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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.
Chapter 7  General Discussion

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 temporoparietal 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 temporoparietal 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 (Karbach 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
Chapter 7  General Discussion

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’ visuospatial 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 neurocognitive 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

152
Chapter 7  General Discussion

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.


