = 2.93$; females: $M = 24.82$, $SD = 3.65$; $t(41) = .65, p = .29$).

Tasks

Scanner task

To examine the neural correlates of divergent thinking, participants performed an adapted version of the AUT (Guilford, 1967, 1950) inside the MRI scanner while neural activity was measured. The task consisted of two conditions: the free association-related Alternative Uses (AU) condition and the more verbal ability-related Object Characteristics (OC) control condition, based on Fink et al., (2009). During AU trials participants had to think of as many unusual and original uses of a common object as possible (e.g. ‘umbrella’, example answer: ‘baseball bat’). During OC trials participants had to think of as many typical characteristics of a common object as possible (e.g. ‘shoe’, example answer: ‘fits on a foot’). Each trial started with a 3-second-instruction screen to instruct the participant to think of either alternative uses, or common object

characteristics. Then, a written item was presented in the middle of the screen for 15 seconds with the text ‘ordinary characteristics’ or ‘alternative uses’ on the top of the screen during OC and AU trials, respectively, to remind participants of the instruction (see Figure 4-1). Directly after the target screen, an evaluation screen appeared for 3 seconds. Participants indicated how many solutions they had found by pressing one of four buttons on a left/right button-box that was attached to their left/right leg respectively; the left middle finger for 0 or 1 solution, the left index finger for 2 solutions, the right index finger for 3 solutions and the right middle finger for 4 or more solutions. Each trial was preceded by a fixation cross that was presented for a variable duration (0 – 7.7 seconds) to optimize the event-related design. A total of 40 items (20 AU and 20 OC) were presented in a random order, divided across three blocks with duration of approximately 7 minutes each. Short breaks were introduced between blocks to prevent fatigue.

For both the AU and OC condition we calculated the percentage of trials for which participants indicated that they thought of zero or one solution, two solutions, three solutions, and four or more solutions. In addition a composite score was calculated for each condition (AU-score and OC-score). The composite score was the sum of a) the proportion of zero or one solution times one, b) the proportion of two solutions times two, c) the proportion of three solutions times three, and d) the proportion of four or more solutions times four.

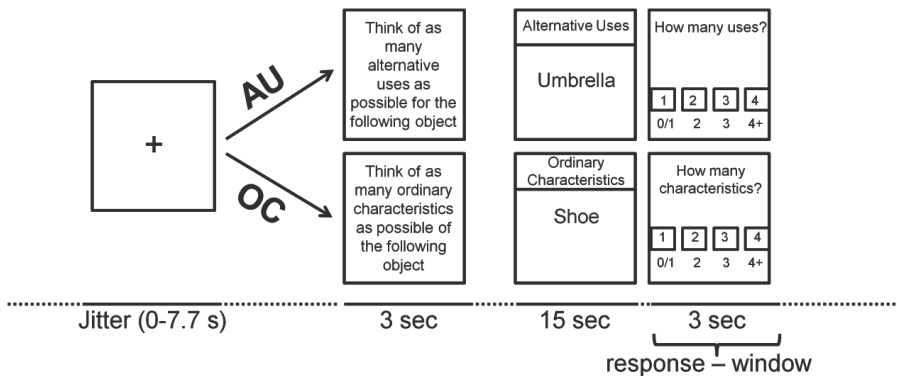


Figure 4-1. Time-line of the AUT-scanner task trial (see text for explanation)

Alternative uses test-brick task (AUT-brick)

A computerized version of the AUT was administered outside the scanner to test for convergent validity. This task measures divergent thinking in the verbal domain, similar to the task administered during the scan-session, but now for an extended period of time. Participants

were given the name of an object and asked to generate as many alternative uses for the object as possible. In the current version, participants were instructed to generate alternative uses for a *brick* (e.g., Friedman & Förster, 2001). Solutions can be unusual but must be appropriate. Participants were instructed to type their solutions one at the time on a laptop. Answers could be typed for a fixed length of 4 minutes. *Fluency* scores were computed by counting the number of correct solutions provided. *Flexibility* was measured by the number of solution-categories. An independent trained rater assigned each solution to one of 35 predefined solution-categories (e.g. building aspect; load; toy; De Dreu et al., 2008; Rietschel et al., 2006). The number of applied solution-categories was counted for each participant individually. *Originality* was measured on a 5-point scale (from 1 = ‘not original’ to 5 = ‘highly original’). An independent trained researcher rated the originality of each solution separately according to a previously developed rating scheme to reliably score originality (De Dreu et al., 2008; Rietschel et al., 2006). Originality scores were calculated for each participant by averaging the rating across all solutions.

Verbal fluency test

The verbal fluency test used in the present study was a subtest of the Groninger Intelligentie Test (GIT, Luteijn & Van der Ploeg, 1983). The test contained two items: animals and professions, which were applied consecutively. For each item, participants were asked to name as many words as possible that fall within the category of that item, within 1 minute. Answers could be given only once. Verbal fluency was scored as the total number of correct answers for both items together.

Procedure

Outside the scanner, participants received oral instructions and completed a four-trial practice session (2 AU and 2 OC trials) of the scanner task. Then they were acclimated to the MRI environment in a mock scanner. After the scanning phase (during which they performed the scanner task), they completed the WAIS subtests Digit Span and Similarities, the Verbal Fluency test and the 4-minutes AUT-brick.

MRI Data Acquisition

Scanning was performed with a Philips 8-channels SENSE whole-head coil on a 3-Tesla Philips Achieva MRI system (Best, The Netherlands) in the Leiden University Medical Center. Three runs of 167 T2*-weighted whole-brain EPIs, preceded by two dummy scans for each run to

allow for equilibration of T1 saturation effects, were subsequently acquired (TR = 2.2 s; TE = 30 ms, flip angle = 80 degrees, 38 transverse slices, 2.75 x 2.75 x 2.75 mm (+ 10% inter-slice gap). Stimuli were presented running E-prime software (version 1.2, Psychology Tools Inc.) and projected onto a screen at the head of the scanner bore. Participants viewed the stimuli by means of a mirror mounted on the head coil assembly. Head motion was restricted by using pillow and foam inserts that surrounded the head. The maximum movement parameters were below 1.75 mm and the maximum rotation was below 0.5 degrees for all participants and all scans. All anatomical scans were reviewed and cleared by a radiologist.

MRI Data Analysis

SPM5 software (www.fil.ion.ucl.ac.uk) was used for image preprocessing and analyses. Images were corrected for slice-time differences, followed by rigid body motion correction. Functional volumes were spatially normalized to EPI templates based on MNI305 stereotaxic space (Cocosco, Kollokian, Kwan & Evans, 1997) using a 12-parameter affine transformation together with a non-linear transformation involving cosine basis functions. Data were resampled to 3 mm cubic voxels. Functional volumes were smoothed using an 8mm full-width half-maximum 3D Gaussian kernel. For each participant, the functional time series were modeled by a series of events convolved with a canonical hemodynamic response function (HRF). Trials were modeled separately based on condition (AU or OC), with the time point of presentation as onset and duration of 15 seconds, and entered in a general linear model along with a basic set of cosine functions to high-pass filter the data, and a covariate for run effects. In addition, the instruction screen preceding the AU and OC trials and the evaluation screen after trials were modeled separately (onset: presentation onset; duration: 0 ms). Another set of analyses was applied to investigate the process of generating *multiple* solutions, a hallmark of divergent thinking. Here, trials were modeled not only based on the condition (AU or OC), but also on the number of solutions (0/1 or 2+) to make it possible to a) contrast trials with *multiple* AU with trials with *multiple* OC (AU2+ > OC2+); and b) contrast trials with multiple alternative uses with trials with only zero or one alternative uses (AU2+ > AU0/1). The least square parameter estimates of height of best fitting canonical HRF for each condition were used in pair wise contrasts (OC > fixation; AU > fixation; AU > OC; AU2+ > OC2+; AU2+ > AU0/1). The resulting first level contrast images, computed on a subject-by-subject basis, were submitted to group analyses. At the group level, contrasts between conditions were computed by performing one-tailed t-tests on these contrasts, treating participants as a random effect, and two-sample t-tests to compare age groups.

Whole brain fMRI analyses were FDR corrected for multiple comparisons at $p < .05$ (voxel level) (Genovese, Laxar, & Nichols, 2002) with at least 10 contiguous voxels. We further conducted whole-brain regression analyses to test for brain behavior relations using the composite AU-score of the scanner task. For whole-brain regression analyses none of the regions survived FDR correction. In addition, we applied the threshold of $p < .001$ uncorrected with at least 10 contiguous voxels to overcome the relatively low power inherent to analyses of individual differences, and focused specifically on prefrontal regions in accordance with our hypotheses. Results are reported in the MNI305 stereotaxic space. Brain regions are derived from the SPM anatomy toolbox v1.8 (Eickhoff et al. 2005, 2006, 2007).

Region-of-Interest (ROI) Analyses

Region-of-interest (ROI) analyses were performed with MarsBaR toolbox in SPM5 (Brett, Anton, Valabregue & Poline, 2005) to illustrate 1) the activation patterns for the AU and OC conditions within temporo-parietal and prefrontal brain regions and, 2) the correlation between activations related to creative idea generation (AU - OC) and AU performance. ROIs were derived from the whole brain contrasts. The output ‘contrast estimates’ was used. Contrast estimates were derived for each condition relative to baseline (i.e., OC-baseline, AU-baseline). Masked ROIs, including SMG, MTG and AG were derived from the contrast AU > OC and were masked with anatomical ROIs derived from the MarsBaR anatomical toolbox.

Results

Performance

AUT-scanner

To test for creative idea generation performance we conducted a 2 (condition) x 4 (number of solutions) x 2 (age group) mixed-model ANOVA with age group as between-subjects factor. The dependent variable was the number of trials for which a certain number of solutions was generated. We applied Greenhouse-Geisser corrections if sphericity was violated.

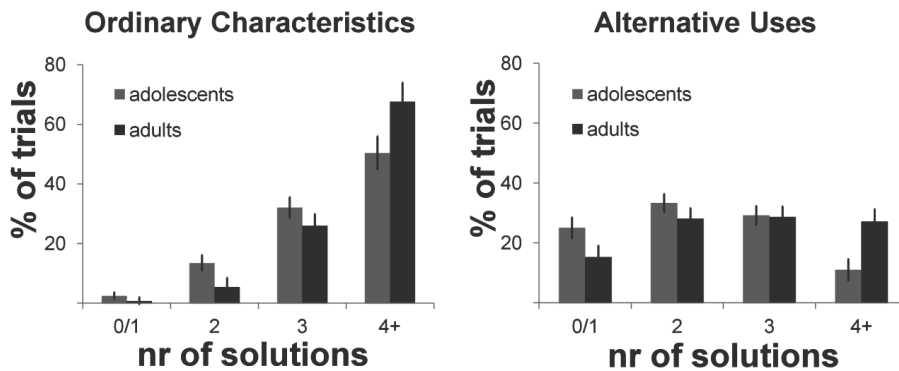


Figure 4-2. Performance on the AUT-scanner task. Percentage of trials (y-axis) for which a certain number of solutions (x-axis) is generated. Results for the Ordinary Characteristics condition are presented on the left; results for the Alternative Uses condition are presented on the right.

Results are presented in Figure 4-2 and show two significant effects: an interaction effect of condition x number with more solutions generated in the OC condition compared to the AU condition ($F(3,123) = 58.81, p < .001; \eta^2 = .56$), and an interaction effect of number x age group ($F(3,123) = 5.44, p = .009; \eta^2 = .12$) with more answers generated by adults than by adolescents. There was no significant condition x number x age group interaction effect ($F(3,123) = .64, p = .56, \eta^2 = .02$), indicating that adults were not specifically more creative, but generated more answers in general. Post hoc analyses for the number of solutions separately (OC0/1, OC2, OC3, OC4+, AU0/1, AU2, AU3, and AU4+) showed that in both conditions, adults generated four or more solutions more often than adolescents (OC4+: $t = 3.44, p = .047$; AU4+: $t = 2.66, p = .014$, corrected for unequal variances); adolescents generated two solutions more often than adults, specifically in the OC condition ($t = 1.6, p = .034$, corrected for unequal variances). Similar results were obtained for the composite AU- and OC-scores, which are presented in Table 4-1 (condition effect: $F(1,41) = 160.84, p < .001, \eta^2 = .80$; age group effect: $F(1, 41) = 7.19, p = .011, \eta^2 = .15$; condition x age group n.s.: $F(1,41) = .68, p = .41, \eta^2 = .02$).

To test for possible gender effects, we conducted additional repeated measures ANOVA on the scanner task composite scores. No main effect of gender was observed ($p > .05$). The interaction effect between condition and gender appeared significant with larger discrepancy between AU-score and OC-score for females relative to males ($F(1,41) = 6.25, p = .02, \eta^2 = .13$). Post hoc analyses showed no significant gender differences for the two measures (AU-score and

OC-score) separately (p 's > .05). Interactions with age group (gender x age group, gender x condition x age group) were not significant (p 's > .05).

Table 4-1. Age group performances

	Adolescents			Adults		
	<i>N</i>	<i>Mean</i>	<i>SD</i>	<i>N</i>	<i>Mean</i>	<i>SD</i>
AUT-scanner						
AU-score*	24	2.26	.50	19	2.68	.61
OC-score**	24	3.32	.48	19	3.61	.37
Verbal Fluency*						
	24	41.50	7.30	18	47.56	6.48
AUT-brick						
fluency*	22	8.45	3.51	17	12.71	5.82
flexibility	22	6.32	2.36	17	7.82	2.74
originality	22	1.72	.27	17	1.61	.37

* $p \leq .05$, ** $p \leq .01$.

Additional tasks

Performances for the tasks taken outside the scanner, the verbal fluency test and the AUT-Brick task, are presented in Table 4-1.

Verbal fluency test

To test for age group differences on verbal fluency an independent samples t-test was applied on verbal fluency scores with age group as independent variable. Results revealed a significant age group effect, showing that adults performed better than adolescents: $t(40) = 2.79$, $p = .008$. No gender effect or age group x gender effect was observed (p 's > .1)

AUT-brick

To examine age group differences for divergent thinking, a multivariate analysis of variances (MANOVA) was performed on the AUT-brick measures fluency, flexibility, and originality. Results showed a significant age group effect ($F(4,34) = 3.34$, $p = .02$). Post hoc analyses showed that the effect was driven by a significant age group effect for AUT-brick fluency with better performance for adults compared to adolescents (AUT-brick fluency: $t(37) =$

2.66, $p = .01$, corrected for variance differences). Age group differences were only marginally significant for AUT-brick flexibility ($t(37) = 1.84, p = .07$). No age group effects were observed for AUT-brick originality. Additional analyses on gender and gender x age group effects revealed no significant results. On a behavioral level, these results are in line with performance on the scanner task, indicating that adults showed greater fluency in general.

Correlations

To validate the processes that are involved in the AU and OC conditions, bivariate correlations were estimated between AU- and OC-scores of the scanner task, and performances on the verbal fluency test and AUT-brick task. Results are presented in Table 4-2. Significant correlations were observed for OC-score with both fluency measures; verbal fluency ($r = .44, p < .001$) and AUT-brick fluency ($r = .36, p = .02$), but not for OC-score with AUT-brick flexibility, or AUT-brick originality. AU-score correlated significantly with AUT-brick fluency ($r = .54, p < .001$) and AUT-brick flexibility ($r = .36, p = .02$), and marginally with AUT-brick originality ($r = .30, p = .07$), but not with verbal fluency ($r = .26, p > .1$). Similar results were obtained when analyses were controlled for gender. When controlling for age, results showed some deviations: OC-scores correlated no longer with AUT-brick fluency scores ($r = .26, p = .12$); AU-scores correlated only marginally with AUT-brick flexibility scores ($r = .29, p = .08$), but significantly with AUT-brick originality scores ($r = .40, p = .01$). In all, these results support the differentiation between the two conditions with the AU condition related to creativity-related divergent thinking aspects and OC condition associated with more verbal ability-related fluency capacities (Fink et al., 2009).

Table 4-2. Bivariate correlations for fluency and creativity measures

	AUT-scanner	
	AU-score	OC-score
Verbal Fluency	.26	.44**
AUT-brick fluency	.54**	.36*
AUT-brick flexibility	.36*	.15
AUT-brick originality	.30~	.07

Note. AU = alternative uses, OC = ordinary characteristics, AUT = Alternative Uses Test

* $p \leq .05$, ** $p \leq .01$, ~ $p \leq .10$

fMRI results

To extract the neural correlates of creative idea generation we conducted whole-brain voxel-wise t-tests on activation levels for the contrast AU > OC across all participants ($N = 43$). Results revealed a number of regions including left SMG, left and right MTG, and left AG (FDR corrected, $p < .05$; see Figure 4-3 and Table 4-3), which is in line with prior studies (Fink et al., 2009; Fink et al., 2010). The opposite contrast OC > AU showed increased activity for retrieval of characteristics relative to alternative uses for common objects in a number of different brain regions (see Table 4-4). Results were most pronounced in left and right posterior SMG/anterior AG and thereby resemble previous findings by Fink et al., 2010.

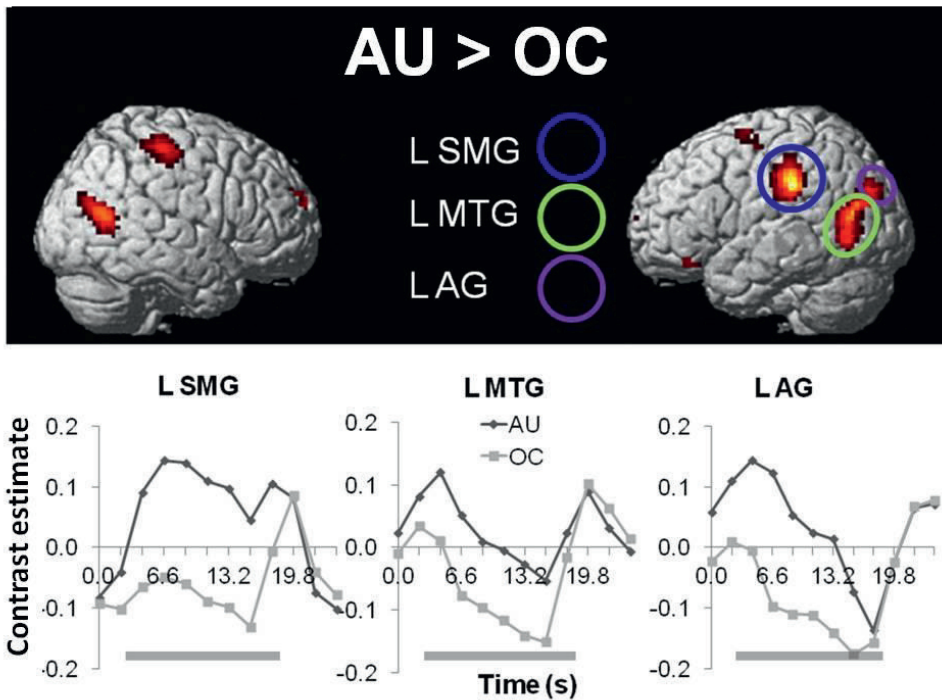


Figure 4-3. Top: Whole brain results for the contrast AU > OC ($N = 43$; $p < .05$, FDR corrected (voxel level), > 10 contiguous voxels). Below: Time series for the anatomically masked functional ROIs for the AU and OC conditions, with onset of instruction screen at time = 0 s. The gray beams beneath the graphs represent object presentation (time = 3.0 – 18.0 s) during which participants are required to generate solutions. Time series are presented for illustrative purposes only. AU = Alternative Uses, OC = Ordinary Characteristics, L SMG = left supramarginal gyrus, L MTG = left middle temporal gyrus, L AG = left angular gyrus.

We conducted a second set of analyses to examine neural correlates for trials on which multiple solutions were generated, a crucial characteristic of divergent thinking success.

Contrasting trials for which participants indicated that they had found two or more alternative uses with trials for which they had thought of two or more ordinary characteristics ($AU_{2+} > OC_{2+}$), revealed similar results as the contrast $AU > OC$, including left SMG, left AG and bilateral MTG. However, additional activation was observed in several regions, including left middle frontal gyrus (MFG) and left inferior frontal gyrus (IFG) pars Triangularis (see Table 4-5). A direct comparison of AU trials with two or more solutions and trials with zero or one solution ($AU_{2+} > AU_{0/1}$) revealed no significant effects. However, applying a more liberal significance threshold ($p < .001$, uncorrected) revealed activations mainly in the left hemisphere, including left middle frontal gyrus (MFG) and left inferior frontal gyrus (IFG) pars Triangularis (see Table 4-6). These findings are in congruence with the findings for contrast $AU_{2+} > OC_{2+}$ and indicate that the differences between the contrasts $AU > OC$ and $AU_{2+} > OC_{2+}$ are not the result of differences between $OC_{0/1}$ and OC_{2+} trials.

To test for developmental differences, whole-brain two-sample t-tests (adolescents versus adults) were conducted on the contrast $AU > OC$. There were no age group differences (significance threshold: $p < .05$ FDR corrected). There were also no age group differences when we analyzed only those trials for which participants gave at least two solutions ($AU_{2+} > OC_{2+}$).

Table 4-3. Neural activations for the contrast AU > OC

Brain regions	L/R	K	Z-value	MNI coordinates		
			peak voxel	x	y	z
Supra Marginal Gyrus	L	189	6.63	-60	-30	36
Inferior Parietal Cortex (PGp), Middle Temporal Gyrus	L	265	5.01	-42	-84	30
			4.25	-54	-66	0
			4.04	-45	-63	9
Anterior Cingulate Cortex, Middle Orbital Gyrus	L	834	4.91	-3	48	0
			4.86	-9	48	-6
			4.76	0	51	12
Postcentral Gyrus	R	199	4.73	36	-30	51
Middle Temporal Gyrus	R	160	4.49	48	-63	15
			3.81	51	-75	21
Hippocampus	L	26	4.06	-24	-12	-18
Superior Frontal Gyrus (BA6)	L	55	3.99	-21	-6	60
Calcarine Gyrus	L	65	3.79	-6	-51	6
			3.47	-9	-60	9
Inferior Frontal Gyrus (p. Orbitalis)	L	31	3.61	-30	33	-15
Inferior Frontal Gyrus (p. Opercularis)	L	12	3.44	-51	6	24

Note. Abbreviations: MNI = Montreal Neurological Institute; L = Left hemisphere; R = Right hemisphere.

