DIVERGENT AND CONVERGENT THINKING

INVESTIGATING UNDERLYING NEURAL MECHANSIMS AND THE SIGNIFICANCE FOR CREATIVITY AND INTELLIGENCE

Vom Fachbereich Sozialwissenschaften
der Rheinland-Pfälzischen Technischen Universität, Campus Kaiserslautern
zur Verleihung des akademischen Grades
Doktor rerum naturalium (Dr. rer.nat.)
genehmigte

Dissertation

vorgelegt von
Vera Eymann

Tag der Disputation:	Kaiserslautern, 18.06.2024
Dekan:	Prof. Dr. Michael Fröhlich
Vorsitzende/r:	Prof. Dr. Johannes Lenhard
Gutachter/in:	1. Apl. Prof. Dr. Daniela Czernochowski
	2. Prof. Dr. Thomas Lachmann

DE 386

Juni 2024

ACKNOWLEDGMENTS

“There is no use going back to yesterday, because I was a different person then.” – Alice
Alice’s Adventures in Wonderland by Lewis Carrol

My transformation from ‘yesterday to today’ was only possible because many people accompanied and supported me along the way. First and foremost, I would like to thank apl. Prof. Dr. Daniela Czernochowski and Prof. Dr. Thomas Lachmann for their supervision. Their expertise, support, feedback and encouragement had a major impact not only on the quality of my scientific publications but also on my growth on a personal level. Both have never failed to make me feel worth the effort they put into my guidance. Furthermore, I would like to express my gratitude to Dr. Ann-Kathrin Beck for accompanying me as Co-author, sharing her knowledge about time-frequency analysis and encouraging me, whenever I had lost my confidence. I hope, there will be more opportunities to work and laugh together in the future. I would also like to thank my Co-author Dr. phil. habil. Saskia Jaarsveld for her work in scoring the CRT and the fruitful scientific discourses while writing our manuscripts.

Special thanks to all of my colleagues and co-doctoral students, especially Maximilian Wolkersdorfer, Nils Beese, and Omar Jubran for scientific discussions, joint lunch breaks, entertaining conversations and especially their emotional support throughout the last four years.

Finally, I would like to thank my little family. Andreas, from the bottom of my heart, thank you for your constant support in every imaginable way. Thank you for believing in my abilities and dreams and for loving me throughout every happy and tough moment. Thank you for being my husband, my best friend and such an amazing father for our little daughter. Lilly, thank you for being such an awesome little person. Thank you for travelling to conferences with me and spending a significant amount of your first one and a half years of life at the lab. Thank you for making me smile every day.

I love you both.

“Genius is one percent inspiration and ninety-nine percent perspiration.”

– Thomas Edison

CONTENTS

REMARKS

This thesis includes three scientific publications that were completed within the scope of this dissertation. The first and the second investigation (i.e., Study 1 and Study 2) were conducted to assess divergent and convergent thinking beyond the influence of working memory-related activity in the visuo-spatial (Study 1) as well as the verbal knowledge domain (Study 2). Both are published in a peer-reviewed journal. The third publication is an Opinion Paper which discusses overarching results of Study 1 and Study 2, as well as a theoretical reflection on these results. This manuscript is currently submitted to a peer-reviewed journal.

- Chapter 7 (Study 1) is published as “Alpha oscillatory evidence for shared underlying mechanisms of creativity and fluid intelligence above and beyond working memory-related activity.” by Vera Eymann, Ann-Kathrin Beck, Saskia Jaarsveld, Thomas Lachmann, and Daniela Czernochowski (2022, in *Intelligence*). The labeling of the figures reflect the original as published according to the standards of the Journal *Intelligence*.

- Chapter 8 (Study 2) is published as “EEG oscillatory evidence for the temporal dynamics of divergent and convergent thinking in the verbal knowledge domain.” by Vera Eymann, Thomas Lachmann, Ann-Kathrin Beck, and Daniela Czernochowski (2024, in *Intelligence*). The labeling of the figures reflect the original as published according to the standards of the Journal *Intelligence*.

- Chapter 9 (Study 3) is submitted as “Reconsidering divergent and convergent thinking in creativity – A neurophysiological index for the convergence-divergence continuum.” by Vera Eymann, Ann-Kathrin Beck, Thomas Lachmann, Saskia Jaarsveld, and Daniela Czernochowski (*Creativity Research Journal*). The labeling of the figure was left in this work according to the standards of the Journal *Creativity Research Journal*.

LIST OF FIGURES

ABBREVIATIONS

ACC	anterior cingulate cortex
AI	artificial intelligence
ALE	activation likelihood estimation
ANOVA	Analysis of variances
APM	Raven’s advanced progressive matrices
AUT	Alternate Uses Task
BOLD	blood oxygen level dependent
CI	Confidence Interval
CRT	Creative Reasoning Task
CRT$_{con}$	Creative Reasoning Task (convergent part)
CRT$_{div}$	Creative Reasoning Task (divergent part)
CT	convergent thinking
DLPFC	dorsolateral prefrontal cortex
DT	divergent thinking
EEG	Electroencephalography
fMRI	functional magnetic resonance imaging
FPN	fronto-parietal control network
Gc	crystalized intelligence
Gf	fluid intelligence
Hz	Hertz
IFG	inferior frontal gyrus
IPL	inferior parietal lobe
ICA	independent component analysis
IQ	intelligence quotient
KΩ	Kiloohm
MFG	middle frontal gyri
ms	milliseconds

MTL	medial temporal lobe
P-FIT	Parieto-Frontal Integration Theory
PFC	prefrontal cortex
PPC	posterior parietal cortex
RAT	Compound Remote Associates Task
ROI	region of interest
RPM	Raven Progressive Matrices
SI-model	structure-of-intellect model
SPM	Standard Progressive Matrices test
STG	superior temporal gyrus
TMS	Transcranial magnetic stimulation
TPJ	temporoparietal junction
TTCT	Torrance Test of Creative Thinking
WEIRD	Western, Educated, Industrialized, Rich, and Democratic
WM	working memory
WMC	working memory capacity
µV	microvolt

italics = important word, term

‘word’ = keyword, new label introduced in the context of this dissertation

“quote” = literal quote

Chapter 1: INTRODUCTION

The fact that the human race has been able to become the cutting edge of evolution can be attributed to mainly two abilities, namely intelligence and creativity. While the first enables us to reason, solve problems, learn from experience, and think abstractly; the latter enables us to change our way of thinking and generate novel strategies for overcoming obstacles we face. It can be concluded that each aspect of our life in regard to innovation and scientific progress can be attributed to either intelligence or creativity, or as I will demonstrate in the course of this work: the interaction of both. For the scope of this work, the *structure-of-intellect model* by Joy Paul Guilford is of particular relevance as he introduced the idea that intelligence encompasses different dimensions of operations, products and contents (see Chapter 2.1). Within this model, divergent and convergent thinking are conceptualized as two distinct operations. Divergent thinking is defined as the production of a set of ideas in regard to a given problem, while convergent thinking encompasses deductive processes that lead to one single solution (Guilford, 1967).

In this dissertation, I will present a literature review on intelligence (Chapter 2.1) and creativity (Chapter 2.2). I will continue to introduce and specify the processes of divergent and convergent thinking (Chapter 3) and how both are assessed and researched within the scope of creative cognition (Chapter 4). As working memory (besides other related processes, such as cognitive control) are related to both, divergent and convergent thinking, I will highlight the role of working memory in this regard (Chapter 5). Furthermore, I will present a comprehensive overview on neurocognitive underpinnings and mechanisms of both divergent and convergent thinking, as well as on neural correlates of working memory (Chapter 6). Subsequently, I will introduce two investigations in which neural oscillatory activity of divergent and convergent thinking was investigated beyond their shared working memory-related activity, for the visuo-spatial (Study 1; Chapter 7) as well as the verbal knowledge domain (Study 2; Chapter 8). Finally, comparisons across both knowledge domains as well as further theoretical considerations are described in a theoretical paper (Study 3; Chapter 9). Following these investigations, I will provide a general discussion including impulses in regard to future directions (Chapter 10). Lastly, overarching results will be summarized in the conclusion (Chapter 11).

Chapter 2: INTELLIGENCE AND CREATIVITY

In this chapter, I will outline the beginning of the scientific investigation of intelligence and creativity. The main focus is put on the *structure-of-intellect model* by Guilford, which has implications for both, intelligence and creativity. Furthermore, it lays the foundation for the research on divergent and convergent thinking. While both have been investigated separately for a long time, I will discuss the relationship between the constructs of intelligence and creativity, also by highlighting the most important empirical findings.

2.1. Intelligence

*"*Intelligence is a very general mental capability that, among other things, involves the ability to reason, plan, solve problems, think abstractly, comprehend complex ideas, learn quickly and learn from experience. It is not merely book learning, a narrow academic skill, or test-taking smarts. Rather, it reflects a broader and deeper capability for comprehending our surroundings – 'catching on,' 'making sense' of things, or 'figuring out' what to do." (Gottfredson, 1997, p.13)

In the following paragraph, I will outline an overview on the historical development of intelligence research. The main focus hereby is put on Guilford's *structure-of-intellect model*, as well as the concept of *fluid intelligence*, proposed by Cattel and Horn. Hence, this overview is not conclusive, but outlines the most important milestones in regard to the research on intelligence.

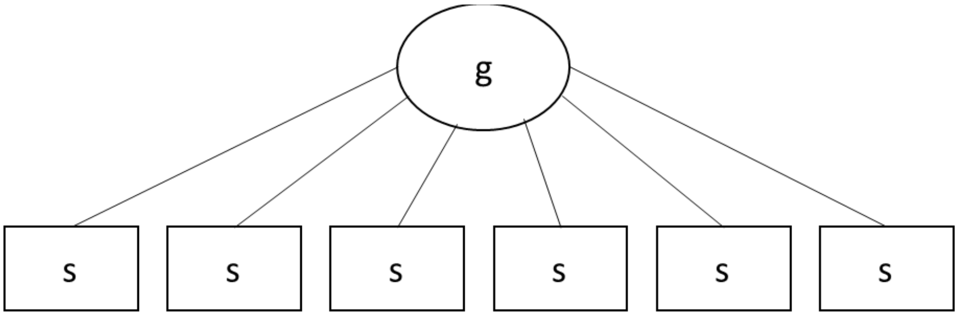
In the 19th century, Francis Galton (1822-1911), cousin of Charles Darwin, combined the idea of natural selection with the ideas of Adolphe Quetelet (1796-1874) about the normal distribution of certain social and behavioral characteristics. This led him to the idea that intelligence is not only normally distributed amongst the population, but it is also a heritable characteristic (Brody, 2004). To investigate individual differences based on intellectual abilities, he tested volunteers using a designated battery of tests of relatively basic cognitive functions, measuring auditory and visual discrimination but also reaction times (Brody, 2004). This work of Galton can be viewed as one of the starting points for a huge area of research on intelligence that continued for the last 200 years, making intelligence to one of the most investigated topics in the field of psychology (Stern & Neubauer, 2016). Inspired by Galton's work, James McKeen Cattell (1860-1944), who was a student of Wilhelm Wundt in Leipzig pursued this line of research by establishing more tests to measure individual differences in mental abilities. In his publication *Mental tests and Measurements* (Cattell, 1890), Cattell introduced measures of 10 different psychological functions, which he described as *mental tests*. Over the next years, a few other psychologists also started investigating individual differences in mental abilities, both in adults and children, still using rather simple cognitive tasks. The psychologist Alfred Binet (1857-1911), together with the physicist Théodore Simon (1873-1961) developed the first batterie to systematically test more complex cognitive functions in school children (see Siegler, 1992; Brody, 2004 for overviews). This test batterie included a variety of measurements for general complex cognitive functions and was used to determine if the administered intellectual performance of the child was appropriate for its age. The work of Binet and Simon included an innovative procedure to assess and classify general intelligence, though the test had some limitations. For example, when assessing gifted or talented children, the test was not suitable to distinguish sharply between the different scores of highly gifted individuals. Moreover, it lacked a theoretical foundation in terms of what general intelligence actually is and how reliable it can be assessed with different tasks of cognitive functions and further, how different sub-domains of general intelligence are related to another.

2.1.1 Hierarchical Models of Intelligence

Charles Edward Spearman (1863-1945) systematically compared measurements and results of cognitive tasks and recognized that most of the earlier studies did not systematically compare correlations between different cognitive functions. He observed positive intercorrelations between several measures of sensory-discrimination abilities with measures of academic achievement (Spearman, 1904). Spearman applied factor analysis, a statistical method he developed to reduce the observed variables to a small number of underlying latent variables (called *factors*). Using this method, he was able to support these postulations (Floyd et al., 2009) and developed a theory to explain the positive yet not perfect correlations. His explanation was the existence of a general intelligence factor (*g*, *general intelligence*) that can share intercorrelations with specific factors (*s*), which he recognized as a second specific source of variance (Brody, 2004; Floyd et al., 2009; see Figure 1). In his *two-factor theory* (Spearman, 1927), he assumes that g encompasses that part of general cognitive abilities that is involved in every mental operation, in contrast the s-factors are regarded as task-specific abilities (e.g., verbal, spatial) that share more or less variance with the g-factor, but do not share variance among other s-factors. According to this assumption, he arranged the s-factors based on the amount of shared variance (*loadings*) with the g-factor, hence creating a hierarchical model of intelligence. Since Spearman's postulation, "hundreds of studies have demonstrated that the general factor accounts for approximately 25-50% of variance shared by such tests – typically the largest percentage of any factor" (Floyd et al., 2009, p. 250). Furthermore, "many studies have demonstrated that scores representing the general factor (e.g., IQs) are strong predictors of representations of personal competence, such as academic success and job performance" (Floyd et al., 2009, p. 250).

Figure 1

Two-factor theory of cognitive abilities (Spearman, 1927)



Note. Every measurement captures a general factor (g), which is measured by and shares intercorrelations with a specific factor (s).

Although Binet's and Spearman's scientific approach to intelligence was vastly different (Binet observing it in the individual, and Spearman approaching it from a mathematical origin), both their work and theory influenced and guided the foundation for the research on intelligence in the 20th century and beyond.

In 1941, Raymond Cattell (1905-1998) introduced the idea of not only one, but two dichotomous factors of general ability, which he called *fluid* (*Gf*) and *crystallized* (*Gc*) intelligence (Cattell, 1963; Schonfeld, 1986). While Gc is regarded as a skill that is the result of prior learning, hence crystallized, Gf comprises the ability to adapt to new situations (e.g. in testing situations), where Gc skills cannot be applied (Cattell, 1963). In particular, Gf involves the capacity to solve novel problems, reasoning, and abstract thinking (Horn & Cattell, 1966) as well as perceiving relations among stimulus patterns, comprehending implications and drawing inferences from relationships (Davidson & Downing, 2000). Cattell further assumed that Gf is genetically determined and stable over time, while Gc depends on cultural habits and education, and thus is susceptible for modification over time. Consequently, he assumed Gf to decline over the adult span due to aging, whereas Gc was assumed to remain relatively stable over time (Brody, 2004). John Horn (1929-2006) extended Cattell's model in 1965 by adding four more abilities to the model, which were visual perception or processing (*Gv*), short-term memory (*short-term acquisition and retrieval, Gsm*), long-term storage and retrieval (*tertiary storage and retrieval*, *Glr*), as well as speed of processing (*Gs*; Schonfeld, 1986; Horn, 1968). With that, he admitted that multiple factors exist, similar to Thurstone's proposal (see next paragraph). Over the following years and even decades, Horn added more factors to the model such as auditory processing ability (*Ga;* Horn, 1968) but also decision speed and quickness in reacting (Schonfeld, 1986), ending up with an eight-factor model. Furthermore, within the model, the distinction is made between factors that represent broad abilities (higher order), and other factors that represent narrow abilities (lower order; Floyd et al., 2009). This hierarchical model is since been known as *Cattell-Horn Gf-Gc theory* (Davidson & Downing, 2000; Schonfeld, 1986).

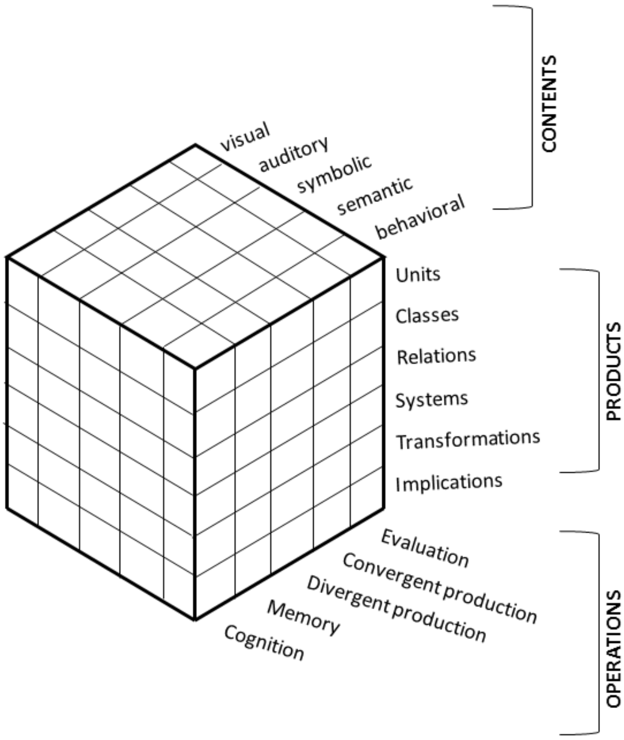
2.1.2 Non-hierarchical Models of Intelligence

In contrast to the hierarchical models of intelligence postulated by Spearman and Cattell, some researchers proposed non-hierarchical models of independent, specific cognitive abilities, as they were convinced that those better display the intercorrelations of different measurements for cognitive abilities. Louis Leon Thurstone (1887-1955) criticized Spearman's two-factor theory and instead proposed the existence of seven factors, which he named *primary mental abilities*: Comprehension, Fluency, Memory, Number, Reason, Space, and Speed (Thurstone, 1935; Floyd et al., 2009).

In 1967, Joy Paul Guilford (1897-1987) introduced his '*structure-of-intellect*'- (SI-) model (see Figure 2). In this model, which is a continuation of Thurstone's model of 'Primary Mental Abilities' (Thurstone, 1935), he described intelligence in a three-dimensional taxonomy of *operation*, *product* and *content* which in turn allows him "to classify any test with respect to its position on the[se] dimensions" (Brody, 2004, p. 20). In his model, he distinguishes five operations: evaluation, convergent production, divergent production, memory, and cognition. These operations can be applied in five further contents, which are figural, symbolic, semantic, and behavioral. These contents in turn, lead to six products: units, classes, relations, systems, transformation, and implications (Guilford, 1977; Brody, 2004). By combining all of these different operations, contents and products, Guilford described first 120 different abilities implicated by his model (Guilford, 1956). Hence, every mental task involves three dimensions of operation, content, and product (Sternberg & Grigorenko, 2001).

Figure 2

Structure-of-intellect model (Guilford, 1977)



Note. The 1977 model contains 150 abilities by combining each of the three dimensions (i.e., contents, products, and operations. Adapted from Sisk, 2021.

Each of these three dimensions does “contain a set of mutually exclusive categories that apply uniformly throughout the classification and each independent factor of intelligence will be found to fall into place in one distinct cross-classification in the model” (Caroll, 1968, p.250). Guilford also stated that these factors are independent, which lead other researchers to test these assumptions and demonstrated evidence against that (e.g., Horn & Knapp, 1973). Over a few decades, Guilford further refined and modified his model which led him to increase the number of factors first to 150, by sub-dividing the figural content into visual, and auditory contents (Guilford, 1977) and later to 180 (Guilford, 1983; see

Sternberg & Grigorenko, 2001 for overview) and further, allowing the addition of higher order structures in the end.

However, under empirical evaluation, on a regular basis, Guilford saw the necessity of rotating the factors to reduce complexity in the factor solution as the unrotated matrix revealed the existence of a general factor. By rotating the factors this general factor diminished in the rotated solution giving "support for a group of factors in the absence of a general factor" (Sternberg & Grigorenko, 2001, p.311). This issue, Guilford (1974) himself called "the most serious weakness" (p.498) of his SI model. Over the years, Guilford tested various methods to rotate the factor matrix, both orthogonal and oblique (Guilford, 1974; Barron & Harrington, 1981; Carroll; 1968; Sternberg & Grigorenko, 2001), however, the resulting factors were hard to interpret and, even worse, the results varied in regard to the methods used to rotate them (Sternberg & Grigorenko, 2001). Only using subjective rotation, "by rotating the principal components into maximum congruence with a target matrix specific to [the] theory" (Sternberg & Grigorenko, 2001, p. 311) resulted in adequate factor loadings according to the theory. At the same time, this procedure is highly problematic as it "forces the data towards a better fit to theory than is justified by the data" (Guilford, 1974, p.499).

In sum, under empirical evaluation hierarchical models of intelligence offered greater potential for explaining variance between individuals in terms of their cognitive abilities, and also for predicting a variety of outcomes such as academic and professional success. Despite of these setbacks, Guilford's SI model in particular gained prominence in the research field of creativity.

John Carroll (1993) provided a comprehensive review and integration of different theories and studies regarding intelligence and cognitive abilities. Hence, he reanalyzed more than 460 relevant data sets using factor analysis and subsequently summarized and integrated these results into his *three-stratum theory of cognitive abilities* (Carroll, 1993; Floyd et al., 2009; Stern & Neubauer, 2016). It features a hierarchical model of three layers (strata) and further integrates various theories on cognitive abilities, such as Thurstone's and Spearman's theory (Stern & Neubauer, 2016). His model describes intelligence as a set of mental abilities at different levels of generality (Floyd et al., 2009). *Stratum III* is the level of general factor (essentially Spearman's g-factor), which also accounts for the correlations among the stratum II abilities. *Stratum II* in turn, the level of broad abilities encompasses eight cognitive abilities such as for example Gf, Gc, processing speed, and general memory and learning (Carroll, 1993; Schonfeld, 1986). *Stratum I* holds a large number of narrow abilities, such as reading comprehension, number facility, length estimation and others (Schonfeld, 1986; Floyd et al., 2009). Bypassing the major differences between both, the Cattell-Horn and Carroll's model (see Schonfeld, 1986 for overview), McGrew and colleagues (1997) proposed an integrated theory, known today as the *Cattell-Horn-Carroll* (*CHC*) *theory*. This theory forms the theoretical basis for the most widely used intelligence tests (see Schonfeld, 1986 for overview) and is regarded as the "state-of-the-art structural concept of intelligence" (Stern & Neubauer, 2016, p. 17).