Significance threshold: $p < .05$, FDR corrected (voxel level); > 10 voxels

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Table 4-4. Neural activations for the contrast OC > AU

Brain regions	L/R	K	Z-value	MNI coordinates		
			peak voxel	x	y	z
Angular Gyrus (hIP3), Inferior Parietal Lobule (PFm), Supra Marginal Gyrus (hIP1)	R	2745	7.54	33	-63	48
			5.99	51	-51	48
			5.11	48	-63	48
Middle Temporal Gyrus, Precentral Gyrus (Area 4a, 3b), Angular Gyrus (hIP1)	L	6441	6.87	-66	-51	48
			6.14	-36	-42	39
			6.02	-33	-36	-6
Inferior Temporal Gyrus, Rolandic Operculum (OP 4)	R	1069	5.43	57	-24	57
			4.35	66	-63	42
			4.21	63	-39	-18
Inferior Occipital Gyrus (hOC3v (V3v), Fusiform Gyrus, Middle Occipital Gyrus	L	1025	4.91	-27	-27	-18
			4.78	-33	-3	12
			4.55	-39	-93	-9
Middle Cingulate Cortex	R	221	4.69	3	-72	-15
Precentral Gyrus (Area 6)	R	61	3.62	21	-87	-3
Middle Temporal Gyrus	L	35	3.60	-54	-33	33
Medial Temporal Pole	R	12	2.71	48	-27	60
Lingual Gyrus (Area 17)	R	19	2.54	9	6	-24
			2.50	3	9	-24

Note. Abbreviations: MNI = Montreal Neurological Institute; L = Left hemisphere; R = Right hemisphere

Significance threshold: $p < .05$, FDR corrected (voxel level); > 10 voxels

Table 4-5. Neural activations for the contrast AU 2+ > OC 2+

Brain regions	L/R	K	Z-value	MNI coordinates		
			peak voxel	x	y	z
Inferior Parietal Cortex (PGp), Middle Temporal Gyrus	L	106	5.34	-42	-84	30
			3.72	-42	-63	15
			3.37	-51	-69	15
Fusiform Gyrus	L	40	4.39	-24	-33	-21
			3.43	-33	-42	-21
Hippocampus	L	18	4.37	-24	-15	-18
Postcentral Gyrus (area 2)	R	39	4.34	36	-33	48
Anterior Cingulate Cortex, Middle Orbital Gyrus	L	147	4.34	0	36	-6
			4.27	-9	51	-6
			3.64	-3	48	0
Olfactory cortex	L	27	4.24	0	12	-6
Inferior Frontal Gyrus (p. Opercularis; Area 44), Rolandic Operculum	L	36	4.14	-51	6	24
			3.36	-42	-3	18
Middle Frontal Gyrus (Area 6)	L	62	4.13	-24	0	60
			3.42	-24	-9	48
Middle Temporal Gyrus/Middle Occipital Gyrus (PGp)	R	65	4.07	48	-63	15
			3.64	51	-75	24
Middle Temporal Gyrus	L	28	4.05	-54	-66	-3
Inferior Frontal Gyrus (p. Orbitalis)	L	29	4.03	-27	33	-15
Superior Frontal Gyrus	L	11	3.88	-18	21	39
Inferior Parietal Lobule (Area 2/hIP3)	L	22	3.65	-39	-39	48
			3.25	-30	-36	39
Superior Frontal Gyrus	L/R	17	3.61	3	57	12
Inferior Frontal Gyrus (p. Triangularis), Middle Frontal Gyrus	L	24	3.60	-45	33	12
			3.54	-45	39	18
Calcarine gyrus	L	12	3.45	-9	-48	6

Note. Abbreviations: MNI = Montreal Neurological Institute; L = Left hemisphere; R = Right hemisphere

Significance threshold: $p < .05$, FDR corrected; > 10 voxels

Table 4-6. Neural activations for the contrast AU 2+ > AU 0/1

Brain regions	L/R	K	Z-value	MNI coordinates		
			peak voxel	x	y	z
Anterior Cingulate Cortex, Cingulate Gyrus	L/R	33	4.40	-6	9	24
			3.24	3	0	27
Rolandic Operculum, Precentral Gyrus (Area 44)	L	71	4.35	-48	3	12
			4.17	-48	3	21
			3.43	-39	-3	15
Postcentral Gyrus (Area 1), Inferior Parietal Lobule (Area 2/hIP3), Postcentral Gyrus (Area 2/3b)	L	122	3.91	-42	-30	63
			3.84	-36	-39	48
			3.55	-42	-27	48
Precentral Gyrus (Area 6)	L	24	3.84	-24	-9	66
			3.27	-30	-21	63
Cerebellum (Lobule VI, Hem)	R	14	3.77	27	-51	-30
Superior Frontal Gyrus	L	25	3.76	-15	21	54
			3.58	-15	12	57
Inferior Frontal Gyrus (p. Triangularis)	L	53	3.63	-45	33	15

Note. Abbreviations: MNI = Montreal Neurological Institute; L = Left hemisphere; R = Right hemisphere

Significance threshold: $p < .001$, uncorrected (voxel level)

Individual differences

To test for brain regions directly related to divergent thinking performance (fluency), we conducted whole-brain voxel-wise regression analyses on the contrast AU > OC with performance on AU trials (AU- score of the scanner task, see methods section) as covariate of interest. No significant findings were observed at the threshold $p < .05$ FDR corrected. However, when the threshold was lowered to $p < .001$, uncorrected, > 10 contiguous voxels, significant correlations were found in a number of regions for which we had a priori hypotheses (see Table 4-7). Specifically, activation levels for the contrast AU > OC were correlated with creative performances in a region in the left lateral PFC (MFG and IFG pars Triangularis, see Figure 4-4a, b). Notably, this region overlapped with the left MFG/IFG regions that were significantly more activated for AU2+ trials relative to AU0/1 trials. As such, our results show both within- and between-subject support for a significant role for left lateral PFC in divergent thinking. In addition

to left lateralized brain regions, the regression analyses with AU-scores ($p < .001$, uncorrected for multiple comparisons) revealed significant results in the right hemisphere, including right MFG and right IFG pars Triangularis (see Table 4-7). Thus, while successful divergent thinking (2+ solutions; within subjects) was associated with increased *left* lateralized prefrontal activations, divergent thinking performance (AU- score; between subjects) related to activity changes in both left and right prefrontal cortices.

Regression: AU > OC with AU-score

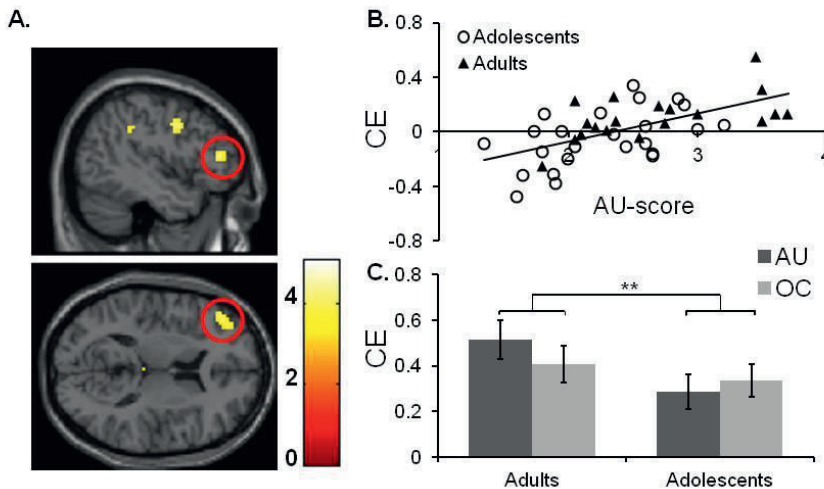


Figure 4-4. A) Whole brain results for the regression of AU-score on the contrast AU > OC, thresholded at $p < .001$, uncorrected; > 10 contiguous voxels (section coordinates: $X = -45, Z = 12$). Color scale represents t-values. B) Correlation between creative thinking related activation (AU-OC) for the left IFG/MFG (ROI-peak-value at MNI coordinates -45, 39, 12) and AU-score for adolescents (open circles) and adults (filled triangles). C) Contrast estimates for AU and OC conditions relative to baseline for left IFG/MFG. Results for adolescents are presented left, results for adults are presented right. CE = Contrast estimate. ** $p \leq .01$

We hypothesized that adolescents would show immature divergent thinking performance related to immature PFC activation patterns. To test these hypotheses we performed ROI analyses on the contrast estimates of the left IFG/MFG cluster, which were derived from the regression analyses described above. First, we examined whether age group differences were present using a 2 (condition) $\times$ 2 (age groups) mixed ANOVA on contrast estimates for AU and OC conditions relative to baseline (AU- baseline; OC- baseline). Results revealed a significant age group $\times$ condition interaction effect ($F(1,41) = 7.21, p = .01, \eta^2 = .15$; see Figure 4-4c). Adults showed

larger condition effects than adolescents, which is in line with our hypothesis that adolescents do not yet recruit left lateral PFC for creative thinking at a similar level as adults.

Second, we applied a 2 (conditions) x 2 (age groups) mixed ANOVA with AU-scores entered as covariate, given that age groups differed in performance. Results revealed a significant interaction effect for condition x AU-score ($F(1,41) = 15.56, p < .001, \eta^2 = .28$) but no significant age group effect ($p = .15$). These results indicate that divergent thinking performance predicts left IFG/MFG activation for creative idea generation across both age groups, and adolescents do not recruit these relevant brain regions at an adult level yet.

Table 4-7. Neural activations for the regression AU > OC with AU-scores

Brain regions	L/R	K	Z-value	MNI coordinates		
			peak voxel	x	y	z
Supplementary Motor Area (bilateral), Superior	L/R	93	4.44	9	15	48
Medial Gyrus (L)			3.48	-3	18	45
			3.43	-9	27	36
Cerebellum (Lobule VI Hem, vermis)	R	190	4.24	15	-75	-24
			4.13	30	-63	-27
			3.54	6	-66	-24
Middle Frontal Gyrus	R	51	4.00	30	9	51
			3.81	27	-3	45
Middle Frontal Gyrus	R	48	3.96	42	42	21
Precentral Gyrus, Superior Frontal Gyrus (Area 6)	L	30	3.90	-33	-9	66
			3.54	-27	-3	69
			3.38	-3	-27	21
Precentral gyrus	L	63	3.85	-36	0	33
			3.82	-45	0	39
Inferior Frontal Gyrus (p. Triangularis), Middle	L	45	3.76	-45	39	12
Frontal Gyrus			3.69	-36	48	15
			3.31	-33	51	24
Cerebellum (Lobule VI, Hem)	L	23	3.75	-9	-78	-21
Inferior Frontal Gyrus (p. Orbitalis)	R	43	3.76	42	27	-9
Inferior Parietal Lobule (hIP1)	L	22	3.51	-39	-45	33
			3.13	-42	-51	42
Supplementary Motor Area (Area 6)	L	10	3.26	0	0	57

Note. Abbreviations: MNI = Montreal Neurological Institute; L = Left hemisphere; R = Right hemisphere

Significance threshold: $p < .001$, uncorrected; > 10 voxels.

Gender differences

To test for possible gender differences (see Abraham et al., 2012) we applied explorative whole-brain analyses. No significant effects were observed (significance threshold: $p < .05$, FDR corrected, > 10 contiguous voxels). Additional mixed ANOVA's on contrast estimates for the AU and OC conditions relative to baseline for the four functional ROIs (IMTG, ISMG, IAG, L IFG/MFG) showed no effects for IAG and LIFG/MFG. For IMTG and ISMG, significant interaction effects were observed for gender x condition (AU > OC) with larger discrepancies for males relative to females (SMG: $F(1,41) = 4.88$, $p = .03$, $\eta^2 = .10$; MTG: $F(1,41) = 6.59$, $p = .01$, $\eta^2 = .14$).

Discussion

The aim of the study was to better understand distinctive neural activation patterns supporting creative idea generation in adolescents and adults. For this purpose, we applied an adapted version of the AUT (Guilford, 1967, 1950; Fink et al., 2009, 2010) while scanning with fMRI. Significant correlations with tests performed outside the scanner (AUT-brick task and verbal fluency test) validated the two conditions used to extract processes underlying creative idea generation (alternative uses and ordinary characteristics). On the behavioral level, adults outperformed adolescents on generating AU as well as naming ordinary characteristics. The fMRI data yielded three important findings: 1) consistent with prior studies, we found increased activation of left supramarginal gyrus (SMG) and angular gyrus (AG), as well as left middle temporal gyrus (MTG) and medial frontal cortex for creative idea generation relative to naming ordinary characteristics; 2) trials during which participants generated multiple solutions (AU2+ > OC2+ and AU2+ > AU0/1), a hallmark of divergent thinking, revealed additional left IFG/MFG activation; 3) individual differences analyses showed that performance on the AU trials predicted left IFG/MFG activations related to creative idea generation, and adults recruited this brain region more than adolescents. The discussion is organized along the lines of these three main findings.

Neural Correlates of Creative Idea Generation

Consistent with prior studies (e.g., Fink et al., 2009, 2010; Bechtereva et al., 2004; Starchenko et al., 2003), generating alternative uses relative to naming ordinary characteristics resulted in increased activity in mainly left hemisphere regions, including AG, SMG and MTG. These temporo-parietal regions are argued to be critically involved in verbal creative thinking

(Bechtevera et al., 2004; Fink et al., 2009). One possible role of these brain regions in the current task concerns semantic processing: activation of an object's semantic information is likely a precursor for generating possible uses of that object. Several prior studies have demonstrated that the AG, SMG (posterior) and MTG are involved during semantic tasks (e.g., Jung-Beeman 2005; Binder, Desai, Graves, & Conant, 2009; Vigneau et al., 2006). Moreover, MTG and SMG have been specifically related to tool use and action knowledge, including semantic information of tools and imaginative tool use (Beauchamp, Lee, Haxby & Martin, 2002, Johnson-Frey, 2004; Lewis, 2006). It is likely that processing these types of information on tool use is especially profitable when thinking about alternative uses of objects. Furthermore, activation of the SMG and AG may contribute to the flexible character of creative thinking: prior neuroimaging and clinical studies indicate the importance of these temporo-parietal regions in the flexible switching between tasks (e.g., Sohn et al. 2000; see also Starchenko et al., 2003; Bechtevera et al., 2004) and between attention foci (e.g., Humphreys et al., 1994).

Besides the anticipated temporo-parietal regions, creative idea generation was associated with activation in e.g., a large cluster within the medial PFC, including (anterior) cingulate cortex (ACC). One possible interpretation for these results is that creative idea generation involves monitoring of information retrieval. The ACC is commonly associated with error or conflict monitoring processes (e.g., Botvinick, Cohen & Carter, 2004). This interpretation would be in congruence with the idea that flexible processing requires an evaluation mechanism ('idea monitor') to judge the appropriateness of generated responses (Nijstad et al., 2010; Dietrich, 2004; Iyer et al., 2009).

Some regions that were more active when thinking about alternative uses than ordinary characteristics, such as the AG and the medial PFC, are part of the default mode network (Raichle, 2001). These areas have previously been associated with free thinking, mentalizing and mind wandering (e.g., Buckner, Andrews-Hanna, & Schacter, 2008; Christoff, 2010; Gruberger, Ben-Simon, Levkovitz, Zangen, & Hendler, 2011; Mason et al., 2007). It is reasonable to assume that these processes are also involved when thinking 'out of the box'. Indeed, mind wandering has been thought of as *micro incubation* (Sawyer, 2011), a process during which one refrains from conscious thought and after which a creative insight 'suddenly' appears in the conscious mind (see e.g. Dijksterhuis & Meurs, 2006). An interesting question for future research is to examine activations of resting state networks in combination with divergent thinking tasks to better

understand the role of these networks in divergent thinking (see also Takeuchi et al., 2011a, 2011b).

Performance Related Activation of lateral PFC

The results in this study showed that generating multiple creative ideas (within subjects) and better creative performance (between subjects) were both related to increased activity in left lateral PFC. This brain region is generally associated with cognitive control functioning and has been shown to be involved in switching between semantic (sub)categories (Hirshorn and Thompson-Schill, 2006). These findings are in line with the conceptions that creative thinking involves cognitive flexibility and working memory (e.g., De Dreu et al, 2012; Vartanian, 2009; Zabelina & Robinson, 2010), as it refers to the generation of original and useful ideas by combining already stored information (Dietrich, 2004). Furthermore, the brain-behavior correlations support the hypothesis that PFC activity is predictive of divergent thinking performance, whereas temporo-parietal activations are related to creative thinking in general. Therewith, our results complement previous studies showing activation levels for PFC brain regions discriminative concerning divergent thinking (e.g., Carlsson et al., 2000; Chavez et al., 2004; Chavez-Eakle et al., 2007; Gibson et al., 2009). Creating alternative uses relative to ordinary characteristics of objects revealed activations in *left* lateral PFC, whereas better, relative to poorer, performance on the AU trials was associated with larger lateral PFC activations in *both* hemispheres. These findings indicate that divergent thinking in general is dominated by left hemisphere activation, but creativity performance is related to the level of recruitment of both hemispheres. It should be noted that performance-related activation was also found in other areas for which we did not have a priori hypotheses. Future studies should examine the robustness of the role of PFC in divergent thinking and the possible role of other areas and their connections with PFC.

Developmental Differences

One additional question that was addressed in this study was whether there would be a difference in neural recruitment during divergent thinking in adolescents compared to adults. This hypothesis was based on the assumption that there is continued development of brain regions implicated in divergent thinking, especially of the lateral PFC (Luna et al., 2010; Giedd and Rapoport, 2010; Shaw et al., 2008), although the specifics are currently debated, with some studies reporting more activation in adolescents compared to adults, and others reporting less

activation in lateral PFC in adolescents compared to adults (see Crone & Dahl, 2012 for an overview). Behaviorally, our results indicate that adolescents are still developing creative abilities, showing immature fluency measures, but not originality or flexibility measures. Notably, these results deviate from a prior study, showing immature originality, but not fluency performance (Kleibeuker et al., 2013). A possible explanation for this difference is that the adolescent age groups slightly differed in mean age, with older participants in the current study. Another possible explanation concerns a shift in the balance of quality (originality) and quantity (fluency) of answers whereby participants in the current study focused more on quality rather than quantity of answers, as a result of the emphasis on *alternative* object uses in the scanner task.

The current neuroimaging findings revealed no age differences at the whole brain level. However, region-of-interest analyses revealed that the left lateral PFC, which was related to individual differences in divergent thinking performance, was more activated in adults than in adolescents. One possible interpretation is that adolescents were not yet able to recruit these task-relevant brain regions to a mature level for the task at hand. Indeed, creativity promoting complex abilities of controlling thought processes and flexibly changing perspectives are thought to develop throughout adolescence (Wu & Chiou, 2008). Specifically, prior studies have suggested that attentional inhibition and cognitive flexibility are still developing in adolescence (Huizinga, Dolan, & van der Molen, 2006). However, it should be noted that this PFC region was extracted from an individual differences contrast and age-effects disappeared when performance was entered as a covariate. Moreover, there were no general age effects for the main contrast AU>OC. A possible interpretation is that higher fluency/divergent thinking performance is associated with higher IFG/MFG activation, and that adults may achieve higher performance by stronger recruitment of this region. How exactly inhibition and cognitive flexibility, and their developmental trajectories, relate to creative cognition, remains an important question for future studies. To our knowledge, this is the first study comparing adults' and adolescents' brain activity during creative divergent thinking, and future studies will provide more insight into these compelling questions.

Gender Differences

Although males and females did not differ in task performance for the two scanner task conditions (AU and OC) separately, there was a small gender difference in relative performance for these two conditions with females showing larger discrepancies between retrieval success and creative thinking. These results might be the consequence of slight differences in creative thinking

strategies (McCarthy et al., 2012). Accordingly, behavioral effects were accompanied with larger creative thinking related activations of left MTG and SMG in males relative to females. These results are in line with previous findings in research on gender differences in creative thinking (Abraham, Thybusch, Piertz & Hermann, 2013). The lack of age related differences in these gender effects indicate that possible discrepancies in creative thinking strategies are already present in adolescence.

Limitations and Future Directions

Some limitations of the current study should be taken into account when drawing conclusions on the underlying processes of creative thinking. First of all, one should be cautious with generalizing the present results. The current study examined neural correlates of flexible, divergent thinking as one of the key drivers underlying creative performance and original ideation. However, the Dual Pathway to Creativity Model (Baas et al., 2008; De Dreu et al., 2008; Nijstad et al., 2010) highlighted another pathway, namely perseverance. Future research is needed to develop fMRI tasks that capture perseverance, so that the neural correlates of flexible processing as well as perseverance can be examined alone and in combination. Here we applied an adapted version of the AUT where creative thinking was operationalized by the processes underlying idea generation. These processes likely involve e.g., semantic processing and (verbal) working memory, inherent to the identity of the task. In the present fMRI design creative *performance* was operationalized as the number of generated alternative uses for common objects as indicated by the participant, implying an indirect measure of creative performance. Another limitation of this study, regarding the interpretability of developmental changes, is that the results were cross-sectional and not longitudinal. The reliability of the observed age differences is therefore limited. Future studies are necessary to understand the development of processes that underlie creative idea generation. Moreover, for future research it would be interesting to focus on possible improvements and related changes in brain recruitment in adolescents, applying practice/training of idea generation. These results are expected to give better understanding of the possibilities and limitations of the adolescent brain regarding creative idea generation.

Conclusion

Taken together, the results of this study demonstrated that creative idea generation in general involves recruitment of mainly left lateralized parietal and temporal brain regions that are associated with semantic activation, imagination and tool use, including AG, SMG and MTG.

However, generating *multiple* creative ideas, a hallmark of divergent thinking, shows additional lateral PFC activation, which is not yet optimized in middle adolescence.

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CHAPTER 5

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

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Abstract

Creativity commonly refers to the ability to generate ideas, solutions, or insights that are novel yet feasible. The ability to generate creative ideas appears to develop and change from childhood to adulthood. Prior research, although inconsistent, generally indicates that adults perform better than adolescents on the alternative uses task, a commonly used index of creative ideation. The focus of this study was whether developmental differences could be reduced by practicing alternative uses generation. We examined the effectiveness of creative ideation training in adolescents (13-16 yrs., $N=71$) and adults (23-30 yrs., $N=61$). Participants followed one of three types of training, each comprising 8 twenty-minute practice sessions within two weeks time: 1) alternative uses generation (experimental condition: creative ideation); 2) object characteristic generation (control condition: general ideation); 3) rule-switching (control condition: rule-switching). Progression in fluency, flexibility, originality of creative ideation was compared between age-groups and training conditions. Participants improved in creative ideation and cognitive flexibility, but not in general ideation. Participants in all three training conditions became better in fluency and originality on the alternative uses task. With regard to originality, adolescents benefitted more from training than adults, although this was independent of training condition. These results are interpreted in relation to a) the different underlying processes targeted in the three conditions and b) developmental differences in brain plasticity with increased sensitivity to training in adolescents. In sum, the results show that improvement can be made in creative ideation and supports the hypothesis that adolescence is a developmental stage of increased flexibility optimized for learning and explorative behavior.

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Introduction

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

In this study we examine the possibility that creative ideation develops from adolescence to adulthood, and can be trained with relatively simple interventions. Adolescence is a phase of development characterized by flexible adaption to a rapidly changing social landscape marked by changes from dependency to autonomy and individuality (Crone and Dahl, 2012). It forms a crucial phase for the development of cognitive abilities assumed to be related to creative cognition such as working memory and cognitive control (e.g., Bunge & Wright, 2007; Crone & Dahl, 2012; Diamond, Kirkham, & Amso, 2002; Huizinga & van der Molen, 2007). Yet, relatively little is known about whether and how malleable divergent thinking is in adolescence. Training in other higher cognitive skills such as working memory (Jolles, van Buchem, Rombouts, & Crone, 2012;

Klingberg, 2010), executive control (Karch & Kray, 2009; Zinke, Einert, Pfennig, & Kliegel, 2012), relational reasoning (Dumontheil, Houlton, Christoff, & Blakemore, 2010) and algebraic equation solving (Qin et al., 2004) emphasize the plasticity of the adolescent brain. In this study we test this hypothesis with regard to the development of creative ideation skills.

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

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

The present study aimed to extend investigations into the development of creative ideation by examining the progression of adults and adolescents within a simple training paradigm. The main question was whether creative ideation in adolescents is limited by maturational constraints or that exposure to divergent thinking training leads to progression in creative ideation thereby narrowing the gap in performance between adolescents and adults. To this end, participants were asked to practice generating alternative uses for everyday objects over a two week period. To examine the effects of training two active control groups employed (Jolles & Crone, 2012), both trained in cognitive processes that were associated with but not directly related to creative

ideation. One control group generated ordinary characteristics of everyday objects (adapted from Fink et al., 2009). This task has successfully served as a general ideation control task (Fink et al., 2009, 2010; Kleibeuker, Koolschijn, Jolles, De Dreu, et al., 2013b). The second active control group practiced in rule-switching. Here, participants were asked to quickly and accurately apply and switch between two rule sets (Huizinga, Burack, & Van der Molen, 2010).

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

Methods

Participants

The sample comprised 71 adolescents ($M_{age}=14.9$, $SD=.7$, Range=13.0-16.2 years, 67% females) and 61 adults ($M_{age}=25.3$, $SD=2.4$, Range=22.1-31.1 years, 50% females). Adolescents were recruited from local high schools (college preparation level) and adults were recruited from Leiden University and colleges in The Hague. All participants provided informed consent. In case of minors, consent was also obtained from primary caregivers. Participation was compensated with gift vouchers, money or course credits. All procedures were approved by the Internal Review Board of Leiden University Institute of Psychology.

The data was gathered in two waves separated by 15 months. In both waves adolescents and adults were recruited and randomly assigned to one of the training conditions (creative ideation; general ideation; rule-switching). There were two drop-outs. During the pretest and posttest not all data was available for all participants on all tasks. In some cases this was due to technical errors and in other cases students were absent from a testing session. Because the data

was missing at random and not due to selection bias or systematic error, the validity of the statistical tests was not affected (Shafer and Graham, 2002). The number of subjects used in statistical analyses is reported separately per task and, as recommended, Maximum Likelihood estimation was used when appropriate.

General cognitive ability

Creativity is associated with verbal fluency (Gihooly et al., 2007), fluid reasoning (Nusbaum & Silvia, 2011) and working memory (De Dreu et al., 2012). Tasks that measure these constructs were administered at pretest in order to check for any differences between training conditions. The verbal fluency test (subtest of the Groningen Intelligence Test, GIT-2, Luteijn & Barelds, 2004) was used to measure general verbal ideation ability. Fluid reasoning was measured with the Raven Advanced Progressive Matrices (APM, Raven, Raven, & Court, 1998). Working memory was assessed using the mental counters task (Huizinga, Dolan, & van der Molen, 2006). Analyses of Variance were conducted with Age (adolescent, adult) and Training Condition (creative ideation, general ideation and rule-switching) as between-subjects factors to assess any differences in performance on these three tasks. See Tables 5-1 and 5-2 for descriptive statistics and *F*-test results respectively. No age group or training condition differences were found with regard to fluid reasoning. Adults outperformed adolescents on the measures of verbal fluency and working memory; however, there were no significant effects for training condition or age-group by training condition.

Table 5-1. Descriptive statistics of pretest and posttest measures per training condition and age group on control variables: fluid reasoning, verbal fluency and working memory

	Creative Ideation training			General ideation training			Rule-Switch training		
	N	M	SD	N	M	SD	N	M	SD
Verbal Fluency									
<i>Adolescents</i>	25	23.16	3.44	23	22.96	5.09	21	23.38	5.18
<i>Adults</i>	21	27.24	5.07	19	26.84	8.30	19	24.79	6.72
Raven APM									
<i>Adolescents</i>	23	9.26	2.01	21	9.38	3.14	20	8.45	3.58
<i>Adults</i>	19	9.68	1.60	18	10.11	3.32	16	10.00	1.97
Working Memory									
<i>Adolescents</i>									
accuracy	19	.88	.08	16	.86	.09	18	.84	.19
reaction time*	19	574	98	16	594	122	18	534	89
<i>Adults</i>									
accuracy	20	.90	.09	19	.91	.09	18	.92	.05
reaction time*	20	487	115	19	555	152	18	502	106

Note. *Reaction time is reported in milliseconds.

Table 5-2. F-test results for comparisons of general cognitive ability measures of verbal fluency, fluid reasoning, and working memory per training condition and age group

	F	df	p	η_p^2
Verbal Fluency				
Age	9.54	1, 122	<.01	.07
Condition	0.43	2, 122	.65	.01
Age x Condition	0.70	2, 122	.50	.01
Raven APM				
Age	3.17	1, 111	.08	.03
Condition	0.34	2, 111	.71	.01
Age x Condition	0.43	2, 111	.65	.01
Working Memory				
<i>Accuracy</i>				
Age	5.95	1, 104	.02	.05
Condition	0.05	2, 104	.95	.00
Age x Condition	0.68	2, 104	.51	.01
<i>Reaction Time</i>				
Age	5.55	1, 104	.02	.05
Condition	2.34	2, 104	.10	.04
Age x Condition	0.65	2, 104	.53	.01

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

Design and Procedure

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

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

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

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

Instruments

Creative Ideation

Alternative Uses Test: Pretest and Posttest

A computerized four-minute version of the Alternative Uses Test (AUT; Guilford, 1950, 1967) was administered to measure creative ideation. Participants were given the name of an object and asked to generate as many alternative uses for the object as possible within a four minute period (e.g., Friedman & Förster, 2001). At pretest the object was 'Tin Can' and at posttest the object was 'Brick'. Participants were instructed to type in their solutions one at the time. After submitting the solution the text was no longer shown on the screen. From the generated ideas, we derived indices of fluency, flexibility, and originality after removing erroneous solutions (e.g., empty solutions, random strings such as 'asdfjk;' and nonsense solutions such as 'blah'). *Originality* was rated on a 5-point scale (from 1='not original' to 5='highly original') by trained

raters according to a pre-specified scheme (De Dreu et al., 2008; Rietzschel et al., 2006). The interrater reliability of the originality scores of this task were $ICC=0.91$. *Fluency* scores were the sum of correct solutions provided. *Flexibility* was measured by the number of solution-categories per participant after trained raters assigned each solution to a set of predefined solution-categories (e.g., building aspect; load; toy; De Dreu, Baas, & Nijstad, 2008; Rietzschel, Nijstad, & Stroebe, 2006). *Unicity* provides an indication of how unique a particular solution was and was scored as the number of persons who provided the same solution, where higher scores indicate less unique solutions.

Combined Alternative Uses / Ordinary Characteristics Task: Pretest and Posttest

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

For each trial the participant was shown an instruction screen (3s) identifying the trial type (‘alternative uses’ or ‘ordinary characteristics’). In the next screen the target object name appeared in the middle of the screen with the instruction ‘alternative uses’ or ‘ordinary characteristics’ reiterated at the top of the screen (see Figure 5-1). The participant was given 20 seconds to list solutions out loud. The solutions were recorded and later transcribed. Per session 30 items (15 AU and 15 OC) were in random order, divided across two blocks (7 min each) separated by a short break. There were 60 items in total; the allocation to session (pretest, posttest) and type (AU, OC) were counterbalanced over participants and training conditions.

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

Alternative Uses: Training

Participants in the AU training condition trials were administered 10 AU items during each of the eight training sessions. The items lasted 2 minutes each. A short break was provided halfway through the training. Each session began with a brief: ‘Generate as many alternative uses

for each presented object.’ This was followed by one screen per item with the instruction briefly reiterated at the top of the screen. The participant typed the solutions into a text box and each submitted solution was posted below on the same screen. After two minutes the next item was shown. A total of 80 stimuli were presented in random order across trials over training sessions. The total duration of training was approximately 20 minutes.

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

General ideation

Combined Alternative Uses / Ordinary Characteristics Task: Pretest and Posttest

General ideation is the second skill assessed in the combined Alternative Uses (AU) and Ordinary Characteristics (OC) task. The OC task was based on Fink et al. (2009) and served as a general control for the creative ideation training, appealing to memory retrieval processes. For each OC trial the participant was shown an instruction screen (3s) identifying the trial type (‘ordinary characteristics’). In the next screen the target object name appeared in the middle of the screen with the instruction ‘ordinary characteristics’ reiterated at the top of the screen (see Figure 5-1). The participant was given 20 seconds to list solutions out loud. The solutions were recorded and later transcribed. Per session 15 OC trials (and 15 AU trials) were presented in random order. There were 30 OC items in total across pretest and posttest; the allocation to session (pretest, posttest) and type (AU, OC) was counterbalanced over participants and training conditions.

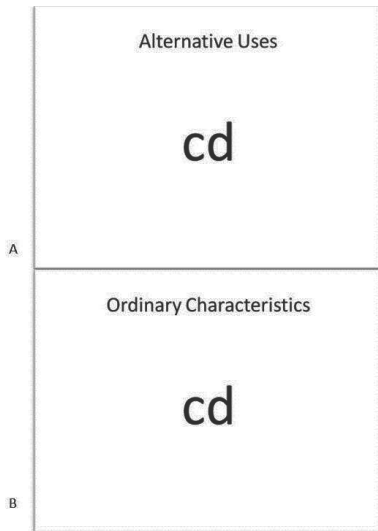


Figure 5-1. Alternative Uses / Ordinary Characteristics task: (A) example Alternative Uses item and (B) example Ordinary Characteristics item. Participants were asked to list as many alternative uses for or ordinary characteristics of an everyday object as possible.

Ordinary Characteristics: Training

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

Rule-switching

Rule-switching was measured and trained with the global/local rule switch task (Huizinga et al., 2010). Participants were shown a rule comprising of two objects: (1) a large square and a rectangle (global rule) or (2) a small square and a small rectangle (local rule). Next the stimulus, a large square or rectangle composed of smaller squares or rectangles (2 x 2 possible stimuli), was presented in between the two rule objects. During this time the participant was asked to indicate

which rule the stimulus belonged to. The decision rule was based on the size of the square and rectangle on either side of the target. If the side figures were large the ‘global’ rule was to be applied – i.e., indicate the stimulus as a whole was a large square or rectangle. If the side figures were small then the ‘local’ rule was required – i.e., indicate whether the stimulus was composed of small squares or rectangles. See Figure 5-2 for an example. During the first and second blocks of this task decisions were based on only one rule (‘global’ or ‘local’). During the remaining blocks the two rules were mixed and the participant had to switch between the rules. The switching costs for accuracy and reaction time computed using the ration between rule repeat trials and trials directly following a rule switch.

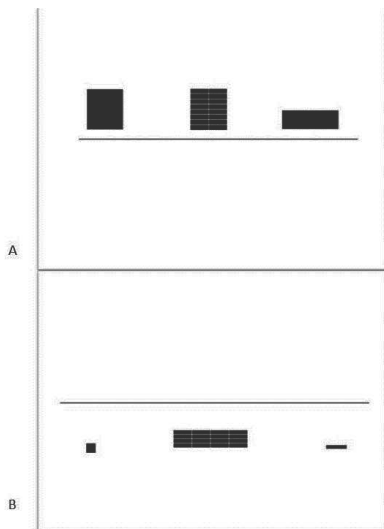


Figure 5-2. Rule-switching task example items: (A) global rule and (B) local rule. The participant was cued to apply the global rule to the figure in the middle when the two side figures were large. The local rule was applied if the side figures were small. Switch blocks involved implying both rules in random order. In both figures the correct solution is on the left-hand side, thus the participant would press the left button.

Rule-switching: Pretest and Posttest

Four blocks of 50 trials were administered. The task lasted approximately 10 minutes.

Rule-switching: Training

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

Results

Descriptive Statistics

Descriptive statistics for all pretest and posttest measures per age group (adolescent, adult) and training condition (creative ideation, general ideation and rule-switching) are shown in Table 5-3. Correlations between each of the pretest and posttest measures are shown in Table 5-4.

Table 5-3. Descriptive statistics of pretest and posttest measures per training condition and age group on the combined Alternative Uses/Ordinary Characteristics task (AUOC task), the Alternative Uses test and the Rule-Switching task. Both versions of the alternative uses task measure creative ideation. The ordinary characteristics task measures general ideation.

	Creative Ideation training			General ideation training			Rule-Switch training		
	N	M	SD	N	M	SD	N	M	SD
<i>Pretest</i>									
Combined AUOC pretest									
<i>Adolescents</i>									
AU originality	23	2.08	0.36	22	2.19	0.41	22	1.99	0.40
AU fluency	23	2.46	0.81	22	2.25	0.73	22	2.76	1.13
OC fluency	23	3.53	1.30	22	3.69	0.85	22	3.75	1.26
<i>Adults</i>									
AU Originality	21	2.37	0.41	19	2.25	0.28	17	2.49	0.39
AU fluency	21	2.65	0.87	19	2.83	0.99	17	2.27	0.71
OC fluency	21	4.16	1.24	19	4.63	1.49	17	4.43	0.89
Alternative Uses pretest									
<i>Adolescents</i>									
fluency	25	11.92	5.53	23	12.83	6.55	23	12.70	6.72
flexibility	25	6.16	2.17	23	5.91	2.17	23	6.17	2.76
originality	25	1.68	0.35	23	1.64	0.27	23	1.69	0.34
<i>Adults</i>									
fluency	22	11.41	3.45	20	11.65	5.71	19	12.74	5.51
flexibility	22	6.91	1.82	20	5.70	3.08	19	6.95	2.12
originality	22	1.73	0.37	20	1.75	0.33	19	1.67	0.29
Rule-Switching pretest									
<i>Adolescents</i>									
accuracy	17	.00	.09	14	.03	.06	14	.02	.04
reaction time*	17	104	115	14	81	76	14	70	35
<i>Adults</i>									
accuracy	21	.00	.04	19	.00	.08	18	.00	.05
reaction time*	21	55	54	19	79	52	18	100	88

<i>Posttest</i>									
AUOC posttest									
<i>Adolescents</i>									
AU originality	25	2.46	0.18	19	2.50	0.27	18	2.47	0.24
AU fluency	25	2.99	1.35	19	2.55	0.85	18	3.15	1.12
OC fluency	25	3.69	0.96	19	4.20	1.02	18	4.23	1.30
<i>Adults</i>									
AU Originality	21	2.61	0.22	20	2.58	0.19	17	2.62	0.23
AU fluency	21	3.07	0.93	20	2.80	0.79	17	2.49	1.28
OC fluency	21	3.96	0.98	20	4.76	1.09	17	3.99	1.10
Alternative Uses posttest									
<i>Adolescents</i>									
fluency	23	14.35	7.99	19	11.32	7.37	20	17.25	7.15
flexibility	23	8.48	2.11	19	7.53	2.46	20	9.85	2.80
originality	23	1.66	0.34	19	1.79	.49	20	1.75	0.44
<i>Adults</i>									
fluency	18	13.39	4.47	15	12.20	4.16	16	10.81	5.74
flexibility	18	9.44	2.18	15	8.33	2.16	16	7.38	2.96
originality	18	1.70	0.30	15	1.60	0.24	16	1.67	0.32
Rule-Switching posttest									
<i>Adolescents</i>									
accuracy	18	-.03	.04	15	-.01	.04	16	-.02	.06
reaction time*	18	89	68	15	45	80	16	30	28
<i>Adults</i>									
accuracy	20	.00	.04	18	.00	.03	20	.02	.07
reaction time*	20	26	34	18	53	38	20	30	30

Note. AU=alternative uses, OC=ordinary characteristics, RS=rule-switching; The rule-switching task reports switch costs.

*Reaction time is reported in milliseconds.

Table 5-4. Correlations between the pretest and posttest measures Alternative Uses test (AUT), combined Alternative Uses/Ordinary Characteristics task (AUOC task) and rule-switch task (RS).

	Pretest					Posttest										
	AU orig	AUOC AU flu	OC flu	AUT orig	AUT flu	flex	Rule-Switch acc	rt	AUOC AU orig	AUOC AU flu	OC flu	AUT orig	AUT flu	flex	Rule-Switch acc	rt
Pretest Tasks																
Combined AUOC																
AU originality	1															
AU fluency	.09	1														
OC fluency	.36**	.49**	1													
Alternative Uses																
originality	.11	.17	.06	1												
fluency	.19*	.21*	.21*	.05	1											
flexibility	.27**	.19*	.28**	.13	.72**	1										
Rule-Switch																
accuracy	-.20*	.01	-.05	.18	-.05	-.05	1									
reaction time	-.05	-.16	-.11	-.14	-.13	-.13	-.04	1								
Posttest Tasks																
Combined AUOC																
AU originality	.23*	-.07	.11	.08	.10	.10	-.03	-.03	1							
AU fluency	-.02	.53**	.27**	.03	.25**	.20*	-.03	-.05	-.04	1						
OC fluency	-.08	.35**	.54**	.09	.27**	.27**	.02	-.05	.09	.42**	1					
Alternative Uses																
originality	.00	.03	-.01	.14	.09	.10	.01	-.10	.18	.15	.07	1				
fluency	-.05	.39**	.11	.11	.21*	.14	-.08	-.03	-.04	.61**	.30**	.16	1			
flexibility	.01	.39**	.14	.15	.21*	.25**	-.08	-.03	-.02	.58**	.30**	.03	.79**	1		
Rule-Switch																
accuracy	.15	-.22*	.04	-.29**	-.07	-.04	-.03	.18	.22*	-.03	-.04	.01	-.12	-.15	1	
reaction time	.02	-.04	-.09	-.17	-.11	-.21*	.07	.41**	-.11	-.09	-.16	-.15	.06	.03	-.11	1
<i>Note.</i> orig = originality, flu = fluency, flex = flexibility, acc= accuracy, rt=reaction time																

Note. orig = originality, flu = fluency, flex = flexibility, acc= accuracy, rt=reaction time

Initial comparisons

Initial comparisons were conducted on each of the pretest tasks between the two age groups and three training conditions to examine whether differences prior to training were present. The results of the Analysis of Variance (ANOVAs) with Age and Condition as between-subjects factors are presented in Table 5-5. Here we see that age effects emerged on the combined AU/OC task for the measures of AU originality and OC fluency. In both cases adults obtained higher scores than adolescents. No further main effects for Age or Training Condition were found on any of the pretest creative ideation, general ideation and rule-switching tasks. Age x Training Condition effects were not present on the AUT or rule-switching tasks; however, an interaction was present on the combined AU/OC task for the AU originality and AU fluency measures. Post hoc analyses with Bonferroni correction revealed that these interaction effects emerged because of Age effects in some but not all Training Conditions (see Figure 5-3). For AU originality Age effects, with higher scores for adults, were present for the AU and RS conditions (AU condition: $F(1, 42)=6.12, p=.02, \eta_p^2=.13$; RS condition: $F(1,37)=15.40, p<.001, \eta_p^2=.29$) but not for the OC condition ($p>.10$). For AU fluency we found a significant Age effect for the OC condition ($F(1,39)=4.65, p=.04, \eta_p^2=.11$), where adults obtained higher scores, but not for the AU and RS conditions. In sum, age-group differences were present on the combined AU/OC task; however, these initial differences were accounted for in our main analyses as we applied repeated measures ANOVAs.

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

	F	df	p	η_p^2
AUOC task				
<i>AU originality</i>				
Age	16.08	1, 118	<.001	.12
Condition	0.14	2, 118	.87	.00
Age x Condition	2.79	2, 118	.07	.05
<i>AU fluency</i>				
Age	0.30	1, 118	.58	.00
Condition	0.01	2, 118	.99	.00
Age x Condition	4.01	2, 118	.02	.06
<i>OC fluency</i>				
Age	12.75	1, 118	<.001	.10
Condition	0.77	2, 118	.47	.01
Age x Condition	0.17	2, 118	.85	.00

Alternative Uses Test				
<i>originality</i>				
Age	0.57	1, 126	.45	.00
Condition	0.04	2, 126	.96	.00
Age x Condition	0.37	2, 126	.69	.01
<i>fluency</i>				
Age	0.30	1, 126	.58	.00
Condition	0.38	2, 126	.69	.01
Age x Condition	0.12	2, 126	.89	.00
<i>flexibility</i>				
Age	1.10	1, 126	.30	.01
Condition	1.39	2, 126	.25	.02
Age x Condition	0.60	2, 126	.55	.01
Rule-switching Task				
<i>switch costs accuracy</i>				
Age	1.47	1, 97	.23	.02
Condition	0.44	2, 97	.65	.01
Age x Condition	0.49	2, 97	.62	.01
<i>switch costs reaction time</i>				
Age	0.14	1, 97	.71	.00
Condition	0.02	2, 97	.98	.00
Age x Condition	1.99	2, 97	.14	.04

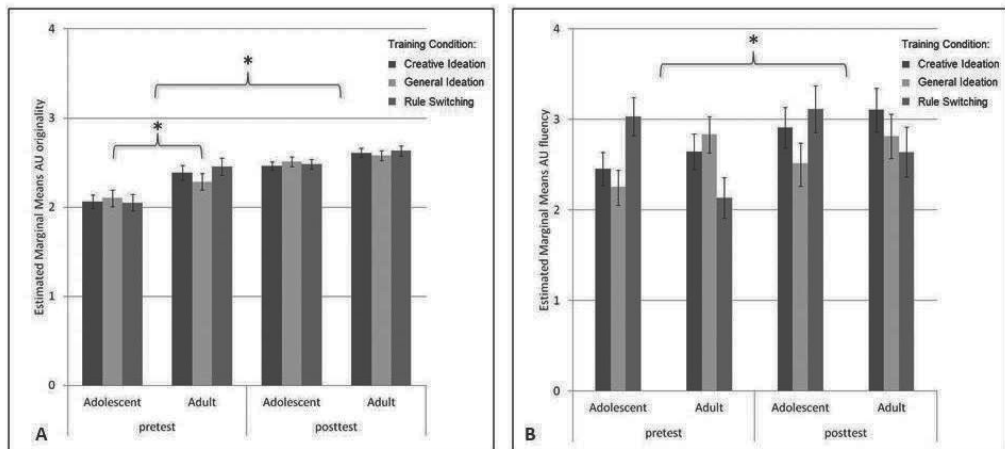


Figure 5-3. Pretest to posttest progression for adults and adolescents on the creative ideation measure of the combined Alternative Uses / Ordinary Characteristics task: (A) originality (1=‘not original’ to 5=‘highly original’) and (B) fluency (number of alternative uses listed). In general participants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

Correlations

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

Correlations between each of the posttest measures were generally as expected and these correlations were often stronger than during the pretest. The two AU originality measures (AUT and combined AU/OC version) were positively correlated.

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

Pretest to posttest change

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

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

Creative Ideation

Two tasks measured creative ideation: (1) the alternative uses part of the combined Alternative Uses / Ordinary Characteristics (AU/OC) task and (2) the Alternative Uses Test. Pretest to posttest change on these two tasks was examined separately and is described in the following subsections. We hypothesized that participants trained in creative ideation would improve more in originality, fluency (number of valid creative solutions) and flexibility (ability to change categories during creative ideation) on the AU tasks than participants trained in general ideation or rule-switching.

Alternative Uses: AU/OC task

The alternative uses part of the combined AU/OC task comprised of measures of AU originality and AU fluency. The first set of analyses tested for training effects on AU originality scores. A main effect of Session showed that participants generally improved on the AU originality measure from pretest to posttest ($F(1,98)=64.02, p<.001, \eta_p^2=.395$). A main effect of Age showed that adults obtained higher scores on the AU originality measure on the whole ($F(1,98)=22.53, p<.001, \eta_p^2=.187$). A Session x Age interaction showed that adolescents progressed more from pretest to posttest on AU originality ($F(1,51)=61.42, p<.001$) than adults ($F(1,47)=14.19, p<.001$): Session x Age effect: $F(1,98)=5.14, p=.03, \eta_p^2=.05$ (see Figure 5-3A). Pretest to posttest change in AU originality did not differ between training conditions (Session x Training Condition effect: $F(2,98)=.13, p=.88, \eta_p^2=.00$); Session x Age x Training Condition effect: $F(2,98)=.23, p=.79, \eta_p^2=.01$).

The same analyses for AU fluency showed that in general, participants improved in AU fluency from pretest to posttest (Session effect: $F(1,102)=8.91, p<.01, \eta_p^2=.09$). No significant differences in AU fluency progression were observed for Age (Age effect: $F(1,98)=0.01, p=.91, \eta_p^2=.00$ or Session x Age effect: $F(1,102)=0.10, p=.76, \eta_p^2=.00$ see Figure 5-3B), Condition (Session x Condition effect: $F(2,102)=0.90, p=.41, \eta_p^2=.02$) or Age x Condition (Session x Age x Condition effect: $F(2,102)=1.20, p=.31, \eta_p^2=.02$).

Alternative Uses Tin Can and Brick

The AU Brick task was the posttest counterpart of the AU Tin Can pretest task. Originality, fluency, flexibility and unicity (inverse of uniqueness) were measured on the AUT. Results are shown in Figure 5-4.