After more than hundred years of investigating human intelligence, it still can be seen as one of the central research areas in modern psychology (Stern & Neubauer, 2016). However, there is still no universally recognized and accepted definition of what intelligence actually is and encompasses. Or, to put it in Hans Eysenck's (1986) words: "Discussions concerning the theory, nature, and measurement of intelligence historically have resulted more in disagreement than in agreement, more in smoke than in illumination" (Eysenck, 1986, p.1). Instead, leading experts in the field agreed on the description of intelligence of Gottfredson (1997; Stern & Neubauer, 2016) as outlined in the beginning of this chapter. Although this description does not meet the standard of a universal definition, it nonetheless encompasses a precise description of the different mental demands that humans need to cope in their day-to-day life and at the same time, it lists different mental abilities that can be represented in intelligence tasks (Stern & Neubauer, 2016).

2.2 Creativity

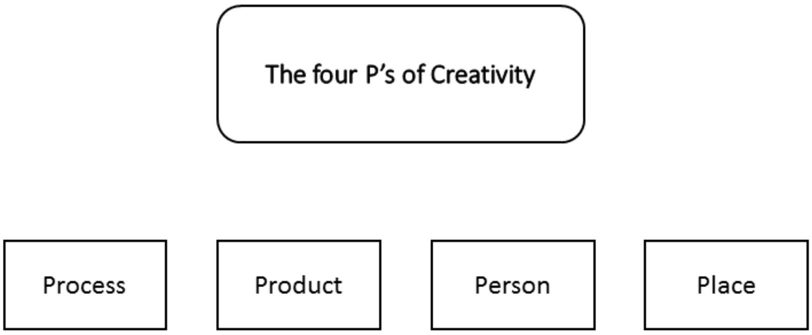
“Creativity is the general term we use to describe an individual’s attitude to, ability for, and style(s) of creative thinking that leads to a structured and intentional activity, mental and/or physical. This activity may be personal and/or collective, occurs in a specific space–time, political, economic, social, and cultural context, and interacts with it. The creative activity aims to realize the creative potential of the creator(s) and leads to tangible or intangible product(s) that is (are) original, useful, and desirable at least for the creator(s). The creative product(s) should be used for ethical and constructive purposes.” (Kampylis & Valtanen, 2010; p. 204).

In the following paragraph, I will outline an overview on the historical development of creativity research. I will mainly focus on different attempts to approach the construct of creativity. Hence, I begin with introducing the model of Rhodes (1961) and his perspective on creativity, as his proposal is not only widely accepted throughout the scientific community, but it also helps to order the different viewpoints on creativity for the reader of this work. Following that, I will introduce scientific models of the creative thinking process and discuss how creativity can be measured using psychometric assessments.

Creativity involves innovation and is defined as the ability to move beyond what is already known (Ghiselin, 1952; Wertheimer, 1945/ 1968). It is also defined as a capacity that allows the generation of ideas that are original (i.e., statistically rare; Runco & Jaeger, 2012; Dietrich & Kanso, 2010) and appropriate/effective (Runco & Jaeger, 2012) or satisfying (Abraham, 2023). Furthermore, creativity can be defined as the ability to generate an idea for an open-ended problem (i.e., a problem with an infinite amount of possible solutions; Getzels & Csikszentmihalyi, 1976; Guilford, 1967). However, especially those early attempts to define creativity failed to exactly conceptualize from which standpoint creativity should be investigated. What exactly encompasses creativity? The creative individual (e.g., the artist), the creative output (e.g., the artwork) or the creative act in and of itself (e.g., the process of creating)? James M. Rhodes (1916-1976) was the first to systematically separate those entities by providing his conceptualization within the term creativity, known as the *four P’s of Creativity* (Rhodes, 1961; see Figure 3).

Figure 3

Four P's of Creativity model (Rhodes, 1961)



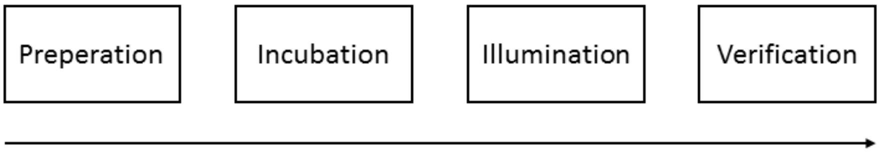
Note. Adapted from Abraham, 2018.

Rhodes (1961) distinguished process, product, person and place within this model. *Product* refers to the investigation of the creative output, either material, such as artwork, or immaterial, such as ideas (Abraham, 2018). Rhodes (1961) also recognized different types of ideas, which he associated with different intensities of creative effort. However, today there is only one theory that focuses exclusively on the product (i.e., the creative contribution; Sternberg et al., 2001) without regarding process, person, or place (Abraham, 2018), which is the *propulsion model of creative contributions* (Sternberg, 1999). The next p in Rhodes' (1961) model belongs to *person*, which involves the investigation of the person that is creative (Abraham, 2018). To be more precise it involves, among others, the investigation of personal traits, habits, personality, intellect, or behavior, but also physical characteristics and value-systems (Rhodes, 1961). This approach enables a researcher to differentiate highly vs. average creative individuals, and also internal or environmental factors that may boost or impede creativity within the individual (Abraham, 2018). Rhodes (1961) stated that *place* refers to the situation and environmental factors in which creative behavior occurs. Research in this field not only investigates the concrete creative situation, but also social or cultural factors that play into it. The last p, for *process*, refers to a mental activity or mental operations, such as for example motivation, learning, or thinking that are involved in creative thinking. This is in accordance with the *Creative Cognition* approach, which assumes that creativity arises from an interplay of several (ordinary) cognitive sub-processes (Mastria et al., 2021), rather than 'the' one creative process (Abraham, 2018). Moreover, the creative process is hypothesized to involve (depending on the research tradition) either successive phases or components (i.e., divergent and convergent thinking; Guilford 1968, 1975; Abraham, 2018; Runco & Acar, 2012; Cropley, 2006). Until today, different approaches to study creativity can be grouped into these four categories (Abraham, 2018; Plucker & Makel, 2010).

Stages within the creative process were described in the *Wallas model* (Wallas, 1926) as well as the *Geneplore model* (Finke, Ward, & Smith, 1996). In the Wallas model (1926), the creative thinking process is described via four consecutive, but discrete stages which are *Preparation*, *Incubation*, *Illumination*, and *Verification* (see Figure 4). In this outline, the creative process starts with an intense exploration of the problem that is presented, followed by a period where no conscious effort is given towards solving the problem. Then, in the third phase a sudden insight enlightens the person how the problem can be solved. During the last phase, the proposed solution is deliberately tested and verified. This model highlights the importance (or even necessity) of an uncontrolled insight/illumination/aha-moment for the creative process (Runco, 2012), assuming that creativity does not involve a deliberate, more trial-and-error based approach. Furthermore, it stretches the assumption that only one outstanding idea is generated and evaluated during this process. However, creative thinking can also involve the generation of several ideas (i.e., fluency of ideas, see Chapter 3.1 for details), which are subsequently narrowed down to the best fitting solution.

Figure 4

Wallas' model of creativity (Wallas, 1926)

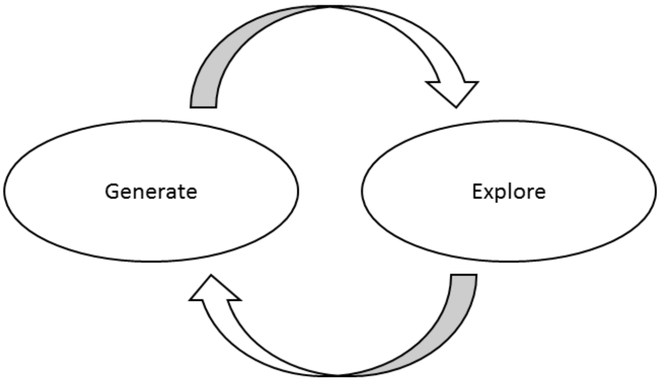


Note. The model includes four consecutive stages of Preparation, Incubation, Illumination, and Verification.

The Geneplore model (Finke et al., 1996; see Figure 5) provides an alternative idea in regard to the phases underlying the creative thinking process. It distinguishes two consecutive phases: *gene*ration and ex*plor*ing, hence *gene – plore* (Abraham, 2018). During the generation phase, the idea is generated in, depending on the task, an either more conceptually focused or more ambiguous, simple or more complex manner (Abraham, 2018). During the explorative phase, the generated idea is evaluated in regard to its applicability and usefulness to the solution (Finke et al., 1996; Abraham, 2018). These two stages are repeated until the reach of a solution.

Figure 5

Geneplore model (Finke, Ward, & Smith, 1996)



Note. The model includes two consecutive phases of generation and exploration, which are repeated multiple times to reach the solution.

The focus of this thesis are cognitive processes underlying creative thinking (i.e., divergent and convergent thinking; i.e. deductive thinking to arrive at a single, correct solution; Guilford, 1967). Hence, in the following I will introduce key assumptions that creativity research has accumulated over the last 150 years in regard to divergent and convergent thinking. Details on the other aspects of creativity, namely the person, place or the product are outside the scope of this thesis and will not be discussed in detail (for further information see Abraham, 2018).

2.2.1 From the Gods to the Laboratory

The interest in creative minds emerged long before the actual research on creativity started. It can at least be tracked back to the ancient Greeks (Niu & Sternberg, 2006; Weiner, 2000; Becker, 1995). While creativity was regarded as a human capacity (e.g. Aristotle; Ludwig, 1995), at the same time it seems to go beyond a mere human capability and was even linked to mystical beliefs (Rothenberg & Hausman, 1976; Sternberg & Lubart, 1996) or the gods by Plato ("divinely inspired"; as cited in Murray, 1996, p.24). This mystical and spiritual understanding of the creative process culminated in the idea of *radical creativity* in philosophy (Rothenberg & Hausman, 1976) which enables the “creatio ex nihilo” (out of nothing; Rothenberg & Hausman, 1976; p. 4), assuming that the creative mind creates otherworldly products without any prerequisites (Sternberg & Lubart, 1996).

Even the consideration of creativity being innate to humans let to the idea that creativity was linked to some type of unusual mental processes, such as mental illness (Runco & Albert, 2010; Ludwig, 1995; Eysenck, 2003) or at least a spiritual process (Sternberg & Lubart, 1996; Sternberg, 1988). This ‘paranormal’ view on creativity and creative individuals for a long time made it hard to approach the phenomenon from a scientific perspective.

One of the first contributions for the empirical investigations in creativity was brought, again, by Galton. As already mentioned before (ct. Chapter 2.1), he believed in the heredity of genius, which he described as “ability that was exceptionally high, and at the same time inborn” (Galton, 1870; p. VIII). Following his convictions, he explored and described individuals with great natural endowment and their close relatives, in particular public personalities among the military, aristocracy, politicians, judges as well as scientists, poets and artists (Galton, 1870). However, his aim was not only the description, but rather promoting the idea of higher birth rates of such individuals (i.e., ensuring that outstanding parents breed outstanding children; Becker, 1995; Bullough et al., 1981). Despite his effort, later re-analyses of his work revealed that there was little to no evidence regarding the hereditary factors for the determination of creativity (Bouchard et al., 2009; Bramwell, 1948). Moreover, Bullough and colleagues (1981) concluded in regard to their aggregated data: “Contrary to the assumptions of Galton, however, significant intellectual and creative achievers did not usually have children who also achieved.”, and stated that “there is […] more to achievement than genetic inheritance” (Bullough et al., 1981, p. 109). With that being said, Galton’s unchallenged contribution was that he grounded genius to humankind, away from the divine and with that as a potential distributed among the population (Runco & Albert, 2010).

A few years later, with the beginning of the 20th century, Binet (see Siegler, 1992; Brody, 2004 for overviews) investigated general intelligence by testing different sub-domains. One of these sub-tests also included items to provoke imagination (Brody, 1992), similarly of what today would be considered as an open-ended, multiple solution test (Becker, 1995) or divergent thinking (i.e., generation of multiple solutions from available information; Runco, 2007; Runco & Albert, 2010; Barron & Harrington, 1981; see Chapter 3).

Guilford (1950), in his APA Presidential Address guided the public's gaze to the relevance of the psychometric research on creativity (Kozbelt et al., 2010; Sternberg & Lubart, 1996), which he claimed to be massively understudied (Runco, 2014; Sternberg & Lubart, 1996; Guilford, 1950) as "fewer than two tenths of one percent of the entries in Psychological Abstracts up to 1950 focused on creativity" (Sternberg & Lubart, 1996, p. 678). In the following years, the interest of the scientific community in creativity somewhat grew, which even resulted in the foundation of research institutes dedicated to the psychological investigation of creativity (Isaksen et al.,1993). Despite these efforts, creativity remained a rather marginalized topic in psychology until the 1990's, as analyzed by Sternberg and Lubart (1996), who researched the number of entries referring to 'creativity', 'divergent thinking', and 'creativity measurement' in the *PsycLIT database*. According to their analysis, about .5 percent of these entries cover creativity (Sternberg and Lubart, 1996). Furthermore, the authors observed a similar ratio regarding psychology textbooks for introductory lectures, which is in vast contrast to what can be observed regarding intelligence, which has constantly received attention in research and academic contexts without questioning (Sternberg and Lubart, 1996). As of today, creativity research, though considerable progress in certain areas, did not develop in line with other psychological research areas (Dietrich & Kanso, 2010; Sternberg & Lubart, 1996). However, in the light of advancing technologies such as artificial intelligence (AI), a rise of creativity-driven economies (Howkins, 2002) as well as the democratization of education and culture (see Lee, 2022 for overview), creativity centered research has been gaining more momentum in recent years (see Mejia et al., 2021 for overview).

2.2.2 Psychometric Assessment of Creativity

When assessing creativity, it is critical to consider the scale of creativity that is about to be investigated (Abraham, 2018). Hence, creativity research in regards to the creative individuum (i.e., person; Rhodes, 1961) focuses on two levels: everyday/ little-c creativity, and exceptional/ Big-C creativity. Kaufman and Beghetto (2009) further refined this idea by adding two more stages to this model. Hence, creativity can be scaled into four different levels: mini-c (personal interpretations, everyday creativity), little-c (“creative engagement beyond the intrapersonal space”; Abraham, 2018, p. 28), Pro-c (higher level of professional expertise with evidence of significant creative accomplishments; Abraham, 2018), and lastly Big-C (genius-level creativity; Kaufman & Beghetto, 2013, 2009). However, the same researchers later observed that Pro-c and little-c essentially merged into one construct (Kaufman & Beghetto, 2013). Hence, for the scope of this work, I will continue to exclusively differentiate between little-c and Big-C creativity, the first encompassing everyday-levels of creativity and potentially measurable via creative cognition tasks, the latter encompassing creativity on a monumental scale that cannot be assessed by psychometric tests but rather only occurs in domain-specific contexts (e.g., art).

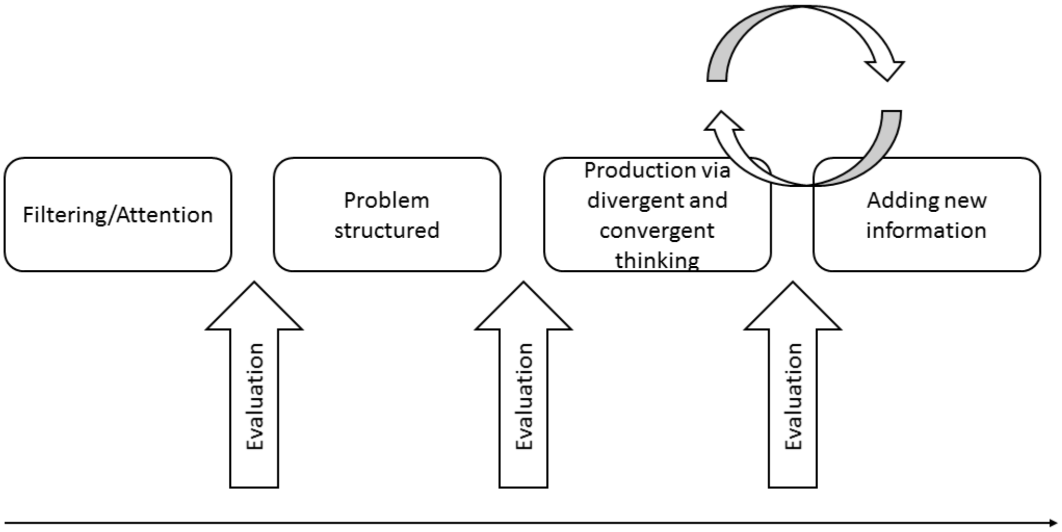
Guilford had a long-lasting influence on the field of psychometric investigation of creativity. In this field of research, however, there has long been disagreement regarding the alignment and basic assumptions of research. Hence, Torrance (1979) noted that there is a division within the field. He claimed that some researchers regard creativity in the light of a personality phenomenon, which is predicted by stable personality traits of a person and therefore measuring these traits will reliable measure creativity (cf. Big-C and little-c creativity; Kaufman and Beghetto, 2009). A related line of argumentation surrounds the discussion of mental disorders in relation to creativity (see Kinney & Richards, 2019; Silvia & Kaufman, 2010 for overviews). At the same time, other researchers focus on a psychometric assessment of the underlying processes of creativity and argue that creativity is based in “[…] cognitive processes of rational and logical thinking […]” (Torrance, 1979, p. 360), that can be assessed by psychometric measurements (ct. Creative Cognition). However, the concern how to objectively score creative outcomes (i.e., products) has been a major issue since the first standardized psychometric creativity tests were invented (Dietrich & Kanso, 2010; Plucker & Makel, 2010; Cropley & Maslany, 1969). In contrast to the domain of intelligence, where performance can be measured using reaction times or number of correct responses, for example, creativity research focuses on innovation and effectiveness, which cannot be quantified so easily.

Guilford’s SI model was already described as a three-dimensional taxonomy (Brody, 2004) of operation, product and content (ct. Chapter 2.1). According to Sternberg and Grigorenko (2001), creativity is represented in several aspects in later versions of Guilford’s model (e.g., Guilford, 1975). Regarding the operations proposed in his model, especially divergent productions have been of major interest for creativity research during Guilford’s time and beyond (Dietrich & Kanso, 2010; Kozbelt et al., 2010; Cropley, 2006; Sternberg & Grigorenko, 2001). Divergent thinking was described by Guilford (1968) as a process of “searching around” (Guilford, 1968, p. 8). It is further characterized by the generation of multiple solutions or answers from available information (Runco, 2007; Cropley, 2006; Sternberg & Grigorenko, 2001; Guilford, 1967) by thinking in many different directions. Convergent thinking, on the other hand involves a more deductive approach to derive at the single, correct solution, without any ambiguity (Cropley, 2006; Guilford, 1968). Both divergent and convergent thinking were and are until today, oftentimes regarded as opposites or even conflicting or competing processes (Cropley, 2006; Eysenck, 2003; Getzels & Jackson, 1962), as divergent thinking has mostly been tied to creativity, whereas convergent thinking has oftentimes been associated to Gf (Eymann et al., 2022). However, Guilford (1968) also highlighted the importance of convergent thinking for the creative process. I will specify divergent and convergent thinking as well as their interplay in detail in the next chapter (see Chapter 3).

Guilford (1967) also proposed a model of creative problem solving involving divergent and convergent thinking (see Figure 6). In this framework, creative problem-solving encounters four stages: (1) *filtering*, in which attention is directed towards the problem; (2) *cognition*, in which the problem is captured and structured; (3) *production*, in which divergent and convergent thinking are used to generate ideas; and (4) *cognition*, in which new information (internal or external; Lubart, 2001) is obtained and considered to refine or modify the idea generation stage (Guilford, 1967). The last two stages are repeated several times until the solution is reached. Lastly, a process of evaluation always occurs when transitioning from one stage to another in order to monitor the progress (Lubart, 2001).

Figure 6

Model of creative problem solving (Guilford, 1967)



Note. The model includes four consecutive stages. The last two stages (i.e., production via divergent and convergent thinking; adding new information) can be repeated in several cycles in order to find the solution. An evaluative process occurs at each transition between stages.

Guilford himself was exclusively interested in the process of divergent or convergent thinking, less in the quality of the outcome (i.e., solutions or ideas that were generated during these processes; Runco, 2010). However, the research on divergent thinking provides measurement tools for both, the process and the product.

2.3 The Relationship between Intelligence and Creativity

My elaborations on intelligence and creativity have highlighted several historical and current overlaps of the two constructs and their exploration. This indicates that both, intelligence and creativity have been intertwined from the very beginning. Yet there is no final consensus about their relationship amongst researchers. Guilford’s model has dominated the discussions about the relationship of creativity and intelligence, as it understood creative thinking as part of intelligence (Barron & Harrington, 1981; Torrance, 1979). However, as of now, creativity has received much less attention in psychology research. While intelligence tests are widely used as a psychological assessment tool, creativity tests are rarely used in that regard (Jaarsveld et al., 2010, 2012; Sternberg & Lubart, 1996). One of the reasons for that could be that traditional intelligence tests do not or rarely include creativity measurements. And this in turn might be because both intelligence and creativity are rather complex constructs und underlie a broad spectrum of different conceptualizations (Frith et al., 2021a; Plucker & Makel, 2010; Sternberg et al., 2001).