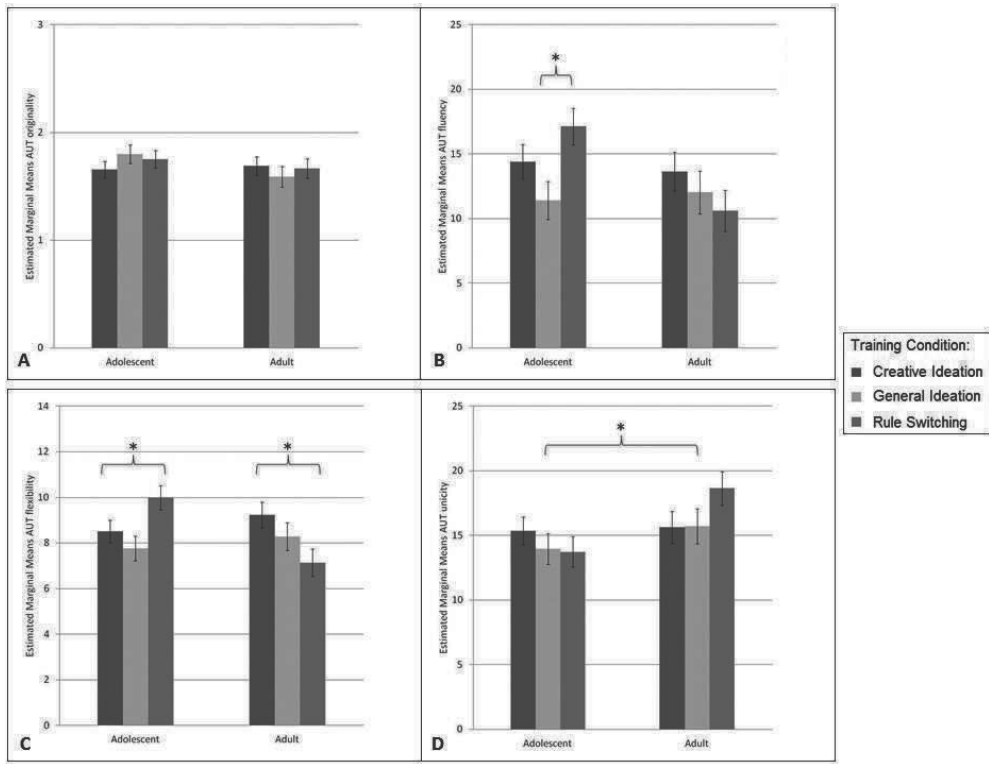


Figure 5-4. Alternative Uses 'brick' posttest performance for adults and adolescents per training condition on measures: (A) originality (1='not original' to 5='highly original'), (B) fluency (number of solutions), (C) flexibility (number of categories used in solutions) and (D) unicity (inverse of uniqueness,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

No main effects for Condition or Age were found for originality (Condition: $F(2,104)=0.10$, $p=.91$, $\eta_p^2=.00$, Age: $F(2,104)=1.48$, $p=.23$, $\eta_p^2=.01$). Also, no Age x Training Condition interaction was found on the measure of originality ($F(2,104)=1.01$, $p=.37$, $\eta_p^2=.02$).

For fluency there were no main effects for Condition ($F(2,104)=1.44$, $p=.24$, $\eta_p^2=.03$) or Age ($F(2,104)=3.33$, $p=.07$, $\eta_p^2=.03$). There was a significant interaction effect between Age and Condition on fluency ($F(2,104)=3.16$, $p=.047$, $\eta_p^2=.06$). Therefore, an additional ANCOVA per age-group with Bonferroni-corrected post hoc comparisons was conducted. These analyses revealed a marginally greater fluency in adolescents in the rule-switching condition versus the

general ideation condition ($\Delta M=5.62$, $SE=2.31$, $p=.05$). No other significant differences between the training conditions were found.

For flexibility there were also no main effects for Condition ($F(2,104)=1.19$, $p=.31$, $\eta_p^2=.02$), or Age ($F(2,104)=1.33$, $p=.25$, $\eta_p^2=.01$). The Condition x Age effect was significant: $F(2,104)=6.42$, $p<.01$, $\eta_p^2=.11$. This was investigated further with an ANCOVA per age-group with Bonferroni corrected post hoc tests for Condition. These revealed greater flexibility for the Rule-switching than General ideation training condition in adolescents ($\Delta M=2.18$, $SE=0.74$, $p=.01$) and marginally greater flexibility for the Creative ideation versus Rule-switching condition in adults ($\Delta M=2.09$, $SE=0.84$, $p=.05$). No other significant differences between training conditions were found.

Adolescents had marginally lower scores for unicity (i.e., higher scores infer less unique solutions) compared to adults ($F(1,104)=3.82$, $p=.05$, $\eta_p^2=.03$), indicating greater uniqueness of solutions for adolescents. There was no main effect for Condition ($F(2,104)=0.25$, $p=.78$, $\eta_p^2=.00$), nor was there an interaction effect for Condition x Age ($F(2,104)=0.98$, $p=.38$, $\eta_p^2=.02$).

AU Tin Can performance was positively related to AU Brick performance; although it was not a significant covariate for originality ($F(2,104)=2.58$, $p=.11$, $\eta_p^2=.02$), it did form a significant covariate for fluency ($F(2,104)=5.78$, $p=.02$, $\eta_p^2=.05$), flexibility ($F(2,104)=8.78$, $p<.01$, $\eta_p^2=.08$) and unicity ($F(2,104)=8.04$, $p=.01$, $\eta_p^2=.07$). In general this shows that individuals with high pretest 'Tin Can' scores also obtained high posttest 'Brick' scores.

General ideation

Repeated measures ANOVAs for OC fluency revealed no significant changes across sessions (Session effect: $F(1,98)=1.69$, $p=.20$, $\eta_p^2=.02$). There was a main effect of Age ($F(1,102)=5.71$, $p=.02$, $\eta_p^2=.05$ see Figure 5-5) where adults obtained higher OC fluency scores compared to adolescents. No significant differences in OC fluency progression were observed for the two age groups (Session x Age effect: $F(2,102)=3.54$, $p=.06$, $\eta_p^2=.03$) or training conditions (Session x Condition effect: $F(2,102)=2.20$, $p=.12$, $\eta_p^2=.04$) or Age x Condition (Session x Age x Condition effect: $F(2,102)=0.15$, $p=.87$, $\eta_p^2=.00$).

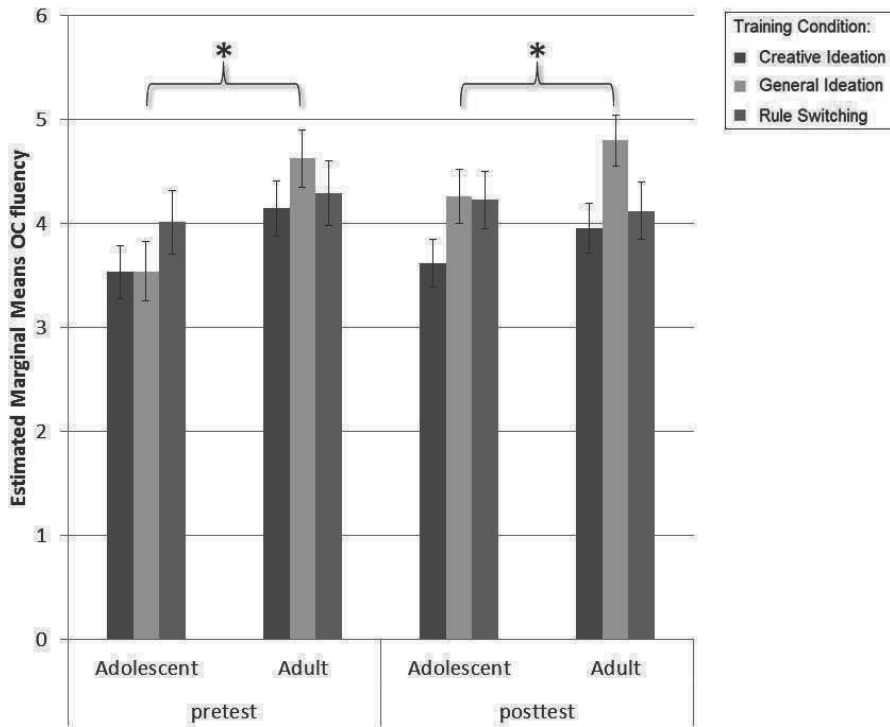


Figure 5-5. Pretest to posttest progression for adults and adolescents on the general ideation measure of the combined Alternative Uses / Ordinary Characteristics task. Adults had higher mean OC fluency scores (number of ordinary characteristics listed) on average; however, no other main or interaction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

Rule Switching

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

Switch costs decreased for accuracy from pretest to posttest (Session effect: $F(1,76)=5.36$, $p=.02$, $\eta_p^2=.07$). A Session x Age interaction was found for accuracy ($F(1,76)=9.40$, $p<.01$, $\eta_p^2=.11$), where adolescents decreased more in switch costs than adults (see Figure 5-6). No Session x Condition or Session x Condition x Age effects were found for accuracy ($F(1,76)=0.61$, $p=.55$, $\eta_p^2=.02$ or $F(1,76)=0.07$, $p=.93$, $\eta_p^2=.00$). There were no main effects for Age ($F(1,76)=0.02$, $p=.89$, $\eta_p^2=.00$) or Condition ($F(1,76)=0.59$, $p=.56$, $\eta_p^2=.02$) or Age x Condition ($F(1,76)=1.29$, $p=.28$, $\eta_p^2=.03$).

For reaction time, switch costs also decreased from pretest to posttest (Session effect: $F(1,76)=10.97, p<.01, \eta_p^2=.13$). No Session x Age or Session x Age x Condition interactions were present ($F(1,76)=1.42, p=.24, \eta_p^2=.02$ and $F(1,76)=0.60, p=.55, \eta_p^2=.02$ respectively). No main effects for Age ($F(1,76)=3.16, p=.09, \eta_p^2=.04$) or Condition ($F(1,76)=1.45, p=.24, \eta_p^2=.04$) were present. A marginal Session x Condition interaction effect was present ($F(1,76)=3.01, p=.06, \eta_p^2=.07$) and a significant Age x Condition interaction was present for reaction time ($F(2,76)=5.76, p<.01, \eta_p^2=.13$). Follow-up repeated measures analyses for reaction time were conducted per age group in order to further investigate the role of training condition. These post hoc comparisons with Bonferroni correction revealed no significant differences within age groups between training conditions.

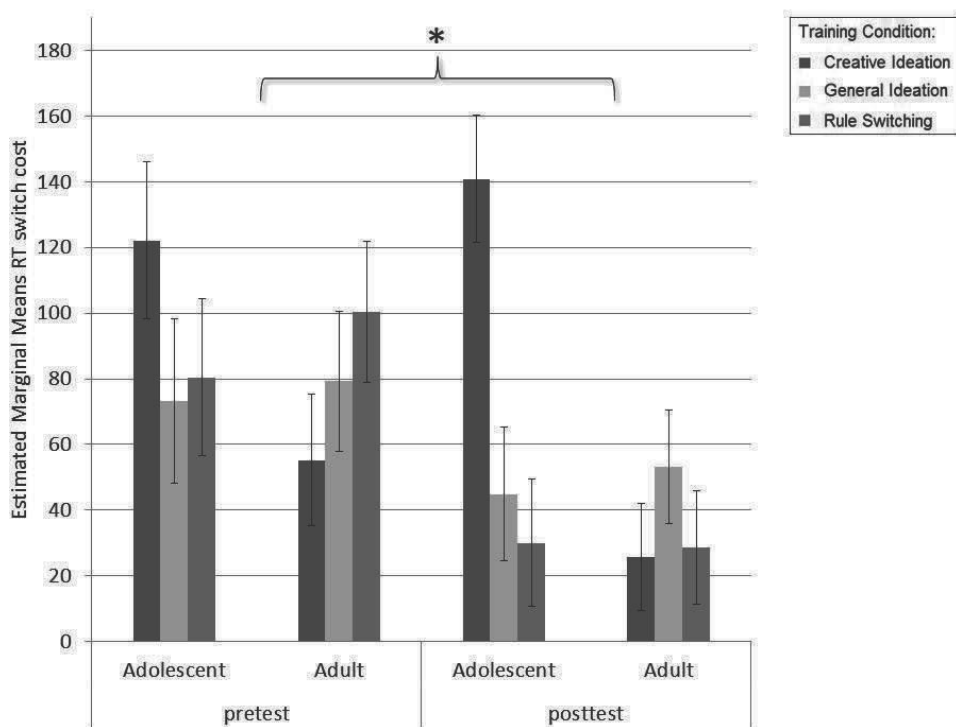


Figure 5-6. Reaction time switch costs (ms) from pretest to posttest for adults and adolescents per training condition. Switch costs were significantly lower on posttest than pretest. Adolescents decreased marginally more in switch costs than adults and individuals trained in rule switching decreased marginally more than those trained in creative ideation or general ideation. Post hoc comparisons of a significant Age x Condition effect did not reveal further differences.

Progression during training

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

Creative ideation training

A depiction of the participant's progression on the measures of originality and fluency, flexibility on the Alternative Uses (AU) training task is shown in Figure 5-7. Adults on average had higher scores on the originality measure ($F(1,44)=9.01$, $p<.01$, $\eta_p^2=.17$), whereas as adolescents on average had marginally higher scores for flexibility ($F(1,44)=3.93$, $p=.05$, $\eta_p^2=.09$). There were no differences between age groups on the fluency measure ($F(1,44)=0.57$, $p=.46$, $\eta_p^2=.01$).

Although there was no main effect for Session on originality ($F(1,44)=0.12$, $p=.73$, $\eta_p^2=.01$), a significant quadratic Session effect emerged for flexibility ($F(1,44)=29.92$, $p<.001$, $\eta_p^2=.42$) and a significant cubic Session effect was present for fluency ($F(1,44)=5.55$, $p=.02$, $\eta_p^2=.11$). Session x Age interactions were not present for originality ($F(1,44)=1.23$, $p=.30$, $\eta_p^2=.04$), fluency ($F(1,44)=0.18$, $p=.88$, $\eta_p^2=.00$) or flexibility ($F(1,44)=0.60$, $p=.65$, $\eta_p^2=.01$). In short, results indicate that although training does not affect originality, it does impact both fluency and flexibility in creative ideation, two critical antecedents of original thinking and insight performance.

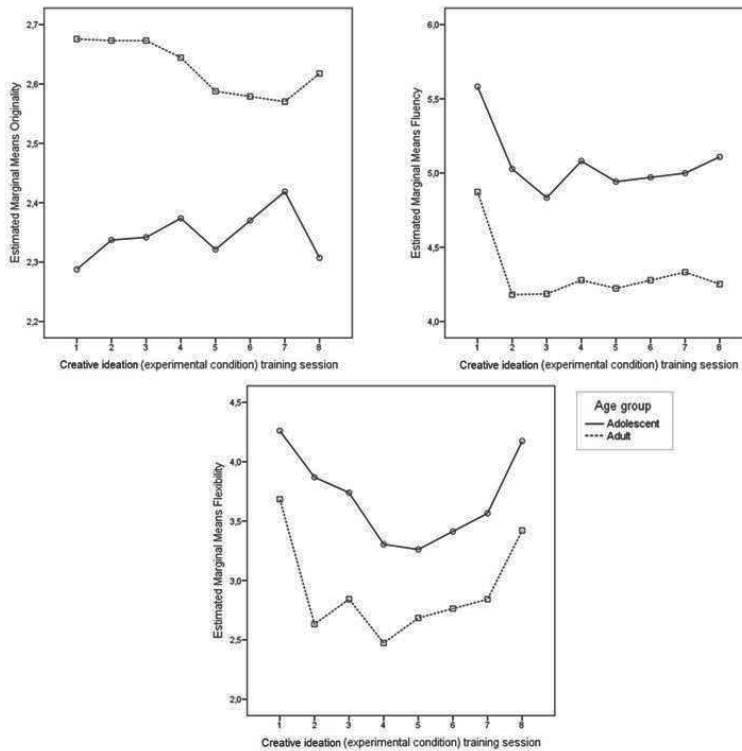


Figure 5-7. Progression during Alternative Uses (experimental) training across sessions for adults and adolescents: (A) fluency (number of solutions), (B) originality (1='not original' to 5='highly original'), (C) flexibility (number of categories used in solutions). There were no significant age group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

General ideation training

Fluency performance for adults and adolescents on the Ordinary Characteristics (OC) training task is shown in Figure 5-8. Analyses do not show a main effect for Age ($F(1,39)=0.64$, $p=.46$, $\eta_p^2=.01$) nor a Session x Age interaction ($F(1,39)=0.96$, $p=.54$, $\eta_p^2=.02$). Thus no discernible differences were present in adolescents and adults progression on the OC task during the training sessions. Training does not affect general ideation.

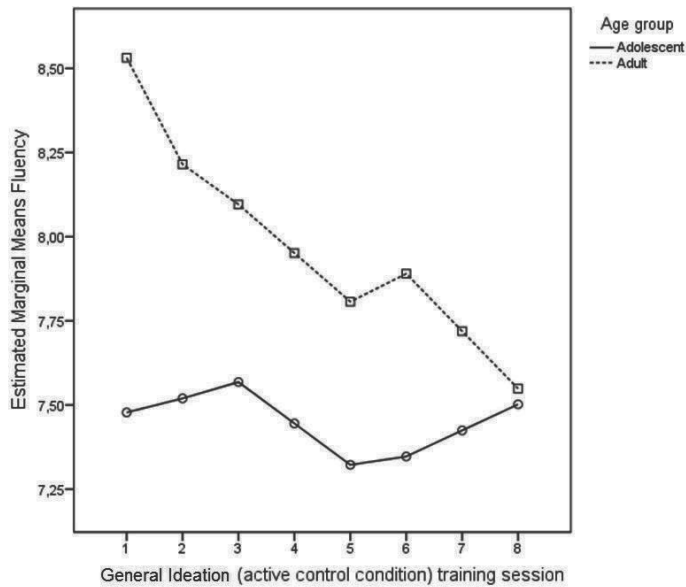


Figure 5-8. Progression in number of solutions (fluency) during Ordinary Characteristics (active control) training across sessions for adults and adolescents. No age differences in fluency of ordinary characteristics ideation were found.

Rule Switch training

Switch costs remained relatively steady across Sessions for both accuracy and reaction time (accuracy: $F(1,39)=1.73$, $p=.10$, $\eta_p^2=.04$; reaction time: $F(1,39)=1.67$, $p=.19$, $\eta_p^2=.04$), as can be seen in Figure 5-9. Adults and adolescents did not differ in average switch costs during training (accuracy: $F(1,39)=1.35$, $p=.25$, $\eta_p^2=.03$; reaction time: $F(1,39)=0.51$, $p=.48$, $\eta_p^2=.01$) throughout the training sessions. No interaction between Session and Age is present for accuracy ($F(1,39)=0.67$, $p=.66$, $\eta_p^2=.02$) or reaction time ($F(1,39)=.64$, $p=.54$, $\eta_p^2=.02$). As for training creative ideation, training does affect rule switching ability yet not differently for age groups.

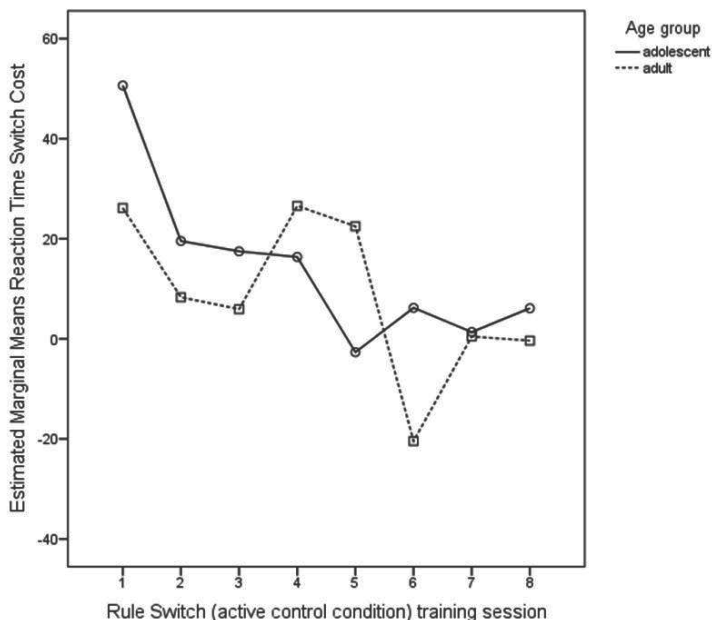


Figure 5-9. Progression in reaction time switch costs (ms) during Rule Switch (active control) training across sessions for adults and adolescents. No age differences in reaction time switch costs were found.

Discussion

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

Initial developmental differences

Before interpreting the effects of training, it is important to consider potential age differences prior to training. The prediction was that adults and adolescents would perform equally well on most creativity measures, but that adults would outperform the adolescent group on originality (Kleibeuker, De Dreu, & Crone, 2012; Wu et al., 2005). We anticipated additional differences for general ideation with better performance for adults compared to adolescents, based

on prior research (Kleibeuker, Koolschijn, Jolles, De Dreu, & Crone, 2013a) and its close relation to verbal fluency performance (Romine & Reynolds, 2005). No initial differences were expected for rule switch performance (Huizinga et al., 2006).

Results for creative ideation in the four-minute Alternative Uses Task resembled previous findings in which adolescents performed at a mature level on most aspects of creativity, including fluency and flexibility. Also fitting earlier work, significant developmental differences were apparent on the measure of originality, with more original and unique solutions for adults compared to adolescents (see also Kleibeuker et al., 2013a). Different factors may account for these developmental differences. First, given their greater knowledgebase and more lifetime experience (e.g., Weisberg, 1999), adults have a greater chance of retrieving original and unique associations with presented objects. Second, individual lifestyles of adults generally involve larger inter-individual variance in experiences in comparison to adolescents. Consequently, adults are more likely to create relatively infrequent and unique associations and ideas. A third possible explanation for differences between age groups concerns developmental changes in flexible coordination between analytic and associative processing (Christoff, Gordon and Smith, 2009a, 2009b; Martindale, 1999; Martindale and Hasenfus, 1978), which is associated with functioning of PFC regions that develop throughout adolescence and into adulthood (Kerns, 2006; Kerns, Cohen, MacDonald, Cho, Stenger and Carter, 2004). Both analytic and associative processing are believed to lead to numerous creative ideas (De Dreu *et al.*, 2012; Kleibeuker et al., 2013c; Nijstad, et al., 2010); however, the quality of generated ideas has been related to the ability to flexibly coordinate between analytic and associative processing. Thus, adolescent participants may not yet have fully developed the ability to successfully shift between the two types of processing (Smolucha and Smolucha, 1986; see also Runco, 2007).

As predicted, we found developmental differences in fluency on general ideation. As with age related differences in creative ideation, and originality in particular, this effect could be explained by age related differences in experiences and knowledge base. A second explanation concerns the development of processes that are related to memory retrieval. These processes are associated with lateral PFC activations (e.g., Buckner et al., 1995) and other brain regions that develop relatively late and mature throughout adolescence (Fair et al., 2007; Giedd et al., 1999). Consistent with prior studies no age related differences were observed for performance on the rule switch task (Huizinga et al, 2005), suggesting that cognitive flexibility is already at adult level in middle adolescence.