Another intelligence model that accounts for creativity as part of intelligence is the Cattel-Horn-Model (Cattell, 1963), more precisely the sub-dimension of Gf as the ability to solve novel problems and understand relationships apart from prior knowledge (Giancola et al., 2022; Cho et al., 2010; Barron & Harrington, 1981; Brody, 2004; Horn & Cattell, 1967). Moreover, Gf enables individuals to abstract from prior experience, imagination, generation of new ideas – all of which also encompass creativity (Giancola, 2022; Frith, 2021a, Abraham, 2018; Beaty et al., 2014; Silvia, 2008; Sligh et al., 2005). On the other hand, creativity involves the generation of ideas that are not only novel, but also adaptive (Silvia et al., 2009; Sternberg & O'Hara, 2000) and appropriate/effective (*effective novelty*; Cropley, 2006; Runco & Jaeger, 2012), implying the need for an analytic consideration of environmental factors. This increases the likelihood that intelligence and creativity are somewhat interrelated constructs. However, Sternberg & O'Hara (2000) pointed out that there are at least five different views on how this relationship is depicted in the scientific community: 1. Creativity is a subset of intelligence; 2. Intelligence is a subset of creativity; 3. Intelligence and creativity are overlapping sets; 4. Intelligence and creativity are essentially the same thing (coincident sets); 5. Intelligence and creativity bear no relation at all to each other (disjoint sets; Sternberg & O'Hara, 2000; p. 611).

The most prominent theory regarding a possible relationship of creativity and intelligence is the *Threshold Theory* (Jauk et al., 2013; Runco & Albert, 1986), which predicts a positive correlation between creativity and intelligence upon a cutoff of approximately an IQ level of 120, and unrelated beyond (Jauk et al., 2013; Runco & Albert, 1986). It states that there is a minimum level of intelligence necessary for creativity (Runco, 2014, 2008), implying that "[…] above-average intelligence is […] a necessary, but not sufficient condition" for creative achievement (Jauk et al., 2013, p. 213). This theory regards creativity as a subset of intelligence, hence suggesting a correlation of both, although not perfectly (Sligh, 2005). However, even empirical findings in favor of the threshold theory only partially support this view. Moreover, in recent years more evidence has been proposed against the theory (Silvia, 2008; Slight et al., 2005; Runco & Albert, 1986) or at least it weakens the sharpness of the proposed relation (Welter et al., 2016; Sligh et al., 2005). On the other hand, there have been several studies that observed the role of other factors such as executive functions, cognitive control, or working memory moderating the intelligence-creativity relationship (e.g., Giancola et al., 2022; Frith et al., 2021b; Cancer et al., 2023; Benedek et al., 2011; De Dreu et al., 2012), impeding the disentanglement of the underlying constructs even more. Other studies showed that the proposed correlation exists between intelligence and divergent thinking, rather than creativity. By using divergent thinking as a proxy for creative behavior, researchers observed a more detailed relationship (fluency vs. flexibility; e.g., Shi 2017; Dietrich & Kanso, 2010).

In conclusion, the prior elaborations illustrate that the association between creativity and divergent thinking, as well as Gf and convergent thinking is oversimplified (Eymann et al., 2022; Dietrich & Kanso, 2010, Runco, 2008). Hence, it seems reasonable to investigate both constructs (i.e., creativity and Gf) on a deeper level by assessing their underlying processes (i.e., divergent and convergent thinking). Although divergent and convergent thinking can at most approximate creative performance and Gf respectively, this process related approach allows us to investigate those constructs in a more finetuned manner by observing their underlying cognitive processes (ct. Creative cognition).

Chapter 3: DIVERGENT AND CONVERGENT THINKING

Divergent and convergent thinking as cognitive operations were introduced by Guilford (1967). He defined divergent thinking as the production or generation of a set of solutions or ideas to a stimulus (Runco, 2007; Guilford, 1967) and specified 24 distinct types of divergent thinking in his model by combining divergent productions (operation) with each type of the six products, and four contents (Jonathan & Makel, 2010). Hence, the testing battery for divergent productions consists of tests within each of the four types of contents, such as semantics, visual, or symbolic; and those divergent productions can be expressed in six different products, such as for example relations, systems or classes (Jonathan & Makel, 2010; Sternberg & Grigorenko, 2001).

In the following, I will provide definitions for both, divergent and convergent thinking and go on to discuss how both interact within creative cognition as well as how both relate to other cognitive processes. Finally, I will discuss how the creative process relies on a specific combination of divergent and convergent thinking, by presenting different proposals regarding their interplay.

3.1 Divergent Thinking

Divergent thinking involves the generation of multiple solutions or answers by thinking in many different directions (Runco, 2007; Cropley, 2006; Sternberg & Grigorenko, 2001; Guilford, 1967). It can further be characterized as the generation of multiple ideas or solutions for an open-ended problem or as problem solving in an ill-defined problem space (Fink & Benedek, 2014; Benedek et al., 2014; Jaarsveld et al., 2012; Dietrich & Kanso, 2010; Getzels & Csikszentmihalyi, 1976; Guilford, 1956). From this perspective, the creative process first consists of the generation of several ideas. This is achieved by activating a maximum number of mental representations that only share weak associative connections to the given stimulus (i.e., divergent thinking; Mölle et al., 1999*)*.

Prototypical tests on divergent thinking, as for example the Alternate Uses task (AUT; Guilford et al., 1978) or the Torrance Test of Creative Thinking (TTCT; Torrance, 1974) evaluate these generated ideas in terms of fluency, flexibility, and originality (see for example Lee & Therriault, 2013; Runco & Acar, 2012; Dietrich & Kanso, 2010; Silvia et al., 2009; Cropley, 2006; Kim, 2006; Guilford, 1967). *Fluency* refers to the number of produced ideas, hence a fluent individual produces a large number of ideas (Runco & Acar, 2012; Dietrich & Kanso, 2010). *Flexibility* quantifies the number of categories of ideas (Dietrich &Kanso, 2010); in other words: it shows how diverse the ideas are in terms of conceptual categories (Runco & Acar, 2012). *Originality* describes how novel or statistically rare an idea is (Runco & Acar, 2012; Runco & Jaeger, 2012; Dietrich & Kanso, 2010). One further possibility to evaluate divergent productions is *elaboration*, which describes if and how long the person followed an associative pathway while generating ideas (Runco & Acar, 2012). However, the mere production of original or flexible ideas does not ensure creativity (Cropley, 2006): In order to be labeled creative, ideas also have to be effective (Runco & Jaeger, 2012). Moreover, without the premises of effectiveness, significance or usefulness, actual creativity cannot be distinguished from mere novelty (Runco & Jaeger, 2012; Cropley, 2006). As an example, randomly pressing keys on a piano cannot be labeled as creative (see also “pseudocreativity”; Cattell & Butcher, 1968, p. 271 or “quasicreativity”; Cropley, 2006).

Divergent thinking can further be described as a top-down process that relies on executive functions (such as memory retrieval, verbal fluency and also Gf; for example, Beaty et al., 2014; and working memory; for example, Lee & Therriault, 2013; Takeuchi et al., 2011) as well as associative processes (Frith et al., 2021a; Beaty et al., 2014; Mednick, 1962). That means, divergent thinking consists of several underlying mental sub-processes (Dietrich & Kanso, 2010). These underlying processes regulate the access to semantic knowledge and inhibit salient, but non-creative ideas (Frith et al., 2021a). Furthermore, executive functions such as cognitive control or working memory can be assumed to underlie divergent thinking, to keep information in an active state in order to compare and evaluate possible solutions or ideas (Benedek et al., 2011; De Dreu et al., 2012) or to follow an associative chain (Lee & Therriault, 2013; Runco & Acar, 2012). Furthermore, some studies reported a serial order effect during divergent productions (Kraus et al., 2019; see Wang et al., 2017 for overview), where responses are generated less frequent, but become more original over time. This observation further argues for divergent thinking as a multi-dimensional rather than a single cognitive process.

But is it possible to create a valid creative output by exclusively using divergent thinking? In such a case, creative ideas would emerge ‘out of the blue’ without any prerequisites or deductive process of evaluation and analysis. Based on the example of several famous creative individuals, Cropley (2006) described two mechanisms how creativity based on purely divergent productions ('effortless creativity', Cropley, 2006, p.392) can occur. The first one, he called *Luck and Chance* in which by chance one "happy combination of ideas occurs" out of several variations ("blind variations"; Campbell, 1960 cited in Cropley, 2006, p. 392). He further describes a sub-classification proposed by Austin (1978, in Cropley, 2006), who proposed four types of happy combinations: blind chance (the creator was not involved in the process, he was only there at the right moment), serendipity (the creator stumbles upon the solution while not looking for it), the luck of the diligent (the creator is working hard on the solution when suddenly an unexpected combination turns out to be the solution), and lastly self-induced luck (knowledge and dedication create the circumstances in which the sudden breakthrough occurs; see Cropley, 2006). However, at least the last two types (i.e., the luck of the diligent and self-induced luck) require a certain amount of preparation or circumstances that are not at all related to luck (Cropley, 2006). The second purely divergent production that results in actual creativity, Cropley (2006) called *Intuition*. This idea is related to the stage model of Wallas (1926; ct. Chapter 2) where the creative process is characterized by four consecutive steps of Preparation, Incubation, Illumination, and Verification. In this model, *Illumination* refers to a sudden insight or intuitive thought that comes through and brings the novel idea. Although, from the first glance these sudden breakthroughs could be assigned to divergent thinking only, upon closer inspection it becomes clear that still many prerequisites (e.g. specific knowledge, dedication, preparation) need to be met in order for the creative moment to occur. Or in the famous words of Louis Pasteur: "[…] chance favors only the prepared mind." (Pasteur, 1854, Lecture).

It is important to notice though that divergent thinking is not the same as creativity, mainly because divergent productions are not always creative as there are circumstances in which divergent productions are only hypothetical, but not necessarily creative (e.g., thinking about the future; Abraham, 2018). This is why divergent thinking tasks cannot directly measure creativity, they can only be used as proxy to estimate creative thinking (Shi 2017; Dietrich & Kanso, 2010) or as an index of creative potential (Runco, 2017). However, this practice has also earned critics in the past. One reason is that convergent thinking also can lead to creative outcomes, for example though the systematic elimination of alternative ideas (Dietrich & Kanso, 2010) or systematically acquiring information and testing of ideas (Cropley, 2006) as it is usual in more scientific or technical frameworks.

While divergent thinking is oftentimes considered as mental basis for creativity, convergent thinking often is assumed to be the mental basis for intelligence (Guilford, 1967; Cho et al., 2010). However, more recent research suggests the necessity for both, divergent and convergent thinking during the creative process (Wang et al., 2023; Giancola, 2022; Cropley, 2006; Dietrich & Kanso, 2010, Runco, 2008), claiming the association between creativity and divergent thinking as well as between Gf and convergent thinking as being oversimplified (Eymann et al., 2022). This raises the question how to exactly differentiate divergent and convergent thinking in terms of their roles for and in terms of their relationship within the creative process.