Training effects

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

The general improvement in fluency and originality could be interpreted as follows. First, given that these effects were non-specific for training conditions, it is possible that the improvements simply reflect retesting effects instead of training effects. Indeed, some crucial aspects of the creative ideation task differed from the training paradigm such as duration (20s versus two minutes), way of answering (audio recording, typing), and task switches (alternative uses to ordinary characteristics versus only one task during training). The task might therefore test processes that are different from those applied during the creative ideation training sessions. However, the correlations between the alternative uses training task and the two alternative uses tasks administered during pretest and posttest suggest that the improvements for the alternative uses training group are at least to some degree related to their practice with the alternative uses task. Perhaps simply practicing with the alternative uses task was not enough to elicit a discernible effect and more extensive training informing people about the nature of creativity and strategies for creative thinking (e.g., Clapham, 1997; Scott et al., 2004; Speedie et al., 1971) or providing exposure to ideas of others (Dugosh and Paulus, 2005; Fink et al., 2010) would improve the impact of creative ideation training. This hypothesis can be studied in future research by examining the effect of different types of training programs with alternative uses tasks of varying lengths. A second explanation may be that practice generating ordinary characteristics or with the rule-switching task may benefit generating alternative uses (performance) through improvements of processes that support creative ideation. Improvements in cognitive flexibility as practiced in the rule-switching condition may benefit generating alternative uses as well as switching between tasks during the combined alternative uses and ordinary characteristics task. Indeed, cognitive flexibility is thought to be important for creative performance (e.g., Baas, De Dreu, & Nijstad, 2008; Bott et al., 2014; De Dreu, Baas & Nijstad, 2008; Gilhooly, Fioratou, Anthony, & Wynn,

2007; Nusbaum & Silvia, 2011; Warren & Davis, 1969). Furthermore, originality and fluency in the generation of alternative uses could be enhanced by improving the ability to successively retrieve relevant semantic information from memory, i.e., general fluency as was the case during the ordinary characteristics task training. For example, creativity training in which participants were instructed to retrieve information about the parts that make up the object appeared to be effective (Warren & Davis, 1969). This role of our two active control tasks can be examined by administering the alternative uses and ordinary characteristics tasks separately.

Developmental differences in training effects

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

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

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

Limitations

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

Conclusions and future directions

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

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

In conclusion, the results support earlier findings in showing that practice in creative ideation is successful within the same domain (Scott et al., 2004) and supports the hypothesis that

adolescence is a developmental stage of increased flexibility optimized for adaptive and explorative behavior during this instable life stage (Crone & Dahl, 2012; Johnson & Wilbrecht, 2011).

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CHAPTER 6

Training in the adolescent brain: an fMRI training study on divergent thinking

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Abstract

Prior research suggests that adolescence is a time of enhanced sensitivity for practice and learning. In this study we tested the neural correlates of divergent thinking training in 15-16-year-old adolescents relative to an age-matched active control group. All participants performed an alternative uses task, a valid measure to test divergent thinking, while fMRI images were acquired before and after a training program. In between the two scanning sessions the experimental group completed 2 weeks of divergent thinking training (8 sessions) and the control group completed 2 weeks of task switching training (8 session). A group x time interaction demonstrated better posttest divergent thinking performance for the experimental group relative to the control group. Generating alternative uses (experimental task condition) relative to generating ordinary characteristics of objects (control task condition) was associated with increased activation in the supramarginal gyrus (SMG), angular gyrus (AG) and middle temporal gyrus (MTG). Test-retest analyses showed that within-individuals-activation in these regions was stable over time in both groups. Changes in alternative uses fluency, however, were positively associated with changes in superior lateral PFC activation. Together, the results indicate that core brain regions for creativity (SMG, AG, MTG) are consistently recruited in adolescence and not sensitive to training, but that changes in performance are associated with changes in activation in lateral PFC.

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Introduction

Some parents may wonder why adolescents have difficulty planning their homework while at the same time they are experts in switching between social media devices, designing clothes or redecorating their rooms. Adolescence is the transition period between childhood and adulthood during which individuals gain their independence from their parents and rapidly adjust to new social contexts (Crone and Dahl, 2012). Even though cognitive control functions still increase between adolescence and adulthood (Luna et al., 2001), both animal (Johnson and Wilbrecht, 2011) and human research (Kleibeuker, et al., 2013a) has shown that adolescence relative to adulthood is a period of increased potential for flexible thinking. That is, adolescence seems to be a period of increased flexibility that is well suited for novel insights and creative problem solving, which is beneficial in a period which asks for rapid adjustments to changing social demands and gaining independence (Crone and Dahl, 2012).

Adolescence is also a period of life that is identified by a significant amount of time involved in training and education, both in- and outside school settings. As such, a better understanding of learning mechanisms and training effects is especially useful in this age period. Prior research indicates that the adolescent brain is indeed sensitive to the effects of training of different cognitive functions including working memory, and mathematical skills (Jolles et al., 2010; Quin et al, 2004), showing increased activations patterns in prefrontal and parietal regions after training. These brain regions have previously been found to develop relatively late in adolescence (Gogtay, 2004; Sowell, 1999; see Crone and Ridderinkhof, 2010; Blakemore and Choudhury, 2006). A question that remains is how the adolescent brain adapts to training of cognitive functions that require flexible and divergent thinking rather than controlled and convergent thinking.

Here, we test the benefits of training creativity in adolescents, by examining neural responses to problems that require divergent thinking, before and after two weeks of divergent thinking training.

Divergent thinking is an important component of creativity and it involves the ability to think of novel solutions for encountered problems (Torrance, 1965). A well-known task to measure divergent thinking is the Alternative Uses Task (AUT) where individuals are asked to think of as many possible ways to use an object, such as an umbrella (e.g., ‘storage place for stuffed animals’). Solutions should be novel and appropriately useful (Guilford, 1967; Kim, 2008).

The answers can be categorized in terms of fluency (number of possible answers), flexibility (number of times individuals switch between different categories; i.e., storage, protection, decoration, etc.), and originality (uniqueness of answers). Prior studies revealed that adults and adolescents perform equally well on the AUT in terms of flexibility (Kleibeuker et al., 2013a), but adults outperform adolescents in baseline fluency (Kleibeuker, et al., 2013b) and originality (Kleibeuker, et al., 2013b; Stevenson, et al., 2014).

Research has shown that divergent thinking performance can be enhanced by two weeks of training, whereas longer time on training would have only minimally positive effects on training outcomes (Scott, et al., 2004; Fink, et al., 2006). These findings have been demonstrated in adults (Kienitz et al., 2014), adolescents (Stevenson et al., 2014) and children (Scott, et al., 2004), although transfer effects to other domains are debated (Kaufman and Baer, 2009). A developmental study demonstrated training benefits after two weeks of divergent thinking training for fluency and originality. Intriguingly, this study revealed larger changes for adolescents aged 13-16 years than for adults for the domain of originality, which transferred to a new divergent thinking task (Stevenson et al., 2014). These findings led to the hypothesis that adolescence is an important time window for creativity development. A key question concerns which are the neural regions contributing to these training related changes in adolescence.

Recently, several studies have examined the neural correlates of divergent thinking by examining neural activity while individuals perform the AUT (Abraham et al., 2012; Cousijn, et al., 2014a,b; Fink et al., 2006, 2009, 2010; Kleibeuker, et al., 2013b). These findings have consistently shown activity in a network of regions including the supramarginal gyrus (SMG), middle temporal gyrus (MTG), angular gyrus, and prefrontal cortex (PFC) (Abraham et al., 2012; Fink et al., 2009, 2010; Kleibeuker, et al., 2013b). Prior studies related activity in angular gyrus to insight (Aziz-Zadeh, et al., 2009; Bechtereva et al., 2004); and MTG to imagination of object use (Beauchamp and Martin, 2007; Johnson-Frey, et al., 2005; Lewis, 2006) and to executive semantic control processes including processes that enable context appropriate semantic retrieval (Whitney et al., 2011). The region that most strongly correlated with fluency performance of the AUT is the lateral PFC, such that higher fluency scores were associated with increased neural activation in the lateral PFC (Kleibeuker, et al., 2013b). Developmental comparisons between adolescents aged 15-17 years and adults showed that adolescents recruited the same network as adults. However, adults had a relatively higher activation in the lateral PFC than adolescents which was accounted for by performance differences. Intriguingly, an AUT training study using EEG showed higher

synchronization in frontal alpha activity after two weeks of AUT training (Fink et al., 2006), but it is not yet known how this relates to neural activation changes in the different brain regions involved in divergent thinking. A recent fMRI study, in which participants were objected to an extensive verbal creativity training for three weeks, activations increased mainly in temporo-parietal regions including bilateral SMG and left (posterior) MTG (Fink et al., 2015). These results were interpreted as suggesting that training increased semantic control that is necessary to effectively combine available semantic information to produce novelty. A more commonly used approach to enhance creative performance in neuroimaging research involves cognitive stimulation by providing (moderately) creative ideas. Several studies have found this approach to be effective and training has been associated with functional changes of the (left) temporo-parietal, including the left MTG and PFC regions (Fink et al., 2012; Wei et al., 2014). An important question addressed in the current thesis concerns how activity in these regions changes through creative thinking training in adolescence. This will allow us to have a better understanding of how training-related changes in adolescents take place. An important question concerns how activity in these regions changes through training in adolescence, which will allow us to have a better understanding of how training-related changes in adolescents take place.

In this study we compared behavior and neural activity in 15-16-year-old adolescents while performing an AUT task in the scanner before and after two weeks of divergent thinking training, and we compared this to AUT activity in an active control group who performed a task switching training program (see also Stevenson et al., 2014). The control training was similar in terms of effort and time investment. The use of such an active control group diminishes possible confounding effects (see Klingberg, 2010 for a theoretical background). This design allowed us to test the following questions. First, given the small number of longitudinal studies on creativity (Claxton, et al., 2005; Scott et al., 2004), we tested whether neural activity was stable within individuals over time, which would inform us about whether creativity is a stable person specific ability or varies within persons over time. This was done by computing the intraclass coefficients for regions which are commonly active during the AUT, which include the SMG, MTG, angular gyrus and lateral PFC. This was found to be a valid method for determining test-retest stability in prior research (Van den Bulk, et al., 2013). Second, we tested whether neural activity was enhanced by training in these same regions. Finally, we tested the hypothesis that the lateral PFC is sensitive to individual differences in performance improvements, given that prior studies showed that this region is most sensitive to individual differences in AUT fluency (Kleibeuker, et al., 2013b).

Methods

Participants

A total of 32 adolescents (18 male) aged 15 to 16 years participated in this study. Participants were recruited through local advertisements. All participants were healthy, right-handed, and MRI compatible (i.e., no braces or metal implants). None of the participants reported a history of neurological or psychiatric disorders.

The participants were randomly divided into two groups matched for gender; an Alternative Uses training group (AU-group) and a Rule Switch training group (RS-group). There was a small but significant difference in age between the two groups; the AU-group was a few months younger than the RS-group ($M_{AU} = 15.84$, $SD = .11$; $M_{RS} = 16.2$, $SD = .14$; $t_{30} = 2.40$, $p = 0.02$). To check for group differences in intelligence, IQ-scores were estimated based on two subtests from the Wechsler Intelligence Scale for Children (WISC; Wechsler 2004): Similarities and Digit Span. Groups did not significantly differ in IQ-scores ($t_{30} = 1.16$, $p = 0.26$).

All participants as well as their primary caregiver signed informed consent before participation. Participants were financially rewarded for their participation. The Medical Ethics Committee from the Leiden University Medical Center (LUMC) approved the study.

Cognitive assessments during pretest and posttest

Participants completed a battery of tests for which some of the results are presented elsewhere (Cousijn, et al., 2014). For this study, we examined performance on the two training tasks during the scan session and in between scan sessions. These tasks are described in detail below.

Alternative Uses Test-scanner

At pretest and posttest the participants performed an adapted version of the Alternative Uses Test (AUT; Guilford, 1967) inside the MRI scanner while neural activity was measured (see Kleibeuker, et al. 2013b for a detailed task description). This task measures divergent thinking in the verbal domain. The task consisted of two conditions: 1) the free-association-related Alternative Uses (AU) condition during which participants had to think of as many appropriate alternative and original uses of common objects as possible (i.e., use a shoe as a baseball bat); and 2) the more general verbal-ability-related Object Characteristics (OC) condition during which

participants had to think of as many ordinary characteristics of common objects as possible (i.e., a shoe fits on a foot). Each trial started with a 3 seconds instruction screen. Then, a written item was presented in the middle of the screen for 15 s with the text ‘OC’ or ‘AU’ on the top of the screen during OC and AU trials, respectively, to remind participants of the trial condition (see Figure 6-1A). Immediately after the target screen, an evaluation screen appeared for 3 s. Participants indicated how many solutions they had found by pressing one of four buttons on a left/right button-box that was attached to their left/right leg respectively; the left middle finger for 0 or 1 solution, the left index finger for 2 solutions, the right index finger for 3 solutions and the right middle finger for 4 or more solutions. Each trial was preceded by a fixation cross that was presented for a variable duration (1.1–7.7 s) to optimize the event.

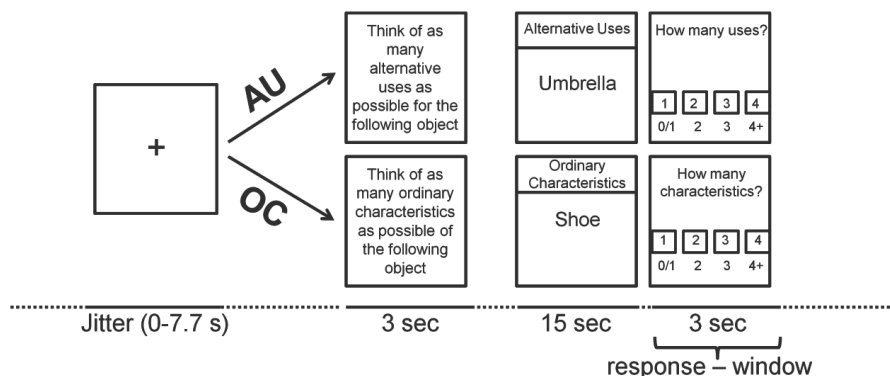


Figure 6-1. Examples of Alternative Uses (AU) and Ordinary Characteristics (OC) trials in the AU/OC scanner task

The AUT-scanner consisted of 60 trials (30 alternative uses and 30 ordinary characteristics) divided over three blocks of 8.2 minutes, during which 30 unique words were presented (once in the AU and once in the OC condition). Two sets of 30 words were created, matched on word length, number of syllabi, and word frequency. Different word sets were used during the pretest and posttest. The order of the two word sets was counterbalanced across sessions. The total task time was 30 minutes.

The task was programmed in E-Prime (version 2.0). Performances were measured for both the AU and OC condition by calculating the percentage of trials for which participants indicated that they generated 0 or 1 solution, 2 solutions, 3 solutions, and 4 or more solutions. In addition a

composite score was calculated for each condition (AU-score and OC-score). The composite score was the sum of a) the proportion of 0/1 solution times 1, b) the proportion of 2 solutions times 2, c) the proportion of 3 solutions times 3, and d) the proportion of 4 or more solutions times 4.

Local Global Task (LGT)

Rule switching was assessed behaviorally at pretest and posttest after scanning with the LGT (adapted from Huizinga, et al., 2006) that was used as the active control task in the control training condition. During the task, the target stimuli were large squares and rectangles (global figures) consisting of small squares or rectangles (local figures). Participants were instructed to focus on either the global or local aspect of the target shape (i.e., square or rectangle) given the presence of a global or local cue. The global cue consisted of a large square and rectangle presented on the left and right side of the target respectively. The local cue consisted of a small square and rectangle presented on the sides of the target. Participants pressed a right or left response button corresponding to the correct (global or local) shape of the target that coincided with the cue on the left or right side of the target. Each trial started with a 500ms presentation of the global or local cue, after which the target stimulus appeared. Participants had 3500ms to respond to the target stimulus (for details see Huizinga et al., 2006).

The task consisted of a global and a local block (each 50 trials, presentation order counterbalanced over participants), followed by a switch block (160 trials). From the switch block trials, median response times (RTs) and proportion correct of local-global switch and control trials were computed.

Training

During the two weeks between the pretest and posttest the AU-group followed an 8-session AUT-training and the RS-group followed an 8-session Local-Global Task switching (LGT); both groups trained online from home.

The AUT-training task resembled the AUT-scanner task; participants had to generate as many appropriate alternative and original uses of common objects as possible. Nine different objects were presented during each training session. The objects were different from the AUT-scanner objects. Word length, number of syllabi, and word frequency were matched across sessions. Participants were given 2 minutes to enter their solutions for each object.

The LGT-training was similar to the LGT at pretest and posttest. Each training session consisted of 8 blocks of 40 trials with self-paced breaks in-between blocks. The blocks contained alternating global and local mini blocks of 4 trials.

A training schedule was created with the participants and their primary caregivers. In case a training session was forgotten, a text-message was sent to the participant's cell phone to suggest another date to catch up. If a second training session was missed, the participant was called to discuss a new schedule. Each training session lasted approximately 20 minutes.

Four participants missed one AUT-training and two participants missed one LGT-training. All participants completed at least 7 training sessions.

MRI data collection

A 3T MRI scanner (Philips Intera, Best, The Netherlands) at Leiden University Medical Center with a standard whole-head coil was used for image acquisition. RS-fMRI data were acquired at the start of the pretest and posttest session. A total of 140 volumes were acquired resulting in a scan time of 5min. The results from the resting state scan have been reported elsewhere (Cousijn, Zanolie, et al., 2014).

Next, participants completed three runs of the AU-OC task, each lasting 8.3 minutes, during which 226 volumes per run were acquired. Bold signal was measured with a T2* gradient-echo EPI sequence (TR 2.2s, TE 30ms, 38 slices, slice thickness 2.75mm, FOV 220x220mm, in-plane resolution 2.75x2.75mm, flip angle 80°, sequential slice acquisition). The first 2 volumes of each run were discarded in order to allow for equilibration of T1 saturation effects. Finally, a high resolution T1 structural scan was acquired for anatomical reference (T1 turbo field echo, TR 9.8ms, TE 4.6ms, 140 slices, slice thickness 1.2mm, FOV 224x178mm, in-plane resolution 0.88x0.88mm, flip angle 8°). Head motion was restricted by using foam inserts between the head and the head coil. Visual stimuli were projected onto a screen in the magnet bore that could be viewed through a mirror attached to the head coil.

SPM8 software (www.fil.ion.ucl.ac.uk) was used for image preprocessing and analyses. Images were corrected for slice-time differences, followed by rigid body motion correction. Functional volumes were spatially normalized to individual T1 scans and subsequently to T1 templates based on MNI305 stereotaxic space (Cocosco, et al., 1997) using a 12-parameter affine transformation together with a nonlinear transformation involving cosine base functions. Data

were resampled to 3 mm cubic voxels. Functional volumes were smoothed using an 8mm full-width half-maximum 3D Gaussian kernel.

fMRI data analyses

SPM8 software was used for image analyses. For each participant, the functional time series were modeled by a series of events convolved with a canonical hemodynamic response function (HRF). Trials were modeled separately based on condition (AU or OC), with the presentation as onset time and a duration of 15 seconds, and entered in a general linear model along with a basic set of cosine functions to high-pass filter the data, and a covariate for run effects. In addition, the instruction screen preceding the AU and OC trials and the evaluation screen after trials were modeled separately (each with a duration of 0 ms).

The least square parameter estimates of height of best fitting canonical HRF for each condition were used in pairwise contrasts (OC - fixation; AU - fixation; AU - OC). Resulting first level contrast images, computed on a subject-by-subject basis, were calculated for pretest (T1) and posttest (T2) data separately. Additional images were created for activation changes from T1 to T2 for the contrast AU - OC using the ImCalc tool in SPM8. These calculations resulted in another set of first level contrast images ((AUT2-OCT2)-(AUT1-OCT1) which will be referred to as AU-OCT2-T1). The first level contrast images were submitted to group analyses. At the group level, contrasts between conditions were computed by performing one-tailed t-tests on these contrasts, treating participants as a random effect, and two-sample t-tests to compare training groups. Whole brain fMRI analyses were FDR corrected for multiple comparisons at $p < .05$ (voxel level) (Genovese, et al., 2002) with at least 10 contiguous voxels. We further conducted whole-brain regression analyses on the contrast AU > OC and AU > OCT2-T1 to test for general brain-behavior relations and relations between brain activation and behavioral changes, respectively. AU-scores at T1 were entered as covariate of interest to find regions showing general brain-behavior relations. Difference-scores (AU-scoreT2-T1) were entered as covariate of interest to find regions showing relations between brain- and behavioral changes. We applied the threshold of $p < .001$ uncorrected with at least 10 contiguous voxels to overcome the relatively low power inherent to analyses of individual differences/ type II error. Results are reported in the MNI305 stereotaxic space. Brain regions were determined based on the SPM anatomy toolbox v1.8 (Eickhoff et al., 2005, 2006, 2007).

Region-of-interest (ROI) Analyses

Region-of-interest (ROI) analyses were performed with MarsBaR toolbox in SPM8 (Brett, et al., 2002) for illustration purposes. The output ‘contrast estimates’ was used. Contrast estimates were derived for each condition relative to baseline (i.e., OC-baseline, AU-baseline). ROIs were derived from the contrast AU > OC at T1 and from the T2-T1 regression analysis with AUT T2-T1 performance change scores as regressor. If the region spanned a large area, the region was masked using anatomical ROIs derived from the MarsBaR anatomical toolbox.

Results

Initial comparisons

Initial comparisons comprised of tests for differences between training conditions on each of the pretest tasks using Analysis of Variance (ANOVAs) with Training as between-subjects factor. Descriptive statistics for all measures per training condition are shown in Table 6-1. None of the measures revealed differences between the two groups (all main effects and interaction effects: p 's > .05) showing that random assignment was successful and that there were no differences between the two groups prior to the training.

Table 6-1. Descriptive statistics for the behavioural measures (AU/OC scanner task and local global task) by training group and testing session.

Task	AU-training group		RS-training group	
	pre-test	post-test	pre-test	post-test
	M (SD)	M (SD)	M (SD)	M (SD)
AU/OC-scanner task				
AU-score	2.13 (0.59)	2.09 (0.68)	2.19 (0.38)	1.84 (0.36)
OC-score	3.00 (0.46)	2.93 (0.52)	3.24 (0.32)	3.04 (0.50)
Local Global Task				
% correct Control	94.04 (3.06)	96.19 (2.16)	90.55 (8.64)	90.85 (7.08)
% correct Switch	94.41 (6.70)	94.67 (8.07)	89.95 (8.50)	90.85 (7.09)
RT <i>ms</i> Control	443.75 (96.67)	385.50 (57.09)	416.41 (79.15)	329.03 (49.80)
RT <i>ms</i> Switch	509.22 (129.11)	428.16 (69.26)	525.25 (211.31)	354.66 (47.23)

Pretest to posttest changes on training tasks

AU/OC scanner task

To examine the training effects on creative idea generation and ordinary characteristic retrieval, we conducted repeated measures ANOVAs with within-subject variables percentage of trials for each Number Solutions (0/1, 2, 3, 4+), Task Condition (AU, OC) and Time (T1, T2) and with Training Group (AU, RS) as between-subject variable (Huynh-Feldt estimates reported when sphericity was violated). Significant main effects of Number Solutions ($F(2,60) = 9.05, p < .01, \eta_p^2 = .23$) and Task Condition ($F(1,30) = 48.03, p < .001, \eta_p^2 = .62$) were found, qualified by a significant interaction effect between Number Solutions x Task Condition ($F(2,60) = 50.15, p < .001, \eta_p^2 = .63$). This interaction demonstrated that participants generated more solutions for OC than AU trials. There was also a Number Solutions x Time interaction ($F(2,60) = 4.21, p = .02, \eta_p^2 = .12$); a closer look revealed that the interaction represents an overall shift from T1 to T2 toward fewer solutions for both AU and OC trials (see Figure 6-2). No other Time or Training Group effects were found (main and interaction effects, all p 's $> .05$).

Next, we conducted analyses on AU-composite scores to examine training effects on creative idea generation separately. As such, repeated measures ANOVAs were conducted on the AU-scores with Time (T1, T2) entered as within-subject variable and Training Group (AU, RS) as between-subject variable. A significant main effect of Time ($F(1,30) = 6.31, p = .02, \eta_p^2 = .17$), and an interaction effect of Time x Training Group ($F(1,30) = 4.14, p = .05, \eta_p^2 = .12$) were found. Post hoc analyses of the interaction effect show that performance in the RS group decreased from T1 to T2 ($F(1,30) = 13.49, p < .01, \eta_p^2 = .47$), whereas results for the AU group remained stable ($F(1,30) = .09, p = .77, \eta_p^2 = .01$).