3.2 Convergent Thinking

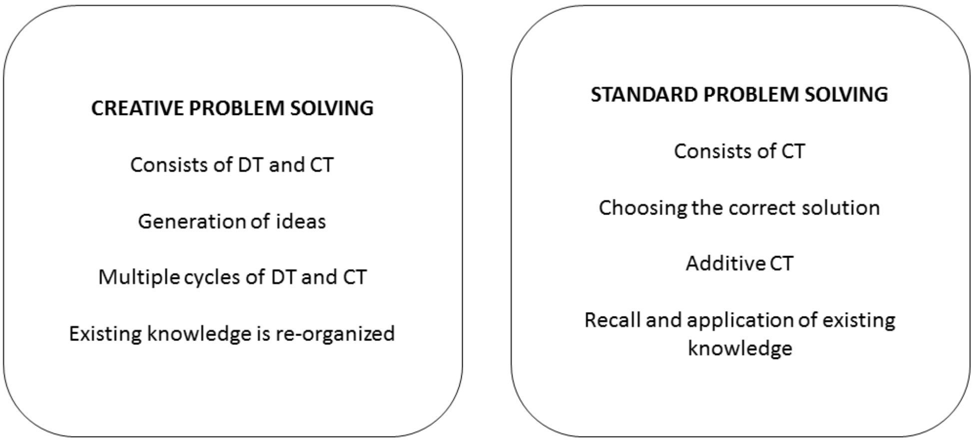
Convergent thinking is often conceptualized as the counterpart of divergent thinking as it involves deductive processes to arrive at a final, single solution which is either correct or incorrect (Lee & Therriault, 2013; Cropley, 2006; Mölle et al., 1999; Guilford, 1967). Hence, there is no room for ambiguity, answers can either be correct or incorrect (Cropley, 2006). This in turn makes it obsolete to evaluate convergent answers as elaborately as with divergent thinking tasks. Furthermore, sometimes the correct answer is directly presented in convergent thinking tasks among other non-correct options, for example in Raven’s Advanced Progressive Matrices (Raven et al., 1998a; see also Chapter 9 for overview). As convergent thinking requires for example accuracy, logic and even domain specific knowledge (Cropley, 2006), convergent thinking tasks are typically used to assess Gf (e.g., Raven’s Advanced Progressive Matrices; Raven et al., 1998a). This link between convergent thinking and Gf is characterized by strong relations of convergent thinking scores to measurements of Gf (Cortes et al., 2019). Lastly, convergent thinking places emphasis on “accuracy, meaning, sense, significance, or interestingness” (Cropley, 2006, p. 391), which in the end also encompasses the definition of creative ideas not only being original, but equally important: appropriate (Runco & Jaeger, 2012; Dietrich & Kanso, 2010).

Cropley (2006) hence coined the term *effortful creativity* (Cropley, 2006, p. 392) to elaborate the specific role of convergent thinking in creativity and how it contributes to a creative outcome as a result of a prior preparation. Cropley (2006) emphasizes the importance of the prepared mind and with that the significance of (domain specific) knowledge and skills, both acquired via convergent thinking in turn. Although "recognizing a solution when one occurs is key to creativity" (Ghiselin, 1955), Cropley (2006) further elaborates that several prerequisites need to be met in order to capitalize this moment: general and specific knowledge, as well as certain specialized skills and effort. This, according to Cropley, shows that the prepared mind is rather "convergent in nature" (Cropley, 2006, p. 394). Furthermore, the observation of individual's outstanding creative achievements shows that, generally speaking, such individuals first undergo a period of earlier learning and education (i.e., relevant knowledge and skill accumulation; Ericsson, 1999; Ericsson & Lehmann, 1996). Moreover, the same authors proposed the idea that creative individuals tend to have their peak in creative power after about a decade of intense preparation (*The 10-Year Rule of Necessary Preparation*; Ericsson & Lehmann, 1996, p. 278). In a related line of argumentation, some researchers suggest a U-shaped relationship between pre-existing knowledge and creativity insofar that both, extremely high (great expertise) and extremely low (ignorance) levels of pre-existing knowledge prevent creativity (i.e., effective novelty; Cropley, 2006). But even beyond the sheer accumulation of prerequisites for the creative outburst, convergent thinking processes also play a major role within the creative ideation process (i.e., idea evaluation and selection; see also Runco & Jaeger, 2012; Dietrich & Kanso, 2010; Getzels & Csikszentmihalyi, 1976; Smilanski & Halberstadt, 1986; Smilansky, 1984). Hence, convergent thinking contributes to the creative process by transforming "mere novelty into effective novelty" (i.e., actual creativity; Cropley, 2006, p.393) by critically evaluating the products of the divergent thinking process. Furthermore, Cropley (2006) argues that for creativity, divergent thinking followed by convergent thinking "(…) is the ideal result." (Cropley, 2006, p.399). Additionally, declarative and procedural knowledge (i.e., knowledge of facts and skills) as well as motivation can additionally influence creative thinking (Runco & Chand, 1995)

This raises the question how exactly creative and non- or less creative processes differ. Guilford (1967, p. 312), who viewed both as categories of problem solving, concluded "(…) something creative about all genuine problem solving" – not specifying which exact subprocesses are present in which type of problem solving (i.e., creative, less creative, or non-creative; Lubart, 2001). A few years later, Mumford and colleagues (1991) elaborate four differences between creative and non-creative processes (see Figure 7). The first difference is that creative processes involve problem solving in an open problem space (i.e., ill-defined problem; Mumford et al., 1991). These problem spaces are characterized by no clear specification of the goal, as well as the information and resources available during the problem-solving process (Mumford et al., 1991). The second difference is that, in contrast to standard problem solving (i.e., closed problem spaces), the creative process requires a generation of a new, rather than choosing the one correct solution out of a range of already given solutions. Thus, the creative process involves both, divergent and convergent thinking, whereas standard problem solving only involves convergent thinking (Mumford et al., 1991). The third difference is that creative problem-solving demands "(…) multiple cycles through multiple stages of divergent and convergent thinking" (Mumford et al., 1991, p. 95; see also Lubart, 2001; Basadur, 1995), while in standard problem solving there is no reason to generate and evaluate different possible solutions to this extent. Fourth, in contrast to non-creative processes where existing knowledge is solely recalled and applied, in creative problem-solving existing knowledge needs to be re-organized and re-combined (Mumford et al., 1991; Lubart, 2001).

Figure 7

Differences between creative and standard problem solving (Mumford et al., 1991)



Note. Abbreviations: divergent thinking (DT), convergent thinking (CT).

This elaboration further indicates that creative cognition does not exclude, but actually heavily relies on convergent thinking. While in standard problem-solving convergent thinking is sufficient, in the creative thinking process however, divergent thinking can be seen as necessary condition, whereas convergent thinking corresponds to a sufficient condition (Eymann et al., 2024). Furthermore, we can conclude that *effortless creativity* (i.e., divergent thinking only without convergent thinking; Cropley, 2006) is the exception, while *effortful creativity* (i.e., including divergent and convergent thinking; Cropley, 2006) can be assumed to be the norm.

3.3 The Relationship between Divergent und Convergent Thinking

The vast majority of successful creative productions can be assumed to be a product of a successful combination of divergent and convergent thinking. The next question that arises is: how do divergent and convergent thinking exactly work together within the creative process? According to Cropley (2006), there are three possibilities on how divergent and convergent thinking complement each other within the creative process. (1) It is possible that convergent thinking precedes divergent thinking insofar as it sets the requirements (e.g., accumulation of relevant knowledge/ skills etc.) for effective divergent thinking. This approach in turn can be subdivided into at least four categories of *Pre-Requisite models* (Cropley, 2006), which are *the summation model* (i.e., divergent and convergent thinking are additive in the sense that they complement or even compensate each other's limitations; see also Sowden et al., 2015 for overview), *the threshold model* (i.e., a certain level of convergent thinking is necessary for effective divergent thinking, above this threshold divergent and convergent thinking are positively correlated; see also Zhu et al., 2019), *the channel model* (information can only reach the system responsible for divergent thinking by a channel/ pathway provided by convergent thinking), and lastly, *the capacity model* (convergent thinking dictates the level of information that reaches cognitive systems and divergent thinking is then applied to this information; Cropley, 2006). (2) Neither divergent nor convergent thinking impact the other ('*Style models'*; Cropley, 2006; see also Cancer et al., 2023; Zhang et al., 2020; ct. *Dual pathway model* in Nijstad et al., 2010, discussed in Chapter 6). Instead, both rely on a specific, higher-order ability that involves the utilization of specific processes, for example processing and storing of information, forming abstract, general associations, and the like. The outcome of this process (creative or non-creative) depends on how this higher order-ability is used and with that, the difference between divergent and convergent thinking is “qualitative, rather than quantitative” (Cropley, 2006, p. 399; see De Vries & Lubart, 2019; Zhang et al., 2020 for neurophysiological evidence). (3) In Wallas’ four stage model (Preparation, Incubation, Illumination, and Verification; Wallas, 1926), both divergent and convergent thinking are required for creativity, although they do not need to be present at the same time during the process. Moreover, they are assumed to alternate depending on the particular phase of the process (Cropley, 2006; Cortes et al., 2019). Some authors even suggest that divergent and convergent thinking “serve complementary functions in the creative process” (Lee & Therriault, 2013, p. 307).

In the case of scientific creativity, which involves the generation of hypotheses and experiments as well as the final drawing of conclusions (Sternberg et al., 2020), evidence has been found supporting the threshold model. Zhu and colleagues (2019) observed that convergent thinking has a threshold effect on divergent thinking performance. The authors hence concluded that convergent thinking moderated the role of divergent thinking in scientific creativity. Divergent thinking predicted scientific creativity performance in participants high in convergent thinking (Zhu et al., 2019). However, the authors also stressed that scientific creativity does not correlate with daily creativity, and furthermore, their findings can potentially vary between knowledge domains. Hence, the exact interplay between divergent and convergent thinking in other creativity domains is still a subject of debate.

To conclude, the creative process involves the generation of ideas, which then need to be selected and evaluated based on their ‘fitting’ to the desired outcome (Campbell, 1960; Ellamil et al., 2012; Jaarsveld & van Leeuwen, 2005). The models described above agree that creativity does not only involve divergent thinking (i.e., idea generation), it also requires convergent processes to fulfill the demands of creative problem solving (i.e., evaluation and selection; see also Guilford, 1967; Getzels & Csikszentmihalyi, 1976; Smilanski & Halberstadt, 1986; Smilansky, 1984; Runco, 2010). It is noticeable that in recent years, researchers have concluded that instead of following a singular, fixed sequence of phases, it is much more plausible that the creative process is recursive, in the sense that it is a more dynamic and reiterating process (Zhang et al., 2020; Jaarsveld et al., 2012; see Lubart, 2001 for overview). However, the exact interplay of divergent and convergent thinking in creative cognition remains to be established.

Chapter 4: INVESTIGATING DIVERGENT AND CONVERGENT THINKING

In the following chapter, I will describe how divergent and convergent thinking can be measured by specific tasks. Hence, I will first introduce three important features when it comes to assessing both divergent and convergent thinking. These features include the problem space, domain knowledge (or expertise), and the knowledge domain. Furthermore, I will introduce the verbal and visuo-spatial tasks that were used in our studies to investigate divergent and convergent thinking across different knowledge domains. Lastly, I will discuss important issues and limitations when using these tasks and also, when assessing divergent and convergent thinking in general.