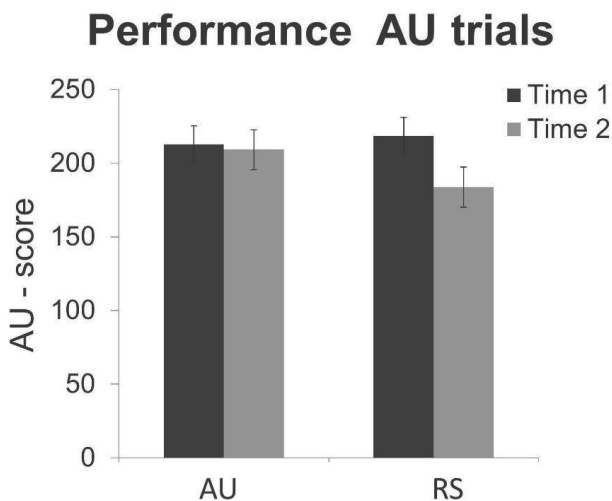


Figure 6-2. Performance on alternative uses trials for the Alternative Uses (AU) Training Group and Rule Switch (RS) Training Group at pretest and posttest. Analyses of composite scores indicated a drop in provision of alternative uses solutions for the RS Training Group and stable performance for the AU Training Group.

LGT

To test for training related effects on LGT accuracy (% correct) and reaction times, repeated measures ANOVAs were performed with Condition (Switch, Control) and Time (T1, T2) as within-subject variables and Training Group (AU, RS) as between-subject variable (see Table 6-1 for descriptive statistics) for reaction times and accuracy.

For reaction times, there were main effects for Time ($F(1,30) = 30.3, p < .001, \eta_p^2 = .50$), showing a general decrease of RTs from T1 to T2, and for Condition ($F(1,30) = 38.02, p < .001, \eta_p^2 = .56$), showing longer RTs for switch relative to control trials. In addition, there was a significant interaction effect of Time x Condition ($F(1,30) = 8.23, p < .01, \eta_p^2 = .22$), showing larger decreases for switch than for control trials at T2 relative to T1. No main or interaction effects were present for Training Group (all p 's $> .05$).

For accuracy, no significant effects were observed for Condition or Time and no interactions with Training Group were observed (all p 's $> .05$).

AU and LGT relations

To test for possible relations between AU and LGT performance, bivariate correlation analyses were performed on AU fluency scores and LGT switch cost accuracy and RT performances at pre test. None of the correlations were significant (all p 's > .05).

fMRI results*T1 analyses*

To extract the neural correlates of creative idea generation we conducted whole-brain voxel-wise t-tests on activation levels for the contrast alternative uses (AU) > ordinary characteristics (OC) across all participants ($N = 32$) at T1. Results revealed a number of regions including left supramarginal gyrus (SMG), left and right middle temporal gyrus (MTG), and left angular gyrus (AG) (FDR corrected, $p < .05$; see Figure 6-3; Table 6-2), which is in line with prior studies (Kleibeuker et al, 2013b; Fink et al., 2009, 2010). The opposite contrast OC > AU showed increased activity for retrieval of characteristics relative to alternative uses for common objects in an extend network including bilateral frontal, parietal, temporal cortex regions (see Table 6-2).

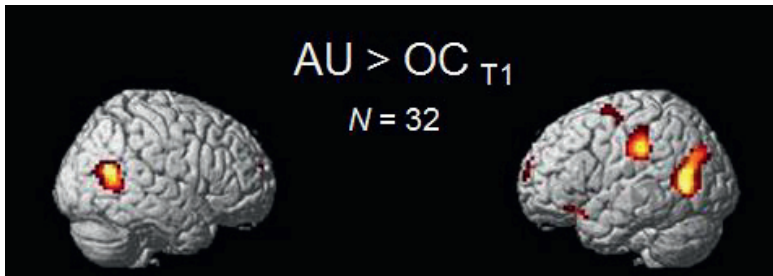


Figure 6-3. Neural regions showing activity for AU>OC at time point 1 (T1), averaged across all participants ($N=32$). This resulted in activation in left supramarginal gyrus (SMG), bilateral middle temporal gyrus (MTG) and left angular gyrus. Thresholded at FDR correction, $p < .05$, at least 10 contiguous voxels. See Table 6-2 for coordinates.

Table 6-2. Coordinates for the contrast AU>OC at T1 across participants (N=32), thresholded at FDR corrected $p < .05$, at least 10 contiguous voxels.

Brain regions	L/R	K	Z-value	MNI coordinates		
			peak voxel	x	y	z
middle temporal gyrus, precuneus, calcarine gyrus	R	330	5.89	57	-66	15
			4.36	21	-48	9
middle temporal gyrus, angular gyrus, middle occipital lobe	L	373	5.72	-51	-66	3
			4.78	-42	-78	33
			4.21	-42	-69	27
supramarginal gyrus	L	157	5.22	-63	-27	36
fusiform gyrus, precuneus, calcarine gyrus	L	360	4.86	-24	-39	-15
			4.65	-9	-57	15
			4.45	-36	-36	-15
medial superior frontal gyrus	L	143	4.84	-3	63	18
inferior frontal gyrus (p orbitalis)	L	73	4.36	-30	30	-12
			4.06	-27	15	-15
Precuneus	L	19	4.16	-12	-54	57
Cerebellum	R	12	3.74	18	-36	-15
superior frontal gyrus	L	48	3.74	-24	-9	57
			3.66	-21	0	63
medial cingulate cortex	L	10	3.41	-12	-27	42

Abbreviations: MNI = montrealneurologicalinstitute; L = lefthemisphere; R = right hemisphere.

To test for group-differences in brain activation patterns during the AU/OC scanner task at pretest, we performed whole-brain two sample t-tests on the contrasts AU>OC. No significant results were observed for the contrasts AU>OC, reassuring that groups did not differ at T1. To determine brain regions that were related to AUT performance, we performed whole-brain regression analyses on the contrasts AU>OC at T1 with AU fluency, operationalized by the AU-composite score at T1, entered as a covariate. No activations were found for the contrast AU>OC. There was however a negative correlation for AU-OC and AU fluency in the right IFG (peak coordinates $x=42$, $y=39$, $z=-6$), showing that individuals with better AU fluency activated this region relatively less during AU trials compared to OC trials.

Test-retest stability

To determine whether the activations related to AU>OC remained relatively stable over time after AU and RS training, we performed test-retest reliability analyses on the ROIs derived from the T1 AU>OC contrast. To this end, we calculated intra-class-correlations ($ICC_{3,2}$) for the two training groups (AU, RS) separately as well as for all participants together. Results are

presented in Table 6-3. Across all participants, ICC's ranged from 0 to .66 with highest correlations for the right MTG/calcarine gyrus/precuneus ($ICC = .66, p = .002$), left AG ($ICC = .65, p = .002$), and left SMG ($ICC = .64, p = .003$). For the AU-training group, ICCs ranged from 0 to .73 (l AG), and revealed fewer significant correlations than the RS training group. For the RS-training group ICCs ranged from 0 to .81 (l precuneus/calcarine gyrus).

Table 6-3. Intra Cluster Correlations for ROIs derived from the contrast $AU > OC$ at T1 over all participants.

	All participants		AU-training group		RS-training group	
	ICC	significance	ICC	significance	ICC	significance
l middle cingulate cortex (-12 -27 42)	0.46	0.05	0.58	0.05	-0.16	0.61
l precuneus (-12 -54 57)	0.5	0.03	0.52	0.09	0.49	0.09
l fusiform gyrus, l inf temporal gyrus, l precuneus, l calcarine gyrus (-24 -39 15)	0.47	0.04	0.33	0.25	0.62	0.02
l fusiform gyrus*	0	0.62	0	0.72	0	0.53
l inferior temporal gyrus*	0	0.58	0	0.69	0.17	0.36
l precuneus, l calcarine gyrus*	0.55	0.01	0.39	0.18	0.81	0.002
l superior frontal gyrus, precentral gyrus (-24 -9 57)	0.52	0.02	0.55	0.07	0.51	0.09
l superior medial gyrus (-3 63 18)	0.51	0.03	0.45	0.13	0.58	0.05
l inferior frontal gyrus (orb), l insula lobe (-30 30 12)	0.21	0.26	0.42	0.16	0	0.57
l inferior frontal gyrus (orb)*	0.11	0.38	0.31	0.24	0	0.69
l insula lobe*	0.3	0.16	0.64	0.03	0	0.55
l middle temporal gyrus, l angular gyrus, l occipital gyrus (-51 -66 3)	0.52	0.02	0.47	0.12	0.62	0.03
l middle temporal gyrus*	0.57	0.01	0.36	0.2	0.75	0.006
l angular gyrus*	0.65	0.002	0.73	0.008	0.52	0.08
l occipital gyrus*	0.47	0.04	0.54	0.07	0.31	0.24
l supramarginal gyrus (-63 -27 36)	0.64	0.003	0.67	0.02	0.56	0.06
r middle temporal gyrus, r calcarine gyrus, r precuneus (57 -66 15)	0.66	0.002	0.61	0.04	0.69	0.01
r middle temporal gyrus*	0.6	0.007	0.64	0.03	0.47	0.12
r calcarine gyrus, r precuneus*	0.66	0.002	0.46	0.12	0.78	0.003

Note: ICC = intraclass correlation; l = left; r = right; MNI coordinates of peak activations are presented between brackets, Grey = Anatomical Masking; *subROI derived from ROI: masked with anatomical ROI from SPM Anatomical Toolbox v1.8.

T2>T1 analyses

Our analyses on brain activation training effects were twofold. First, whole-brain analyses were applied on the T2>T1 contrast images for the contrasts AU>OC and OC>AU. No significant results were observed for the contrasts AU>OC or for the opposite contrast OC>AU.

Second, we analyzed possible training related effects within divergent thinking related brain regions. Therefore we applied repeated measures ANOVAs on ROIs from the contrast AU>OC at T1. This ROI approach was chosen in addition to the whole-brain analyses, because analyses at the ROI level have more power to detect smaller differences in the task-related brain regions. These analyses included Time (pretest, posttest) and Condition (AU, OC) as within-subject variables and Training (AU, RS) as between-subjects variable. We focused on three ROIs: Left SMG, and left and right MTG/angular gyrus.

The Time (2) x Condition (2) x Training Group (2) repeated measures ANOVA for the separate ROIs only showed a time effect at trend level for left MTG/angular gyrus cluster (coordinates: -51 -66 3; $F(1,30) = 4.42$, $p = .058$, $\eta_p^2 = .13$) as well as a trend level Time x Training Group interaction effect ($F(1,30) = 3.30$, $p = .08$, $\eta_p^2 = .10$). The interaction showed a larger increase of activation over time for the AU-training group relative to the RS-training group for both the AU and OC trials. Post hoc analyses on the two groups separately showed significant changes over time for the AU group ($F(1,15) = 15.95$, $p = .001$), but not for the RS group ($F(1,15) = .027$, $p = .87$). No Training effects or interactions were found for the other regions.

T2>T1 analyses, relations with performance change

Our final aim was to test for brain activation patterns that were related to changes in AUT performance over time. To this end, we conducted whole brain regression analyses on the contrasts AU>OC_{T2-T1} with AU difference scores (T2-T1). A significant positive relation was observed in the left cerebellum (peak coordinate: -30 -75 -21, 150 voxels) and left middle frontal gyrus (MFG; peak coordinate: -39 24 9, 14 voxels; see Figure 6-4a,b).

Post hoc ROI analyses on the left MFG showed that the effect remained significant when controlling for Training Group, for activation at T1 (AU > OC), and for AU fluency scores at T1. These results indicate that the regression analyses outcomes are not due to individual differences at T1 or to group differences in training related changes. The independence of training group is also indicated by whole brain regression analyses for the two training groups separately (p uncorr

< .001; > 10 consecutive voxels). For both groups the performance regression results showed regions within the left MFG that overlapped with the region found in the analyses that included all participants (see Figure 6-4c; AU-training: peak voxel at -42 51 0; RS-training: peak voxel at -33 54 12).

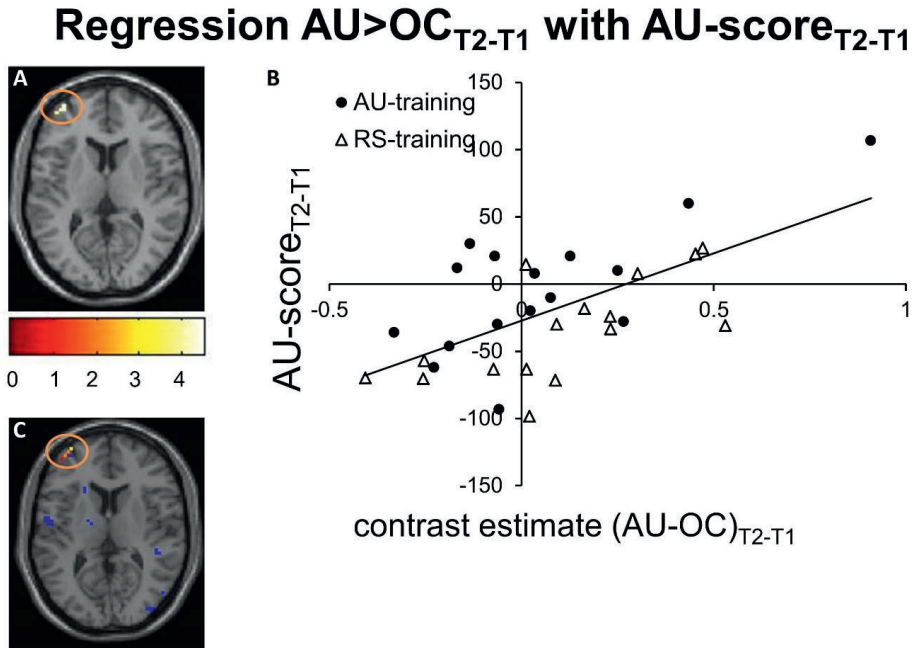


Figure 6-4. (A) Regression analysis for AU>OC T2>T1 with AUT fluency T2>T1 as predictor, averaged across all participants ($N=32$). Threshold: $p<.001$, uncorrected for multiple comparisons, at least 10 contiguous voxels. The analysis resulted in two clusters in the PFC at $x=24$, $y=30$, $z=54$, voxel size = 11, $T=3.99$. (B) Data of ROI analyses for the cluster in the left MFG are presented with circles for AUT Training Group and triangles for RS Training Group for illustration purposes. (C) Results for the regression analyses across all participants ($N=32$; red), for the AU training group ($N=16$; yellow), and RS training group ($N=16$; blue).

Additional tests for lateral PFC performance relations

To test for commonalities with an earlier study on AUT neural responses using the same task in both adolescents and adults, bivariate correlation analyses were performed on a set of predefined ROIs in the lateral PFC. ROIs were derived from whole brain regression analyses on the contrast AU>OC with AU-score as covariate (see Kleibeuker et al., 2013b). Correlations were estimated between AU>OC changes from T1 to T2 and AU difference scores (AU-score at T2

minus AU-score at T1). We found a significant positive correlation between right middle frontal gyrus (coordinates: 42, 42, 21) and AU difference scores. These results support the importance of right lateral frontal functioning in creative idea generation.

Discussion

The aim of the study was to examine changes in neural activations related to divergent thinking practice in adolescents. To this end, 15-16-year-olds were scanned while performing an adapted version of the AUT (Guilford, 1956, 1967; Kleibeuker, et al., 2013b) before and after two-weeks of alternative uses training. Behavioral and neural changes were compared to an age-matched active control group who practiced with a rule-switching task for the same training period. Behavioral results support the effectiveness of divergent thinking practice, showing better divergent thinking performance after training for the AU group compared to the control group. The fMRI results yielded three important findings: 1) activations of the creative ideation related network remained relatively stable over time, 2) were not sensitive to training manipulations; and 3) right lateral frontal cortex activation changes were associated with changes in divergent thinking over time. The discussion is organized in line with these findings.

Training effects of divergent thinking training

The behavioural results showed a group x session interaction effect with better training outcomes for the AU training group. These results indicate that training creativity in adolescence is potentially beneficial. However, this conclusion needs some restraint given that the interaction effect was due to a performance decrease for the rule switch group, whereas performances for the alternative uses group remained stable over time. The behavioural outcomes could be interpreted as a negative effect of rule switch training on divergent thinking performance. However, the lack of significant correlations between AU scores and LGT performances from both the current and a previous study (Cousijn et al., 2014) is in contradiction with such an interpretation: If rule switch training affects divergent thinking negatively, one might expect to find negative correlations between rule switch performances and AU performances. A second possible explanation for the behavioural interaction effect is that the RS group lacked motivation to perform during the second session. However, if this was the case, one might have expected a similar negative effect for other test performances. Results of additional tests administered outside the scanner (results are described in Cousijn et al. 2014) do not support this explanation. Alternatively, the results might

be influenced by secondary aspects such as the test environment. Indeed, MRI scanner environment has been related to changes in cognitive functioning showing both increases and decreases in cognitive control performances (Van Maanen, Forstmann, Keuken, Wagenmakers, Heathcote, *in press*). Results have been interpreted e.g., in terms of stress-induced increase in attentional control (Hommel, Fischer, Colzato, van den Wildenberg, & Cellini, 2012; see also Plessow, Fischer, Kirschbaum, & Goschke, 2011) or arousal (Koten, Langner, Wood, & Willmes, 2013), and decreased attentional focus (Asseondi et al., 2010). Interesting, both these interpretations (increased arousal and decreased attentional focus) could account for better divergent thinking performance during a first scanner session relative to a second scanner session. Indeed, prior studies have revealed positive effects of moderate levels of arousal on creative fluency and originality (De Dreu, Baas, Nijstad, 2008; Byron et al., 2010), whereas attentional focus is negatively associated with creativity performances (e.g., Wiley and Jarosz, 2012, Ansburg and Hill, 2003). As such, it is reasonable that potential training related increases in creative thinking are hidden by negative session effects, and future research should focus on possible environmental effects in training studies.

4.2 Stability of creative ideation network activations

The stability (ICC) analyses showed that activations of the core network related to creative ideation, represented by regions that are more active during alternative uses generation than ordinary characteristics retrieval at T1, remain relatively stable over time. The network is dominated by parietal-temporal regions including bilateral MTG, left angular gyrus and left SMG, but also includes frontal regions, including left superior-, and inferior gyrus and bilateral cingulate cortex. Thus, the results are consistent with prior research that indicates critical involvement of both parieto-temporal (Fink et al., 2010; see also Arden, et al., 2010 for an overview) and frontal brain regions in verbal creative thinking (e.g., Abraham et al., 2012; Carlsson, et al., 2000; Chávez-Eakle, et al., 2007; Howard-Jones, et al., 2005). Several studies have shown that the angular gyrus, SMG (posterior), and MTG are involved during semantic tasks (e.g., Binder, et al., 2009; Jung-Beeman, 2005; Vigneau et al., 2006). In part, the semantic information processing might be focused specifically on tools. Indeed, the MTG and SMG have repeatedly been related to tool use and action knowledge, including semantic information of tools and imaginative tool use (Beauchamp and Martin, 2007; Johnson-Frey et al., 2005; Johnson-Frey, 2004; Lewis, 2006). Accordingly, processing of these types of information are likely profitable when thinking about alternative uses of objects. Recent experimental research also indicates a specific function for the

left posterior MTG together with the left inferior frontal gyrus (IFG) in semantic processing. These regions have been related to executive mechanisms that direct semantic retrieval according to the task or context at hand (e.g., Jung-Beeman, 2005; Whitney, et al., 2012). Notably, especially the angular gyrus and SMG showed strong stability within individuals over time in both training groups, suggesting that this is a core network that is engaged for divergent thinking performance.

The ICC values for left inferior frontal gyrus were not significant in both groups. These findings suggest that these frontal regions are less consistently active within individuals across sessions, which is consistent with the notion that these regions are sensitive to performance differences (Kleibeuker et al., 2013b). In prior studies, it was suggested that in semantic control processes the IFG regulates the cognitive control devoted toward semantic retrieval and this system may be more sensitive to fluctuations in effort and attention (Whitney et al., 2012).

Finally, the left MTG showed significant ICCs for the Rule Switch training group but not for the Alternative Uses training group, whereas the left cingulate cortex showed significant ICCs for the Alternative Uses training group but not for the Rule Switch training group. The absence of left MTG stability for the Alternative Uses training group may indicate that this region is more malleable to training in this domain, whereas the absence of left cingulate cortex stability in the Rule Switch training group is consistent with several studies that reported that switching places demands on anterior cingulate cortex / pre-supplementary motor areas (e.g., Crone, et al., 2006; Nachev, et al., 2007), and training in this domain may generalize to different activation patterns in the AU task as well.

Taken together, the within-individual consistency in neural activity across the two measurements was highest in those areas that are also most consistently reported in single session measurements, including the angular gyrus, SMG and (right) MTG, further confirming the relevance of this network for divergent thinking (Abraham et al., 2012; Bechtereva et al., 2004; Benedek et al., 2014; Fink et al., 2009, 2010, 2014; Kleibeuker, et al., 2013b).

Effects of AU training on left MTG activity

The comparison of neural activation before and after training indicates that two weeks of alternative uses training increases activity in the left MTG after during idea generation. These findings are consistent with prior research on verbal creative thinking training. One possible interpretation is that the left MTG is important for demanding executive semantic processes, including (Whitney, et al., 2012). The change in left MTG activity was found for both the

alternative uses and the ordinary characteristics trials, suggesting a general increase in a process that is demanded for both types of trials, which was enhanced by two weeks of AU training. The change in left MTG activity was not related to individual differences in performance change. It is possible that these relations are due to small sample sizes and that relations will be found in studies with larger samples. Yet, the absence of a performance relation is consistent with the hypothesis that the change represents a general ideation effect which is not specific to thinking of alternative uses.

PFC activity and performance change

In two separate comparisons performance correlations were found for regions within the PFC. These findings are consistent with an earlier study that showed that especially lateral PFC activity was associated with individual differences in alternative uses fluency (Kleibeuker et al., 2013b). In the current study, change in activity in a region in the left middle lateral PFC, adjacent to (minimally overlapping) the region in Kleibeuker et al. 2013b, was related to a change in alternative uses fluency. Thus, those individuals increasing in fluency over time showed more activity in this region of lateral PFC over time, whereas those individuals decreasing in fluency over time showed less activity in lateral PFC over time. These change by change correlations have also been found in a prior study examining longitudinal changes in performance monitoring in children, adolescents and adults (Koolschijn, et al., 2011).

Interestingly, in a prior study this region of lateral PFC was less active in adolescents than adults during divergent thinking as measured with the AUT, which was accounted for by differences in fluency performance (Kleibeuker et al., 2013b). Although the exact function of the lateral PFC in the applied paradigm and in divergent thinking in general is still under debate, it has been related to working memory, monitoring, and inhibition of common answers (Carlson et al., 2000; Chavez et al., 2004; Chavez-Eakle et al., 2007; Martindale, 1999; Zabelina & Robinson, 2010). It should be noted that divergent thinking benefits by Alternative Uses training were characterized by an absence of a decrease in fluency, whereas the Rule Switch training group showed a decrease in fluency over time. A possible explanation in terms of environmental factors has been described above (Assecondi et al., 2010; Hommel et al., 2012; Koten et al, 2013; van Maanen et al, in press) but more studies are necessary to better understand the dynamics of divergent thinking performance across multiple measurements.

Limitations

This study had several limitations which should be addressed in future research. First, the study only included adolescents, and future studies should test if training effects are different for children and adults (e.g., Stevenson et al., 2014). Second, the study focused on practice, and future studies should use other training designs as well, such as using feedback including exposure to others' ideas (Dugosh and Paulus, 2005; Fink et al., 2010; Paulus and Nijstad, 2003). Finally, this study examined effects over a relatively short time period of two weeks, measuring neural correlates before and after training. Future studies should examine long term effects of training as well, for example across several months (e.g., Bott et al., 2014; Scott et al., 2004), and incorporate more measurements across time to increase the understanding of the training process and account for possible session effects.

Conclusion

Taken together, this study was the first to show that over time, there is stability in the neural responses during divergent thinking, as indicated by moderate to high ICCs. This result shows that creativity can be reliably assessed and has some level of stability that is difficult to show based on behavioral findings alone. Individual differences in performance changes were most strongly related to changes in lateral PFC activity. These findings are interesting in relation to studies that have shown that especially executive control processes, which rely heavily on PFC, develop further during adolescence. Future studies should test the hypothesis that adolescence is a sensitive period for training related changes in neural activity by comparing adolescents and adults, given that behavioral studies have suggested that training benefits in the domain of divergent thinking are larger for adolescents than for adults (Stevenson et al., 2014).

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Supplement

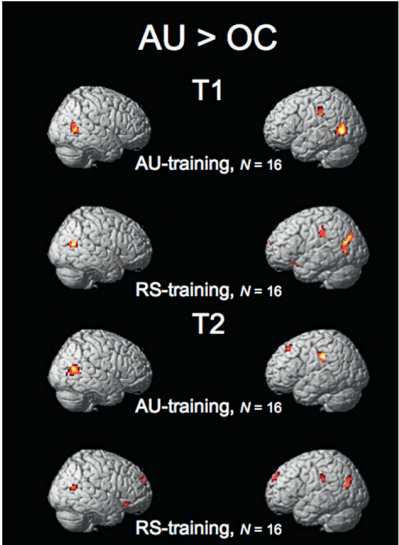


Figure 6-S1. Activation for AU>OC for each Training Group for T2 and T1 separately.

CHAPTER 7

General Discussion

This thesis provides a comprehensive approach to unraveling how creative performance develops during adolescence, which neural mechanisms are involved during creative thinking, and how, if possible, creativity can be improved during this age period. A better understanding of these questions will enable us to improve models of neuro-cognitive development that reflect the complexity of the developing brain; to develop useful training paradigms for creativity; and to further inform studies on creativity training and development during adolescence.

In this thesis, I have built upon the *creative cognition approach*, which directly associates creativity with basic cognitive processes and functions (Ward, 2007; Nijstad et al., 2010; Sowden et al., 2014), and, consequently, implies that creativity training success depends on the trainability of these function.

Prior research on creativity in adolescence is not only scarce, but also inconclusive, as presented by a wide variety of methods. Inconsistency of results makes it difficult, if not impossible, to create a uniform picture of the development of creativity in adolescents.

The approach in this thesis, combines behavioral measures with brain activations, measured with fMRI, across domains and ages, in single test and longitudinal training-designs, in order to capture creative cognition development throughout adolescence. In addition, both age- and experience-related effects on creative thinking performance during functional brain development were tested. The main findings and conclusions are presented in the following sections. The chapter closes with a number of critical considerations and recommendations for future studies.

Development of different creativity aspects throughout adolescence

Chapter 2 describes an empirical study, focused on gaining insight into the developmental trajectories of creative thinking across adolescence. We were interested in identifying whether differences exist in the developmental patterns associated with creative processes. It is argued that creative thinking is an important skill facilitating the advancement toward adult functioning (Jaquish & Ripple, 1980); thus, adolescence is expected to involve important changes in creative capacities. To address developmental changes for the broader domain of creative thinking, participants of four age groups (12/13 yrs, 15/16 yrs, 18/19 yrs, and 25-30 yrs) were subjected to an extensive battery of tests, gauging insight and divergent thinking in the visual and verbal domain. The results of this study support the distinctiveness of creative aspects and demonstrated different developmental patterns, as described below.

Creative insight

We observed that creative insight (both visual and verbal) continued to develop into late adolescence; creative insight refers to the ability to successfully restructure and unify complex or remote information, as required for insight success. Two explanations for prolonged development include: (1) an increasing knowledge base from which information can be retrieved; and (2) the development of the ability to manipulate and control information retrieval. This is in agreement with prior studies that demonstrate protracted developmental trajectories throughout adolescence for both knowledge and cognitive control such as working memory and executive functions (Huizinga et al., 2006; Luna et al., 2004). Noteworthy are the shapes of the developmental trajectories, which were best described by step-wise (visual) and curvilinear (verbal) models. In particular, the visual domain results are indicative of qualitative changes in underlying cognitive processes and related neural underpinnings. This is in agreement with a previous study by Uhlaas et al. (2009), who reported similar patterns for Gestalt perception development, as a result of a reorganization of functional neural networks. I recommend, therefore, that future studies on insight development should include research designs that allow us to examine underlying (neural) processes and information processing strategies, such as neurophysiological and latent-class analysis, or eye-tracking techniques.

Divergent thinking

Divergent thinking tasks revealed developmental patterns that were quite different from insight tasks, and identified distinct developmental trajectories for the two studied domains (verbal and visuospatial).

Verbal divergent thinking

To test verbal divergent thinking, we implemented the Alternative Uses Test (AUT). Outcomes of the AUT suggest that the capacity to generate multiple ideas (fluency) from different conceptual categories (flexibility) is already developed in adolescence, but that the quality of solutions (originality) continues to develop. That is, no differences were observed between age groups for the number of invented uses and the number of conceptual categories of uses for a brick, but the two older age groups outperformed the two younger age groups on the uniqueness of invented applications for a brick. Two different factors suggested to underlie the age-related differences for originality include: 1) increasing knowledge from which associations can be made, including increasing intra individual differentiation of knowledge as late adolescents become more autonomous; and 2) development of cognitive processes that support the ability to flexibly coordinate between associative and analytic processing, as both types of processing result in multiple solutions; the quality of ideas, however, depends on the ability to flexibly switch between them (Christoff et al., 2009a, 2009b; De Dreu et al., 2010; Nijstad et al., 2012; Martindale, 1999), an ability that develops only in late adolescence (e.g., Kerns, 2006; Kerns et al., 2004). Notably, the developmental pattern for divergent thinking originality was quite similar to those for the insight tasks, indicating that the underlying processes reveal similar developmental changes. It is, however, unlikely that the underlying mechanisms were identical as relations between performances disappeared when results were corrected for age.

Visuo-spatial divergent thinking

Visuospatial divergent thinking was assessed by applying the Creative Ability Test (CAT). This task requires participants to find as many matching figures as possible according to a set of pre-specified rules. Success is relatively independent of knowledge, but requires generating and shifting between representations of the provided visual information, applying a set of rules, and monitoring behavior; cognitive functions that are commonly associated with prefrontal cortex (PFC) functioning and are still developing in adolescence (Huizinga et al., 2006). In accordance with these developmental changes of cognitive functions, task results showed marked increases

from early to middle adolescence. No differences were identified between the early adolescents and the two oldest age groups, indicating a relative advantage for middle adolescents for visuospatial divergent thinking. It has been suggested that these positive outcomes may be related to the relatively widely-focused, explorative behavior of this age group. This behavior has indeed been shown to be characteristic for adolescence (Dahl, 2011; Johnson & Wilbrecht, 2011).

In summary, the results in Chapter 2 support the distinctiveness of creativity aspects and indicate both immaturities (insight, verbal divergent thinking originality) and creative potentials (visuospatial divergent thinking) during middle adolescence. Although the exact factors underlying the differences in developmental patterns are still unknown, possible explanations include 1) different degrees to which task success depends on knowledge (higher for insight and verbal divergent thinking than for visuospatial divergent thinking); and 2) differences in the extent to which task success relies on; retrieving and manipulating *internally* stored information (high for verbal idea generation; low for visuospatial divergent thinking); and exploring *externally* provided information (low for verbal idea generation; high for visuospatial divergent thinking).

A further question arising from this study is how these results are related to the development of underlying brain functioning. In particular, how the different developmental changes relate to functioning of late developing PFC, since creative success of both verbal divergent thinking and visuo-spatial creative problem solving have been associated with PFC functioning (e.g., Chavez et al., 2004; Gibson et al., 2009; Goel and Vartanian, 2005). This question has been addressed in Chapters 3 & 4.

Neurocognitive development of creative cognition from middle adolescence to adulthood

The aim of the following two chapters (Chapters 3 & 4) was to expand insight into the differential developmental patterns of creative aspects and their underlying mechanisms. To this end, we applied fMRI during visuospatial creative problem solving (Chapter 3) and verbal creative idea generation (Chapter 4) in middle adolescents and adults.

Prior neuroimaging studies have shown profound structural and functional changes during adolescence, mainly in the (lateral) PFC (Gogtay et al., 2004; Adleman et al., 2002; Crone et al., 2006c). These changes are commonly associated with the development of executive functions, such as working memory, interference control and task-switching (see Bunge & Wright, 2007) ;

cognitive functions that have also been associated with creative success (De Dreu et al., 2012; Ward, 2007). Prior studies on PFC related cognitive functions have shown both age related increases and decreases of PFC activations. These studies interpret positive changes as increased ability to recruit brain regions, and negative changes as increasing efficiency of brain regions. Recent studies of complex cognitive functions have revealed more complex developmental patterns with peak activations in adolescence (Crone et al., 2006; Dumontheil et al., 2010). Based on this, an important question considered in this thesis concerned the over-simplicity of the above-mentioned interpretations of PFC development. Building on the findings in Chapter 2 (visuospatial divergent thinking), together with previous reports of peak PFC activations during adolescence, I hypothesized, in Chapter 3, that adolescence is a period of enhanced PFC activations for exploration and adaptive purposes.

To test this, adolescents (15-17 yrs) and adults (25-30 yrs) were subjected to both a matchstick problem task (MPT), while scanning neural activation with fMRI, and a visuo-spatial divergent thinking task (creative ability task; CAT) outside the scanner. Results indicate that creative problem solving is already developed in middle adolescents, showing no age differences in overall MPT performance. Interestingly, adolescents outperformed adults on experimental problems (seeking alternative solutions for the matchstick problem) indicating an advantage for this age group for problems that require exploration and shifting between representations.

The brain imaging data underscored the importance of prefrontal brain regions in creative thinking. Results demonstrated increased activation in several left lateral PFC regions during successful creative problem solving across individuals. Additional individual difference analyses demonstrated a positive relation between creative problem solving performance and left inferior frontal gyrus (IFG) activations. Prior research suggests particular relevance of this brain region for switching between representations (Crone et al., 2006; Hirshorn & Thompson-Schill, 2006). Activations in right dorso-lateral PFC (DLPFC) were associated with better visuospatial divergent thinking capacities (CAT performance). Thus, individuals with greater visuo-spatial thinking abilities have the tendency to recruit right DLPFC during creative problem solving more than individuals with poor visuo-spatial thinking abilities. This region is suggested to be involved in planning and manipulating internal representations as well as in working memory processes and monitoring behavior (Crone et al., 2006; Curtis & d'Esposito 2003; Jolles et al., 2011; Shallice, 2004; Ruh et al., 2012; Ridderinkhof et al., 2011).

Interestingly, a direct comparison between age groups revealed increased activation in left (IFG) and right (DLPFC) during successful creative problem solving for adolescents compared to adults. These results indicate that middle adolescents, relative to adults, a) have the tendency to recruit important PFC regions that allow for a flexible and explorative manner of processing, and b) show activity patterns that are common to individuals with higher divergent thinking capacities. This study therefore supports the hypothesis that adolescence is not only a phase of immaturity but also a period of enhanced PFC activation for exploration and adaptive purposes (Crone & Dahl, 2012).

In Chapter 4, the neuro-developmental changes of verbal creative idea generation were investigated. In contrast to visuo-spatial creative problem solving, we hypothesized that verbal ideation would not be fully developed in middle adolescence, and that underperforming would be related to immature cognitive control processes and PFC functioning. As predicted, adults (25-30 yrs) outperformed adolescents (15-17 yrs) on creative idea generation (tested through an adapted version of AUT, while scanning with fMRI); adults generated significantly more alternative uses than adolescents. The fMRI results for creative idea generation indicated involvement of a temporo-parietal network including the left angular gyrus (AG), the left supramarginal gyrus (SMG), and the bilateral middle temporal gyrus (MTG) in both adults and adolescents. In addition, we performed individual difference analyses and found a positive correlation between activations in left IFG/MFG and divergent thinking performance. These findings resemble previous findings (e.g., Fink et al, 2010; see also Arden et al. 2010; Dietrich & Kanso, 2010) and suggest the importance of semantic processing during creative ideation. Interestingly, when trials with only *multiple* solutions, a hallmark of divergent thinking, were analyzed, results included additional left IFG/ MFG activation. These results suggest that the ability to generate multiple creative ideas, or divergent thinking, involves cognitive control functioning, such as attentional inhibition and cognitive flexibility (see e.g., De Dreu et al., 2012; Vartanian, 2009; Zabelina & Robinson, 2010). Our findings, together with those of previous studies, highlight the importance of these lateral frontal regions and support the idea that temporo-parietal activations are related to creative idea generation in general, whereas PFC activity is discriminative for divergent thinking success (Carlsson et al., 2000; see Arden, 2010; Dietrich & Kanso, 2010). Notably, activations in these frontal regions were more pronounced in adults than adolescents. One possible explanation could be that adolescents are not yet able to activate these brain regions and associated cognitive processes to a mature level for the task at hand. It should, however, be noted that the age-related differences were not significant at whole brain level and future research should replicate the

developmental changes of lateral PFC activations to be clear about the role of PFC functioning in divergent thinking development.

In summary, fMRI results support the idea that the lateral regions of the PFC function as ‘the organ of creativity’, generating novelty and complexity (Fuster, 2002). Moreover, the fMRI results underscore the complexity of the functional development of lateral PFC as middle adolescents, relative to adults, showed both increased (Kleibeuker et al., 2012b) and decreased (Kleibeuker et al., 2012c) activations. In addition, these age-related differences were associated with better and worse creative task performances, respectively. It thus seems unlikely that the observed adolescent brain activation patterns simply represent immature brain functioning in terms of less efficiency or deficient recruitment of essential brain regions.

Here we focused on prefrontal brain activations. It should, however, be noticed that other regions than PFC were involved in creative thinking, brain regions for which we did not have a priori hypotheses. Future research should explore their roles in creative thinking development to further our understanding of the mechanisms underlying creative performance across adolescence.

Creative ideation training in adolescence

To extend investigations into the development of creative ideation, two empirical studies examined the progression of creative thinking abilities within simple training paradigms. Various studies have already demonstrated the effectiveness of training paradigms in improving creativity in both adults (Glover, 1980; Bott et al., 2014; Kienitz et al., 2014) and children (Torrance, 1972; Cliatt et al., 1980). However, relatively little is known about how malleable creative thinking is in adolescence. Training studies in other higher cognitive skills include working memory (Klingberg, 2010; Jolles et al., 2012), executive control (Karch and Kray, 2009; Zinke et al., 2012), relational reasoning (Dumontheil et al., 2010), and algebraic equation solving (Qin et al., 2004) emphasize the training susceptibility regarding performance and brain function during adolescence. These studies have led to the hypothesis that adolescence is a period of enhanced sensitivity to training of high-level cognitive skills, compared to adults (see also Steinberg, 2005; Jolles & Crone, 2012).

This hypothesis was tested in Chapter 5 for creative thinking training by applying a simple creative ideation training paradigm. The main aim of the study was to examine whether creative ideation could be improved by practicing alternative uses generation in adolescents (13-16 yrs)

and adults (23-30 yrs). In this study, participants followed one of three training types, (1) alternative uses generation (creative ideation; experimental condition), (2) object characteristic naming (general ideation; control condition), or (3) global local rule switching (rule-switching; control condition). Performances prior to training sessions resembled previous research and revealed that adolescents already performed at adult level on ideation fluency and flexibility, but that adults outperformed adolescents on originality measures. Post-training results demonstrated that participants in general (irrespective of age group and training condition) progressed on creative ideation originality and fluency. With regard to originality, adolescents progressed further after two weeks of training than adults, independent of the type of training. These results therefore, support the above-mentioned hypothesis and indicate greater training susceptibility for adolescents than for adults. In addition, these results support the idea that adolescence is a period of enhanced flexibility in cognition and learning (Crone & Dahl, 2012; Johnson & Wilbrecht, 2010). A question stemming from these results is, what are the (brain) mechanisms underlying training success in adolescents, and to what extent are training effects related to the reorganization of the PFC and associated regulatory systems during adolescence (Keating, 2004; Steinberg, 2005)?

These questions were targeted in the final empirical chapter, Chapter 6. Here, the benefits of training creativity in adolescents were tested by examining neural responses to problems that require divergent thinking before and after two weeks of divergent thinking training. To this end, participants followed one of two training types: creative ideation or rule switching. All participants performed an adapted version of the alternative uses task, while fMRI images were acquired before and after the training program. Training outcomes for creative idea generation were better for the experimental group than for the control group: performances for active control group decreased over time, whereas performances for the creative ideation group remained stable. Although the decline in performance for the control group and stable pattern for the training group may seem counter intuitive, similar training patterns have previously been found for adults (Fink et al., 2015). The exact mechanisms behind these findings are, however, not yet understood and are target for future research. One hypothesis is that individuals were more conservative when testing for the second time.

The fMRI results indicate that core brain regions for creative ideation (SMG, AG, MTG) are consistently recruited in adolescence and recruitment remains relatively stable after training. This study further supports the involvement of lateral PFC in creative ideation output, establishing

that performance changes, irrespective of training, were positively associated with activation changes in late developing IFG/MFG. This further indicates that lateral PFC activation is predictive for divergent thinking success, but that the involvement of the lateral PFC is not changed by creative thinking training. The exact functions of lateral PFC regions in creative thinking still need to be deciphered. Future research could distinguish different aspects of the creative process and examine the relation between lateral PFC regions and the brain networks that support these divergent thinking aspects.

Conclusion and future directions

In the current thesis, I aimed to gain insight into the capacities and potential of creative cognition in a life period that is associated with significant changes in cognitive functioning and increasing individuality. Adolescence is often seen as a ‘difficult’ transitional phase characterized by rebellious and risky behavior (Ayman-Nolley & Taira, 2000; Steinberg, 2007), yet it is also a natural time of learning and adjustment and provides opportunities for explorative behavior as individuals gain autonomy and develop their identity (Marcia, 1980). Recent developmental neuroimaging studies recognize the complexity of the adolescent brain as several studies have now reported different patterns of age related changes in brain functioning, particularly in (lateral) PFC structure and function. The results of the present dissertation complement and elaborate on our current understanding of adolescent (creative) cognition providing us with insight into both the potentials and limitations, associated with complex functioning of lateral prefrontal brain regions.

It is, however, important to recognize the complexity of the creativity construct as it covers multiple facets across various domains. Here I focused only on a limited set of aspects, and, although these aspects have been recognized as essential and predictive for creativity success (e.g., Kim, 2010), some reservations should be made regarding the generalizability of the results. Moreover, in the current thesis, simple practice paradigms were used to gain insight into the trainability of creative thinking in adolescence. To better understand the potentials for creative success in general, future research should incorporate alternative training paradigms. Such paradigms could include informing individuals about the nature of creativity, or the use adaptive designs to distinguish between levels of difficulty, both of which have been shown to be effective interventions (e.g., Clapham, 1997; see also Scott et al., 2004). Another focus for future research concerns differentiating between creative thinking strategies, enabling to distinguish

developmental trajectories and training potentials for different pathways to creative success (e.g., flexible and persistence; see Nijstad et al., 2004).

Nonetheless, the current findings provide important insights in the functionality of the adolescent brain when confronted with problems that desire *out of the box* thinking. In addition, these findings serve as a starting point for future research and provide several relevant implications.

One of the main findings of the current thesis is the distinctiveness of developmental trajectories for the different creativity aspects, with a relative peak for middle adolescents' visuo-spatial divergent thinking and relative worse performances for verbal idea generation for the same age group. Interestingly, success for both types of creative was related to lateral PFC activations so that, relative to adults, middle adolescents showed both increased and decreased activations of these PFC regions. These findings can serve as starting point to develop models of neuro-cognitive development that recognize the complexity of functional brain development during this transitional phase. In turn, such models could provide useful implications for educational purposes as a better understanding of how the adolescent brain processes information, and provides opportunities to adjust educational programs to optimize successful processing of learning material.

In our current knowledge society, in which creative abilities are valued more than ever before, an interesting question for future research is to what degree the observed increased (and decreased) performances for middle adolescents are age-related and associated with structural and functional brain development. More particularly, is it possible for adults to increase creative success (at certain aspects) when addressing problems in a way similar to middle adolescents? If so, knowledge about how the adolescent brain processes information could also be used to develop training paradigms for organizations that require their employees to think creatively.

A second important finding from the current thesis is that middle adolescents showed more progress after creative thinking training than adults. These findings complement previous reports of trainability of higher-level cognitive functions in adolescence (Jolles et al., 2012; Wu et al., 2010) and suggest that educators should make use of this sensitive period to encourage flexible thinking and enhance creative abilities. These results, however, also raise questions about long-term consequences of creative thinking training: is improving divergent thinking skills during this sensitive period advantageous for creative outcomes later in life? To answer this question, longitudinal (brain imaging) studies are necessary to test whether a) divergent thinking training

during this phase leads to durability of adolescent (brain) flexibility, or b) whether training simply leads to accelerated development of involved brain networks, including lateral PFC regions, and, accordingly, increases brain efficiency but reduces flexibility (see e.g., Jolles & Crone, 2012; Crone & Dahl, 2012 for argumentation). Outcomes of such study designs are important for educational purposes: the aim of education programs fully exploit a student's potential and create opportunities for success in future society.

Several outcomes of the current thesis point toward the importance of knowledge in creative success. However, in today's world, where information is available and easily accessible, it is not the knowledge itself, but the capacities to *find* and *apply knowledge*, that are recognized as discriminative for success. Schools and other educational institutes incorporate these capacities and related skills, including 'creativity', into their programs as part of the so-called '21st century skills'. An important question arising, then, is to what extent do knowledge and the capacities to handle knowledge, support creative success? Insight into the role of these two separate aspects would be informative for education developers and, subsequently, could contribute to the optimization of individual and societal success (see Ward et al., 1999) in our ever changing *knowledge society*.

In conclusion, the current thesis provides an extended overview of the (dis)abilities and potential of creative thinking in adolescence. The results support the hypothesis that the adolescent brain is not only associated with (cognitive) immaturities, but also allows for increased flexibility in cognition and learning. Such flexibility is advantageous in a period that requires adaptive and explorative behavior, and reveals a potential for creative success. The current results, therefore, provide interesting directions for future research and have implications for the field of fundamental developmental cognitive neuroscience as well as for more applied educational purposes.

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Nederlandse Samenvatting

Creatief denken wordt gezien als één van de belangrijkste menselijke vaardigheden voor de 21e eeuw en dat is niet zonder reden. In onze huidige kennismaatschappij is continue innovatie van cruciaal belang. Informatie bases groeien en veranderen in een hoog tempo. Als gevolg hiervan worden competenties als flexibiliteit, ‘out-of-the-box’ denken, divergent denken en oplossingen genereren, meer gewaardeerd dan ooit tevoren; creatief denken en de ontwikkeling van deze competentie is belangrijker dan ooit. De huidige wetenschappelijke kennis van creatieve cognitie is echter beperkt en eerder onderzoek naar de ontwikkeling van creatieve cognitie geeft geen consistent beeld.

Verandert de mogelijkheid om creatief te denken gedurende de ontwikkeling in de late kindertijd en adolescentie, en hoe verandert dit? Welke neurale mechanismen zijn betrokken bij (veranderingen in) creatieve prestaties, en hoe (indien mogelijk) kan creativiteit worden verbeterd?