4.1 Problem Space, Domain Knowledge, and Knowledge Domain

Creativity is oftentimes described with a focus on problem-solving in open-ended (i.e., ill-defined) problem spaces (see for example Jaarsveld & Lachmann, 2017; Runco, 2014; Benedek et al., 2011; Jaarsveld et al., 2010; Mumford, 1991; Getzels & Csikszentmihalyi, 1976; Guilford, 1967). While *problem* can be defined as “a situation with a goal and an obstacle” (Runco, 2014, p. 15), *problem space* refers to the “degrees of freedom” (Jaarsveld & Lachmann, 2017, p.1) that are available to solve the problem. Hence, the less defined the constraints of the problem are, the broader the cognitive search path is going to be and vice versa. In this regard, divergent thinking is elicited by open-ended problems (i.e., more degrees of freedom), whereas convergent thinking is elicited by closed-ended problems (i.e., less degrees of freedom). With this logic, divergent thinking tests encompass open, while convergent thinking tests encompass closed problem spaces to assess one or the other. However, some researchers do not agree with the view that creativity is (a kind of) problem solving, but argue that in contrast problem solving is (a kind of) creativity. The reason is that there are artistic performances for example, that cannot easily be viewed as an attempt to solve a problem but more as self-expression of the artist (see Runco, 2014 for overview). In the end, it also depends on the definition of the problem, as problems can vary in their concreteness in regard to the solution. For example, generating alternate uses for a brick is much more concrete to the problem as an artistic expression to compose and perform a song to the problem (such as childhood trauma or loss; see Jones et al., 1997; or illness; see Reynolds, 2004). However, the latter also can be seen as an attempt to heal, by lively remembering and finally release the trauma, referred to as "abreactive catharsis" by Csikszentmihalyi (1988; cited in Runco, 2014, p. 15; Runco, 2015).

As already discussed, especially Big-C creativity is (through convergent thinking) inseparably linked to knowledge, more specific: domain-specific or expert-knowledge (Kozbelt et al., 2010). In the following, I will elaborate more on the relevance of both, expertise (i.e., domain knowledge) and knowledge domain for divergent and convergent thinking and the systematic investigation of both processes.

The term *domain knowledge* refers to knowledge, including declarative, procedural, or conditional knowledge a person possesses about a particular field of study (Alexander & Judy, 1988; Alexander, 1992). Undeniable is that there are various domains in which creativity occurs, for example areas such as artistic (visual), performance, artistic (verbal), or science (see Kaufman et al., 2009 for overview). This raises the question if creativity is domain specific rather than domain general. Or in other words: is a scientifically creative person also creative in other domains or is creativity bound to a specific domain? If we take domain-specific knowledge or expertise as pre-requirement for creativity (Mumford, 1991; Cropley, 2006; Ericsson, 1999; Ericsson & Lehmann, 1996), it is much more likely that creativity is domain specific. In fact, evidence goes towards that especially Big-C creativity might be domain specific (Abraham, 2018; Said- Metwaly et al., 2017). For example, a highly skilled composer can potentially also produce creative outcomes in poetry, as it is the same (verbal) artistic domain. However, it is rather unlikely that the same composer also engineers a high-tech medical device. The reason is that domain knowledge provides the base on which creative ideas can grow. Furthermore, only domain knowledge enables the identification of an idea as creative vs. pseudocreative (Cropley, 2006). Therefore, Big-C creativity has to be assessed through domain-specific measures (Abraham, 2018). On the other hand, to assess little-c creativity, researchers have used rather domain-general assessments, that can be mainly subdivided in verbal vs. figural forms (Abraham, 2018; Kaufman & Baer, 2004). However, Frith and colleagues (2021a) stated that a lack of domain-generality in divergent thinking tasks explains frequent observations that show a lack of consistency between real-world creative contributions and creative productions assessed by these tasks. Furthermore, for the same reason, divergent thinking tests have limited validity as they have only a limited capacity to represent the construct of creativity comprehensively (Said- Metwaly et al., 2017; Diakidoy & Spanoudis, 2002). By putting the focus on the underlying processes of creativity (i.e., divergent and convergent thinking), rather than on the person (ct. The Four P's of Creativity; Rhodes, 1961) the question if creativity is domain-specific or not moves into the background in favor of another question: what is the role of the knowledge domain in divergent and convergent thinking?

Generally speaking, *knowledge domain* "represents disciplines or fields of study organized by general principles" (Jaarsveld & Lachmann, 2017; p.6) and with that determines the type of stimuli that are presented in divergent or convergent thinking tasks (e.g., verbal stimuli such as words). Hence, the knowledge domain is important for the assessment of these processes and the generalizability of the obtained results. For example, Lubart (2001) stated that it is not only possible that differences in tasks elicit different creative processes (i.e., different tasks in different knowledge domains), but that there might also be differences in processes within the same knowledge domain (for example "writing a novel or a sonnet", Lubart, 2001, p. 304). Hence, it is crucial to account for the knowledge domain when assessing and even more, when comparing divergent and convergent thinking (as done by Eymann et al., 2022; Eymann et al., 2024; Zhu et al., 2019; Jaarsveld & Lachmann, 2017; Jaarsveld et al., 2010). When contrasting divergent and convergent thinking (or creativity and Gf, respectively), the problem space differs due to the specific requirements for cognition (i.e., operating in open vs. closed problem space; Jaarsveld & Lachmann, 2017). Furthermore, oftentimes these tasks are based on entirely different experimental designs. Some convergent thinking tasks require participants to identify logical relations for figural stimuli, whereas some divergent thinking tasks involve the (written) generation of ideas in regards to objects. Hence, these convergent and divergent thinking tasks operate neither within the same problem space nor the same knowledge domain. If the knowledge domain is not constant for both tasks (for example the divergent thinking tasks operates in the figural, while the convergent thinking tasks operates in the verbal knowledge domain), no meaningful comparison of those processes is possible. Hence, it is crucial to assess both processes within the same knowledge domain while solely the problem-space (i.e. open vs. closed) differs between them (Jaarsveld & Lachmann, 2017; Jauk et al., 2012; Jaarsveld et al., 2010).

In the following, two divergent and convergent thinking tasks used in Study 1 and Study 2 are described. Furthermore, I will elaborate how, by choosing to contrast these tasks, the knowledge domain was kept constant across the tasks to meet the premise to only vary the problem space. The goal was to compare divergent and convergent thinking within the same knowledge domain (i.e., visuo-spatial or verbal) in well- and ill-defined problem-spaces, respectively. Finally, some limitations in relation to the tasks presented are discussed.

4.2 Visuo-spatial Tasks: Creative Reasoning Task and Raven's Advanced Progressive Matrices

The Raven's Advanced Progressive Matrices test (APM; Raven, Raven, & Court, 1998a) is a nonverbal standard test of Gf for adults with above-average intellectual abilities that requires convergent thinking. It compromises 48 items in total, presented in two sets. In the APM Set I, participants are presented with 36 items in total. Each item consists of nine geometric patterns arranged in a 3 × 3 matrix. Eight cells of this matrix contain a figure composed of one or several geometric components. These eight figures form a logical pattern, both row- and column-wise. The ninth cell of the matrix is left empty. During the task, participants are asked to choose the one correct solution out of eight presented alternatives that completes the matrix in a logical way (i.e., multiple choice). Despite the APM being a clearly visuo-spatial convergent thinking task, some studies (for example Carpenter et al., 1990; Chen at al., 2017; Srivastava et al., 2023) have provided evidence that the APM items can be solved using different strategies, encompassing visuo-spatial strategies, verbal analytic strategies, both, or neither. Furthermore, it has been argued that the visuo-spatial items require a Gestalt approach, while the verbal-analytical strategy encompasses a more descriptive and rule-based approach (see Srivastava et al., 2023 for overview). These findings show that also within the APM, convergent thinking might differ due to different strategies that participants apply in order to solve the task. Furthermore, using those different strategies has been observed to influence both neural patterns of activation (Chen at al., 2017) and eye movement (Srivastava et al., 2023; Carpenter et al., 1990). To keep the overall testing time within an acceptable range for the participants, it is common praxis to shorten the APM, by imposing a time limit of 15 or even 10 minutes (see for example Unsworth & Spillers, 2010; Li et al., 2021). The APM is scored based on correct vs. incorrect responses. Hence, convergent thinking during APM occurs within a well-defined problem space, in which participants infer logical relations of a set of geometric figures.

Creative reasoning encompasses the specific processes in which divergent and convergent thinking fulfil mutually supportive and complementary roles in order to solve a creative problem (Jaarsveld et al., 2010; Jaarsveld et al., 2012). The creative reasoning task (CRT; Jaarsveld et al., 2010; Jaarsveld et al., 2015) is based on the work of Smilansky (1984), who introduced a task in which participants were asked to generate their own Raven matrices within a problem finding task. Hence, the CRT assesses divergent and convergent thinking within the same open problem space and the same task. It requires participants to create a 3×3 matrix of logically connected geometrical patterns. However, in contrast to the APM, participants generate a well-defined problem rather than solving it. To accomplish this task (the version used in Jaarsveld et al., 2015 and Eymann et al., 2022), participants are handed a form-sheet that contains a rectangular field on the top where participants are asked to draw the components that they want to use (i.e., Toolbox), as well as an empty 3x3 matrix (i.e., Row 1, Row 2, and Row 3; please refer to Figure 10 in Chapter 7) where they are asked to draw the components with logical relations. Creating matrices in the CRT involves generating the components of the geometrical figures as well as thinking about the logical relations of the patterns (Jaarsveld et al., 2012; Jaarsveld et al., 2015). The beginning of each trial (Toolbox, Row1) requires mostly divergent thinking (i.e., idea generation), whereas towards the end of each trial (Row 2, Row 3) the task requires more convergent thinking (i.e., assembling components based on logical relations). The individually created matrices are rated using two sub-scores. The first sub-score *Relations* (i.e., *Rule* in a prior version; Jaarsveld et al., 2010) refers to an assessment of the logical complexity of the produced geometric pattern and is hence considered to quantify convergent thinking. The second sub-score *Components and Specifications* assess originality, fluency, and flexibility (i.e., traditional evaluations of divergent thinking) and hence, is considered to quantify divergent thinking (Jaarsveld & Lachmann, 2017; Jaarsveld et al., 2012, 2010). Hence, in CRT divergent thinking starts in an ill-defined problem space that becomes successively more well-defined as participants move forward with the task, so that convergent thinking (towards the end of each item) is assessed in a rather well-defined problem space.