In dit proefschrift is getracht antwoorden te vinden op deze vragen. Onderzoek naar de creatieve ontwikkeling gedurende de adolescentie en jonge volwassenheid is schaars, terwijl adolescenten toch de innovators van de toekomst zijn. Uit studies in verwante onderzoeksvelden, zijn er aanwijzingen dat de adolescentie een cruciale periode is voor de ontwikkeling van belangrijke cognitieve vaardigheden (Casey, Jones & Hare, 2008; Steinberg, 2005) en dat deze ontwikkelingen zijn gerelateerd aan veranderingen in de structuur en functie van (met name prefrontale gebieden van) de hersenen van adolescenten (Luna, Padmanabhan & O’Hearn, 2010; Shaw et al, 2008). Het doel van dit proefschrift is om een beter inzicht te krijgen in de (1) de ontwikkelingstrajecten van verschillende aspecten van creatief denken, (2) de ontwikkeling van de onderliggende neurale processen en (3) de mogelijkheid om creatief denken in de adolescentie door middel van training te verbeteren. Om dit bereiken is een aantal studies uitgevoerd waarin verschillende aspecten van creatief denken getoetst zijn. In deze studies is er gekeken naar gedrag en naar de activiteit in de hersenen middels fMRI. Daarnaast is er binnen de studies gekeken naar de verschillen tussen leeftijdsgroepen, maar ook naar de effecten van training op de prestaties binnen een groep. Deze combinatie van studies biedt de mogelijkheid om een beter inzicht te krijgen in zowel leeftijds- als ervaringsgerelateerde effecten op creatief denken, in een periode die gekenmerkt wordt door essentiële structurele en functionele veranderingen van (met name de prefrontale gebieden van) de hersenen.

Theoretische achtergrond

Creativiteit wordt in het algemeen aangeduid als het vermogen ideeën, inzichten en oplossingen te genereren, die zowel origineel als uitvoerbaar zijn (bijv. Amabile, 1996; Sternberg & Lubart, 1996). Als zodanig moeten creatieve uitkomsten nieuw en ongebruikelijk, maar ook potentieel nuttig en relevant, zijn; originele maar onuitvoerbaar ideeën worden doorgaans beschouwd als vreemd, terwijl de ideeën die haalbaar, maar niet origineel zijn, worden gezien als alledaags en oninteressant.

Om de ontwikkeling van creativiteit te begrijpen, bouwt dit proefschrift voort op de ‘creatieve cognitie benadering’, die creatief denken interpreteert als zijnde inherent aan normale menselijke cognitieve functies (Ward, Smith, & Finke, 1999). Deze cognitieve benadering benadrukt de afhankelijkheid van fundamentele cognitieve functies, zoals werkgeheugen en executieve controle (Nijstad, De Dreu, Rietzschel & Baas, 2010) en voorspelt dat creatieve cognitie ontwikkelt in relatie tot deze functies.

Hoewel de exacte processen in de hersenen, die ten grondslag liggen aan creatieve prestaties nog ter discussie staan, is er een groeiende consensus onder wetenschappers uit de sociale en cognitieve (neuro) psychologie dat creatieve prestaties het resultaat zijn van (1) snelle, impliciete en associatieve verwerking en (2) opzettelijke, bewuste en logische verwerking van informatie (Chaiken & Trope, 1999). Deze algemene opvatting is verder ontwikkeld in het ‘*Dual Pathway to Creativity Model*’ (DPCM; De Dreu, Baas, Nijstad, 2008), waarin creatieve output wordt beschreven als het resultaat van (1) cognitieve flexibiliteit en (2) cognitieve persistentie. Cognitieve flexibiliteit maakt het mogelijk om bij het oplossen van problemen veel verschillende conceptuele categorieën aan te wenden, flexibel te schakelen tussen deze categorieën en een globale verwerkingsstijl met een brede focus toe te passen (Förster, Friedman & Lieberman, 2009). Cognitieve persistentie wordt daarentegen geassocieerd met gerichte en systematische inspanning, diepgaande verkenning van een relatief klein aantal cognitieve categorieën en een lokale verwerkingsstijl met een smalle focus (De Dreu et al., 2008). Er wordt aangenomen dat creatieve prestaties het product zijn van beide types verwerking, waarbij de verhoudingen van de bijdragen van de twee types afhankelijk is van de taak en het individuele functioneren.

In de afgelopen jaren hebben verschillende onderzoekers creatieve cognitie onderzocht met behulp van laesie studies en ‘*neuro-imaging*’ technieken, waaronder functionele Magnetische Resonantie Imaging (fMRI). Ondanks dat er verschillende resultaten zijn (Arden et al, 2010;

Dietrich & Kanso, 2010), is er consensus dat de laterale delen van de prefrontale cortex (PFC) betrokken zijn bij creativiteit. Dit frontale hersengebied wordt veelal geassocieerd met cognitieve controlefuncties en het coördineren van lagere orde (associatieve) hersengebieden (zie bijv. Miller & Cohen, 2001). Interessant is dat dit hersengebied nog aanzienlijk verandert tijdens de adolescentie (Mills & Tamnes, 2014).

De adolescentie (leeftijd van ongeveer 10 tot 20 jaar) wordt gekenmerkt door een periode van transformaties naar onafhankelijkheid en volwassenheid. Succesvolle ontwikkeling naar volwassen functioneren wordt geassocieerd met creatief denken en daaraan gerelateerde functies, zoals exploratie en cognitieve flexibiliteit. Exploratief gedrag is essentieel om een eigen identiteit te ontwikkelen en adolescentie is een periode waarin leren en aanpassen centraal staan. Dit zijn vaardigheden die flexibiliteit in denken en gedrag vereisen. Adolescentie is dus een periode waarin belangrijke veranderingen in creatieve capaciteiten te verwachten zijn.

Samenvattingen van de studies

In **hoofdstuk 2** is een uitgebreide gedragsstudie beschreven waarin de ontwikkeling van twee aspecten van het creatieve potentieel onderzocht zijn: Divergent denken en inzicht. In deze studie werden de proefpersonen, verdeeld over vier leeftijdsgroepen (12-13 jaar, 15-16 jaar, 18/19 jaar en 25-30 jaar), onderworpen aan meerdere testen, met als doel een beter inzicht te krijgen in de ontwikkelingstrajecten van de verschillende aspecten van creatief denken (divergent denken en inzicht). Deze tests waren gericht op verschillende domeinen (visueel en verbaal).

Divergent denken is het meest geteste aspect in creativiteitsonderzoek. Het wordt beschouwd als een belangrijk onderdeel van het creatieve proces en is voorspellend voor creatief succes (Kim, 2008). In ‘divergent denken taken’ wordt de proefpersoon gevraagd meerdere oplossingen voor een bepaald probleem te genereren. Bij dit type taken is er geen eenduidig correct antwoord (Guilford, 1967). Prestaties worden beschreven in termen van vloeïendheid (aantal antwoorden), flexibiliteit (aantal antwoord categorieën) en originaliteit. In **hoofdstuk 2** is divergent denken onderzocht aan de hand van twee verschillende taken: de ‘Alternatieve toepassingen taak’ (*Alternate Uses Task*; AUT), die divergent denken in het verbale domein meet, en de ‘Creatieve Aanleg Test’ (CAT), die divergent denken in het visuospatieële domein meet. In de AUT wordt proefpersonen gevraagd zoveel mogelijk alternatieve toepassingen te bedenken voor een object, bijvoorbeeld voor een baksteen. De resultaten van de AUT geven aan dat het vermogen om meerdere ideeën (vloeïendheid) uit verschillende begripscategorieën (flexibiliteit) in

het verbale domein te genereren al in de vroege adolescentie is ontwikkeld; er waren geen verschillen tussen de leeftijdsgroepen. De kwaliteit van deze oplossingen (originaliteit) is echter nog tot in de late adolescentie in ontwikkeling. Twee mogelijke verklaringen voor de gevonden verschillen in originaliteit van oplossingen zijn dat er (1) veranderingen zijn in verworven kennis, en / of (2) ontwikkelingen zijn van cognitieve processen, die flexibele coördinatie tussen associatieve en analytische verwerking ondersteunen (Christoff, Gordon, & Smith, 2009; De Dreu et al, 2010). Dit laatste is een vermogen dat zich ontwikkelt in de late adolescentie (Huizinga et al, 2006).

De resultaten voor creatieve prestaties op de ‘visuospatieële divergent denken taak’, de CAT, bieden een indirecte ondersteuning voor de eerste verklaring. Op deze taak scoorden mid-adolescenten relatief beter in vergelijking tot jongere adolescenten en jonge volwassenen. Succes op de CAT is relatief onafhankelijk van kennis. De CAT vereist daarentegen cognitieve functies, die nog in ontwikkeling zijn in de vroege adolescentie (Huizinga et al., 2006) zoals; (a) het genereren van en het switchen tussen representaties van gepresenteerde visuele informatie, (b) het toepassen van een set van regels en (c) het monitoren van eigen gedrag. Deze functies worden vaak geassocieerd met de werking van de prefrontale cortex (PFC).

Naast de ‘divergent denken taken’, werd een aantal ‘inzicht taken’ afgenomen. Deze taken hebben, in tegenstelling tot ‘divergent denken taken’, wel concrete correcte oplossingen. Om tot deze correcte antwoorden te komen is het nodig informatie te herstructureren en associaties te leggen tussen niet- of weinig-gerelateerde informatie (Förster, Friedman & Liberman, 2004). Creatief inzicht wordt daarbij gekenmerkt door (1) het hebben een ‘aha!’ ervaring bij het vinden van de juiste oplossing, (2) een impasse, een toestand van hoge onzekerheid over hoe verder te gaan, voorafgaand aan het vinden van de oplossing en (3) het niet of moeilijk kunnen herleiden hoe men tot de oplossing gekomen is.

In de studie die staat beschreven in **hoofdstuk 2** is een drietal ‘inzicht taken’ toegepast; de ‘*Gestalt Completion Task*’ (GCT; Eckstrom et al, 1976), de ‘*Snowy Picture Task*’ (SPT; Eckstrom et al, 1976) en de ‘*Remote Associates Task*’ (RAT; Mednick, 1962). De eerste 2 taken (GCT en SPT) meten creatief inzicht in het visuele domein terwijl de RAT inzicht meet in het verbale domein. De resultaten op de drie taken geven aan dat creatief inzicht (zowel binnen het visuele als verbale domein) zich nog ontwikkelt tot in de late adolescentie. Opvallend was dat de ontwikkelingstrajecten stapsgewijze (visueel) en gecurvde (verbale) patronen lieten zien. Deze ontwikkelingspatronen, die voor de visuele inzichtstaken in het bijzonder, zijn indicatief voor

kwalitatieve veranderingen van de onderliggende cognitieve processen (zie ook Uhlaas et al., 2009).

Samenvattend impliceren de resultaten in **hoofdstuk 2** dat er verschillende aspecten van creatief denken te onderscheiden zijn met afzonderlijke ontwikkelingspatronen. Daarbij geven de resultaten aan dat adolescentie een periode is van zowel creatieve ontwikkeling met onvolwassen prestaties (inzicht en verbaal divergent denken) als van creatieve mogelijkheden (visuospatieel divergent denken).

In **hoofdstuk 3 en 4** is de ontwikkeling van de neurale processen, die gerelateerd zijn aan creatief denken, onderzocht. **Hoofdstuk 3** gaat in op de ontwikkeling van creatief probleem oplossen in het visuospatieële domein en **hoofdstuk 4** beschrijft een onderzoek naar de ontwikkeling van verbale aspecten van creatief denken.

In **hoofdstuk 3** is gebruik gemaakt van de ‘Lucifer taak’ (*Matchstick Problems Task*; Guilford, 1967) om te onderzoeken welke hersengebieden betrokken zijn bij visuospatieel creatief probleem oplossen bij mid-adolescenten en jong volwassenen. Bij de ‘Lucifer taak’ moeten proefpersonen in gedachte de samenstelling van gepresenteerde lucifers veranderen naar een voorgeschreven doelplaatje. Om zo’n probleem op te lossen, moet een proefpersoon het mentale ‘beeld’ van de uitgangssamenstelling los kunnen laten (Guilford, 1967). Eerdere neuropsychologische en ‘*neuro-imaging*’ onderzoeken, die de ‘Lucifer taak’ of vergelijkbare taken gebruiken, laten zien dat de laterale PFC betrokken is bij het oplossen van dergelijke creatieve problemen (Goel & Vartanian, 2005).

In het onderzoek in **hoofdstuk 3** moesten adolescenten (15-17 jaar) en volwassenen (25-30 jaar) een ‘Lucifer taak’ uitvoeren terwijl hun hersenactiviteit gescand werd met behulp van fMRI. Daarnaast werden zij onderworpen aan de eerder gebruikte ‘visuospatieële divergent denken taak’ (*Creative Ability Task*; CAT) buiten de scanner (Kleibeuker et al, 2013b). Adolescenten scoorden beter dan volwassenen bij het oplossen van de opgaven van de ‘Lucifer taak’. Dit laat zien dat deze leeftijdsgroep in het voordeel is bij het oplossen van problemen waarvoor exploratief denken en het vermogen om te switchen tussen representaties nodig zijn. De ‘*neuro-imaging*’ resultaten geven aan dat de prefrontale hersengebieden betrokken zijn bij creatief denken. De resultaten laten verhoogde activatie in de linker laterale PFC gebieden zien tijdens het oplossen van de opgaven van de ‘Lucifer taak’. Een directe vergelijking tussen de beide leeftijdsgroepen laat hogere activatie in deze frontale gebieden zien bij adolescenten dan bij volwassenen. Daarnaast werd er een positief verband gevonden tussen prestaties voor het oplossen van opgaven van de ‘Lucifer

taak' en activatie in de linker Gyrus Frontalis Inferior (*Inferior Frontal Gyrus*, IFG), een gebied dat in eerder onderzoek is gerelateerd aan het switchen tussen representaties (Crone et al., 2006; Hirshorn & Thompson-Schill, 2006). Bovendien is er een positieve relatie gevonden tussen activatie in de rechter dorsolaterale pre-frontale cortex (DLPFC) en prestaties op de CAT. Personen die beschikken over betere visuospatiële vaardigheden, gebruiken hun rechter DLPFC dus meer tijdens het oplossen van creatieve problemen dan mensen met een slechte visuospatiële vaardigheden. De uitkomsten uit dit onderzoek ondersteunen de hypothese dat de adolescentie niet alleen een fase van onvolwassenheid is, maar ook een periode van versterkte PFC-activatie voor exploratief denken en handelen (Crone & Dahl, 2012).

In **Hoofdstuk 4** is wederom de 'Alternatieve Toepassingen Taak' (*Alternate Uses Test*; AUT) gebruikt om verbaal divergent creatief denken te onderzoeken. Bij dit onderzoek is ook gekeken naar de hersenactiviteit met behulp van fMRI. Eerdere onderzoeken bij volwassenen vinden relatief consistente betrokkenheid van (links) temporo-pariëtale gebieden, waaronder de Gyrus Angularis (*Angular Gyrus*; AG) en Gyrus Supramarginalis (*Supramarginal Gyrus*; SMG). Dit zijn gebieden die in eerdere onderzoeken gerelateerd zijn aan semantische verwerking (Arden et al, 2010; Dietrich & Kanso, 2010). Daarnaast laat een aanzienlijk deel van deze studies positieve relaties zien tussen PFC-activatie en creatieve prestaties (bijv. Carlsson et al, 2000; Chavez-Eakle et al, 2007; Gibson, Folley, & Park, 2009).

In het onderzoek in **hoofdstuk 4** is gekeken naar de hersenactiviteit bij het genereren van creatieve ideeën bij zowel adolescenten (15-17 jaar) als volwassenen (25-30 jaar). Kijkend naar de uitkomsten van de gedragsstudie uit **hoofdstuk 2** was het de verwachting dat de volwassen beter zouden scoren bij het genereren van creatieve ideeën dan de adolescenten. De volwassen groep kon ook significant meer alternatieve toepassingen bedenken voor alledaagse objecten (AUT) dan adolescenten. De fMRI resultaten zijn in lijn met eerdere studies en impliceren de betrokkenheid van temporo-parietal gebieden bij het genereren van creatieve ideeën. Interessant is dat problemen waarvoor *meer dan één* oplossing gevonden is (een kenmerk van divergent denken), leidden tot additionele activatie in de laterale PFC. Dit betekent waarschijnlijk dat het vermogen om meer ideeën te genereren (lees: divergent denken), ondersteunt wordt door cognitieve controlefuncties, zoals aandacht gerelateerde inhibitie en cognitieve flexibiliteit (zie bijv. De Dreu et al., 2012). Interessant is dat vergelijkingen tussen de leeftijdsgroepen aangeven dat er meer activatie van deze prefrontale gebieden te zien is bij volwassenen dan bij adolescenten. Een mogelijke uitleg voor de gevonden gedragsresultaten is dat adolescenten nog niet in staat zijn deze frontale gebieden

optimaal te activeren en dat als gevolg hiervan gerelateerde cognitieve controle processen nog niet op een volwassen niveau functioneren tijdens het genereren van creatieve toepassingen van objecten.

Dit in ogenschouw genomen, ondersteunen de fMRI resultaten in **hoofdstuk 3 en 4** het idee dat de laterale delen van de PFC betrokken zijn bij het genereren van nieuwe en complexe ideeën en oplossingen. Daarnaast onderschrijven de resultaten de complexiteit van de ontwikkeling van de PFC gebieden in de adolescentie, gegeven dat adolescenten, afhankelijk van de taak, zowel meer als minder prestatie- gerelateerde-activatie laten zien in deze gebieden tijdens creatief denken.

Om de ontwikkeling van creatief denken verder te onderzoeken is in de **hoofdstukken 5 en 6** onderzoek gedaan naar de effecten van simpele ‘creatief denken trainingen’ bij adolescenten. Training studies naar andere hogere cognitieve vaardigheden, zoals het werkgeheugen (Klingberg, 2010; Jolles et al, 2012), executieve controle functies (Karch & Kray, 2009; Zinke et al, 2012) en het oplossen van algebraïsche vergelijkingen (Qin et al. 2004), laten zien dat training een positieve invloed heeft op de prestaties en het functioneren van de hersenen tijdens de adolescentie.

In **hoofdstuk 5** is de uitgevoerde gedragstraining studie beschreven. Het belangrijkste doel van de studie is om te onderzoeken of creatief denken kan worden verbeterd door training. De studie is uitgevoerd bij adolescenten (13-16 jaar) en volwassenen (23-30 jaar) en er is getraind op het genereren van alternatieve toepassingen bij bestaande voorwerpen (AUT). Proefpersonen volgden gedurende twee weken één van de drie trainingsprogramma's: (1) bedenken van alternatieve toepassingen voor een object (experimentele conditie), (2) benoemen van standaard eigenschappen van een object (controle conditie) of (3) het switchen tussen twee taken (*global-local rule-switching*; controle conditie).

De resultaten gaven aan dat proefpersonen in het algemeen (ongeacht leeftijd en trainingsconditie) beter werden in het genereren van creatieve ideeën. Adolescenten verbeterden echter meer dan volwassenen. Daarmee impliceren de resultaten dat adolescenten ontvankelijker zijn voor training dan volwassenen. Dit is consistent met de hypothese dat de adolescentie een periode is van meer flexibiliteit in cognitie en leren (Crone & Dahl, 2012; Johnson & Wilbrecht, 2011).

In **hoofdstuk 6** zijn (divergent denken) trainingseffecten op neurale activiteit bij adolescenten onderzocht. Hiertoe voerden proefpersonen in de leeftijd 15/16 jaar voor én na een twee weken durende trainingsinterventie een aangepaste versie van de AUT uit in de scanner. Proefpersonen trainden (1) het genereren van alternatieve toepassingen (experimentele groep); of (2) het switchen tussen twee type taken (*global-local rule switch task*; controle groep). Deze trainingen waren vergelijkbaar met de trainingen uit **hoofdstuk 5**. Ook hier lieten de resultaten activatie van een temporo-parietal netwerk zien tijdens het genereren van creatieve ideeën. Test en hertest analyses geven aan dat de mate van activatie tijdens het generen van creatieve ideeën in deze gebieden relatief stabiel blijft over de tijd (voor en na training). De fMRI resultaten toonden daarnaast opnieuw de betrokkenheid aan van de laterale PFC bij creatieve prestaties. De veranderingen in de activatie van gebieden in de IFG en MFG zijn positief gerelateerd aan veranderingen in prestaties op de AUT (bedenken van alternatieve toepassingen voor objecten).

Conclusie en toekomstig onderzoek

Het doel van dit proefschrift was om meer inzicht te verkrijgen in de creatieve capaciteiten en potenties in de adolescentie en om te bepalen in welke mate deze gerelateerd zijn aan ontwikkelingen in de hersenen, met name in de laterale PFC. De resultaten onderschrijven de complexiteit van creatieve cognitie. Deze resultaten ondersteunen het idee dat bij creatieve prestaties, afhankelijk van het type taak en domein, verschillende cognitieve processen worden aangewend. Daar aan gerelateerd, heeft creatief denken een andere betekenis bij verschillende taken en domeinen. De studies in dit proefschrift richten zich met name op divergent denken en op inzicht. Ondanks dat divergent denken erkend wordt als essentieel en voorspellend voor creatieve prestaties (bijv. Kim, 2010; Nijstad et al, 2010), kunnen de resultaten niet zonder meer worden gegeneraliseerd. Daarnaast is er in dit proefschrift gebruik gemaakt van eenvoudige training paradigma's, om inzicht te verkrijgen in de trainbaarheid van creatief denken en prestaties in de adolescentie. Toekomstig onderzoek zou alternatieve training paradigma's kunnen toepassen zoals (1) het informeren van proefpersonen over de cognitieve processen die gerelateerd zijn aan creatieve prestaties, en/of (2) adaptieve designs die onderscheid maken in moeilijkheidsgraden van problemen. Beide typen designs zijn in eerdere onderzoeken effectief gebleken (zie Clapman, 1997; Scott et al., 2004). Een andere richting voor toekomstig onderzoek is het differentiëren in oplossingsstrategieën, bijvoorbeeld flexibele en persistente strategieën, om meer inzicht te krijgen

in de ontwikkeling en potenties van verschillende ‘cognitieve routes’ naar creatieve prestaties (zie *Dual Pathway to Creativity Model*; Nijstad et al., 2004).

Ondanks beperkingen in generaliseerbaarheid bieden de huidige bevindingen belangrijke inzichten in het functioneren van de hersenen van adolescenten, wanneer deze geconfronteerd worden met problemen, die vereisen dat er *out-of-the-box* wordt gedacht. Interessant zijn daarbij de verschillende ontwikkelingspatronen voor creatieve prestaties en gerelateerde activatie van laterale PFC gebieden voor verschillende creativiteitsproblemen. Deze bevindingen kunnen dienen als uitgangspunt voor het ontwerpen van neuro-cognitieve ontwikkelingsmodellen, die de complexiteit van de functionele hersenontwikkeling in de adolescentie onderkent. Dergelijke modellen kunnen nuttig zijn voor diverse educatieve doeleinden. Ze vergroten het begrip van hoe de hersenen van adolescenten informatie verwerken. Dit creëert op zijn beurt weer kansen om educatieve programma’s aan te passen aan de cognitieve capaciteiten van adolescenten en zo lesmateriaal en onderwijs verder te verbeteren.

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Curriculum vitae

Sietske Kleibeuker was born on November 1st 1979 in Rotterdam, the Netherlands. She graduated from 'Scholengemeenschap Augustinianum' (VWO) in Eindhoven in 1997. In 2002 she started her study Psychology at the University of Amsterdam where she received her BSc degree in 2005. In 2008 she completed the Research Master program in Psychology at the University of Amsterdam, where she obtained experience in brain imaging research ((f)MRI and EEG) and experimental design. From 2009 to 2015 she carried out her PhD research on the development of creative cognition in adolescence in the Brain and Development Lab at the Psychology department of the Leiden University, under supervision of Prof. dr. E.A. Crone and Prof. dr. C.K.W. De Dreu (University of Amsterdam).

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