4.3. Verbal Tasks: Alternate Uses Task and Compound Remote Associates Task

The Compound Remote Associates task (RAT; Mednick, 1962) is one of the most widely used convergent thinking tasks (Cortes et al., 2019; Japardi et al., 2018; Lee & Therriault, 2013; Lee et al., 2014; see Wu et al., 2020 for overview). In the RAT, participants are presented with three, seemingly unrelated words and are instructed to deduce the third word as a compound to the other three words. For example, participants are shown the three words AGE – MILE – SAND, and they are asked to generate the compound word which is STONE (resulting in STONEAGE – MILESTONE – SANDSTONE). These presented items vary in their degree of abstractness and figurativeness (see Marko et al., 2019 for details). As the RAT is verbal convergent thinking task, participants provide their ideas verbally or in written format. Similar as in APM, the responses are scored into correct and incorrect responses. The RAT can be solved in two manners, which is (a) an insight-driven strategy (which can be probed by specific instructions; see Landmann et al., 2014; Wu et al., 2020) or (b) a deliberate process of combining or associating that leads to the correct solution (Gonen-Yaacovi et al., 2013). Wu and colleagues (2020) argue that by applying the insight-driven strategy, the RAT evokes divergent thinking, while the deliberate strategy exclusively evokes convergent thinking. In both cases, there is only one correct response for each item, hence by instructing the deliberate strategy (as we did in Study 2) the RAT measures convergent thinking within a closed-ended problem (i.e., less degrees of freedom).

The Alternate Uses Task (AUT; Guilford et al., 1978), is one of the most widely used divergent thinking tasks (Cortes et al., 2019; Japardi et al., 2018) in which participants are asked to generate unusual and original ideas for the use of an everyday object, such as a shoe or a tire. Participants are then asked to provide their ideas verbally or in written format. Hence the AUT is considered a verbal creativity task. Similar as in the CRT, in the AUT divergent thinking productions are traditionally scored in terms of three qualities: fluency, originality, and flexibility (Runco & Acar, 2010). Hence, in AUT divergent thinking is verbally assessed in an ill-defined problem space.

4.4 Limitations of Divergent and Convergent Thinking Tasks

As outlined above, creative thinking is the result of both divergent and convergent thinking combined. Furthermore, I elaborated on several proposals on how both interact within the creative process. Hence, the tasks I presented above (i.e., AUT, CRT, RAT) cannot simply measure pure divergent or convergent thinking. The only of these tasks that systematically accounts for both processes occurring within each item is the CRT.

Regarding the CRT, divergent and convergent thinking are both assessed within the same task by two designated sub-scores. As mentioned above, the CRT sub-score *Relations* is considered a convergent production sub-score, whereas the CRT sub-score *Components and Specifications* is considered a divergent production sub-score (Jaarsveld et al., 2012, 2010). Psychometric studies revealed a correlation of the convergent CRT sub-score with performance in the Raven Progressive Matrices (RPM; Raven et al., 1989a) and the Standard Progressive Matrices test (SPM; Raven et al., 1989b) in children age 8 and 12 (Jaarsveld et al., 2010) and between 7 and 10 years of age (Jaarsveld et al., 2012), respectively. Furthermore, results from the divergent sub-score of the CRT correlated with performance in sub-scores of the TTCT – Drawing Production (Urban & Jellen, 1995; see Jaarsveld et al., 2012, 2013). In addition, the CRT total score correlated with the SPM score (Jaarsveld et al., 2012). These results imply that divergent and convergent thinking performances can be independently assessed within the CRT (Jaarsveld et al., 2012). Yet there is the limitation that the CRT does not provide the possibility to fully unravel which thinking process is present to exactly which quantity at which stage (i.e., Toolbox, Row 1, Row 2, and Row 3).

Regarding the tests for the verbal knowledge domain (here: AUT and RAT), it has been demonstrated that performance in RAT shows little to no relationship with different measures of divergent thinking, but does show correlations for example with Gf or executive function measures (for example Lee & Therriault, 2013). That means, the type of convergent thinking that is probed by the RAT is independent from what is considered divergent thinking performance within one person. Does that mean that divergent and convergent thinking are two completely separate mental processes? Not necessarily! It is also possible that this observation is prompted by the specific requirements of both, the RAT and the AUT task. As I mentioned above, the AUT requires the generation of ideas on how to use an object. Hence, the idea generation process (i.e., divergent thinking) occurs within different concepts/objects that have a semantic closeness, at least it starts with semantically close concepts.

Subsequently, the semantic space is then gradually explored and extended from close to distant relationships.

On the other hand, when performing RAT most of the time there is “no legitimate semantic relation” (Cortes et al., 2019, p.92) neither within the three presented words, nor with the compound. Moreover, RAT problems require the active inhibition of “semantically related associates” (Cortes et al., 2019, p. 92) in order to find the correct solution, for example with the item CRAB – SAUCE – PINE (solution word: APPLE). The quality of semantic networks and their role for high vs. less creative thinking productions have been investigated in several studies. For example, it was highlighted that semantic networks in highly creative individuals show higher connectivity, lower modularity (i.e., the amount of smaller sub-networks within the main network), as well as shorter distances between concepts (i.e., between any pair of nodes in the network; see Mastria et al., 2021; He et al., 2020 for overviews). However, these relations between creativity and the characteristics of the semantic memory structure were only observed for the verbal but not the figural (visuo-spatial) knowledge domain (He et al., 2020). These implications regarding semantic relations, as well as some specific differences regarding the structures and timings of these tasks in general could result in observed variations, due to specifics of the measurement instruments. Hence, our research attempts to eliminate confounds regarding the structure, timing and task presentation.

Chapter 5: WORKING MEMORY

Working memory (WM) plays a fundamental role in every type of complex mental task. It can be defined as “a brain system that provides temporary storage and manipulation of [the] information” (Baddeley, 1992, p.556). In cognitive psychology, WM is a theoretical construct that is defined as a system or mechanism that supports the maintenance of task-relevant information (Miyake & Shah, 1999; Daneman & Carpenter, 1980). Despite the widespread circulation and usage of the term WM, there is no consensus about how precisely this function is achieved. Furthermore, the term WM is oftentimes equated with *short term memory* (e.g., maintenance vs. manipulation of information; see Miyake & Shah, 1999; Berti, 2010 for overviews). However, for the scope of this thesis, I will follow the above definition and refer to the corresponding underlying brain system as ‘WM network’.

In the following chapter, I will provide a brief overview of the history and the current conceptualization of WM. Furthermore, the role of WM in divergent and convergent thinking is discussed, in particular with regard to the visuo-spatial and the verbal knowledge domains.

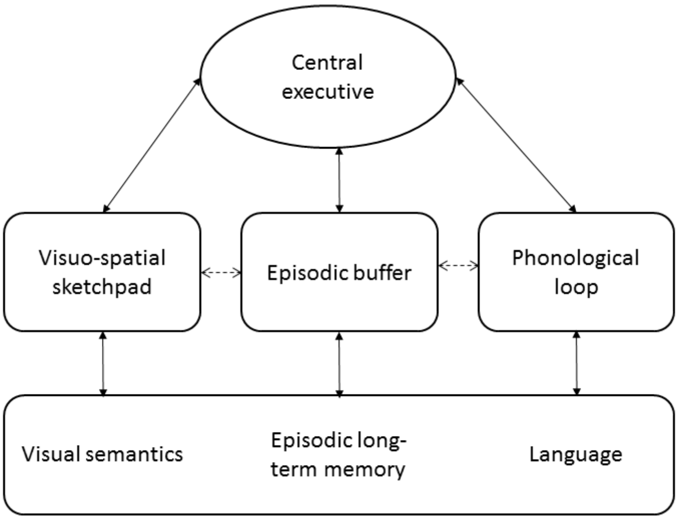
5.1 Models of Working Memory

In 1968, Atkinson and Shiffrin went beyond a merely stimulus-response driven view on learning and memory (which was prominent at that time) and proposed a modal model that integrated many innovative ideas on human information processing (Wixted, 2023). This model involves three memory components (i.e., *Sensory register*, *Short-term store*, and *Long-term store*; Atkinson & Shiffrin, 1968) for processing different modes of incoming information (e.g., auditory, visual). Atkinson and Shiffrin (1968) classified these three different memory systems based on their functional and structural differences. The model further encompasses different control processes (e.g., attention, rehearsal, and retrieval; Wixted, 2023), which regulate the flow of information. After incoming information (e.g., in the auditory modality) passes the sensory register, it reaches a short-term memory storage. Here, the information can be rehearsed (e.g., for immediate recall, or manipulation) and also be transferred into long-term memory for long-term storage (Berti, 2010; Shiffrin, 1993). Additionally, information can be lost (or be subject to decay) at each processing stage. Over the following years and decades, this model has been revised and refined by Atkinson and Shiffrin as well as other researchers (see below).

Following the same tradition of regarding memory as an entity consisting of different sub-components (Berti, 2010), Baddeley and Hitch (1974) proposed a new model, in which they expanded the short-term store by Atkinson and Shiffrin (1968) to a three-component system encompassing an attentional controller (i.e., central executive) that is complemented by two subsidiary systems (Baddeley & Hitch, 1974, 2007; Baddeley, 2010). The first of the two subsidiary systems is referred to as *phonological loop* (at that time ‘articulatory loop’, Baddeley & Hitch, 1974), which was assumed to guide processes of rehearsal and temporary storage of vocal or auditory information. The second of the two subsidiary systems is referred to as *visuospatial sketchpad* (at that time ‘visuospatial scratchpad’, Baddeley & Hitch, 1974), which was assumed to be used for making visual sketches as well as verbal notes (Baddeley & Hitch, 2007), and with that allows spatial and object-based visual processing (Smith & Jonides 1997). Later, a fourth component, the *episodic buffer*, was added to the model (Baddeley, 2000; see Figure 8). This entity is assumed to serve as a temporary storage system with limited capacity, which integrates information from a variety of sources and is controlled by the central executive (Baddeley, 2000, 2010).

Figure 8

Multicomponent model of working memory (Baddeley & Hitch, 2000)



Note. The multicomponent model comprises the central executive, which controls attentional processes as well as the two subsidiary storage systems (i.e., visuo-spatial sketchpad; phonological loop) and the episodic buffer, which binds and integrates information. Finally, the accumulated information can be organized into long-term knowledge (i.e., visual semantics; episodic long-term memory; language). Adapted from Baddeley, 2010.

Although the model by Baddeley and Hitch is currently the most popular concept of WM and its underlying mechanisms, there are definitely several concepts of what WM encompasses within the scientific discourse. However, according to Jonides and colleagues (1996), all of these proposals share a common set of characteristics which are: 1) briefly storing of information; 2) a limited storage capacity; 3) the information is rapidly accessible; 4) the memory system is frequently updated; and 5) is used in service of higher order processes. *Working memory capacity* (WMC) refers to individual differences in regard to this limited capacity of a person's WM (Wilhelm et al., 2013; Engle, 2001). Hence, even though there might some differences in certain nuances, the basic function and purposes of WM are well established and widely recognized today.

5.2 Visuo-spatial and verbal Working Memory

Over time, a new question arose in WM research: Is the incoming information maintained in a domain-general capacity-limited storage system or are there domain-specific storage entities for different modalities of information (for example verbal or visual; Fougnie et al., 2015)? Baddeley's model already proposes separate WM entities for processing incoming verbal-acoustic and visuo-spatial information (Baddeley, 2010). In recent years, more evidence has been brought forward in favor of this domain-specific WM systems (Cocchini et al., 2002), especially through dual-task paradigms, in which participants are presented with two stimulus sets one after the other, which are to be remembered and subsequently tested (see Cowan & Morey, 2007) and also, through neuropsychological studies with patients with specific cognitive impairments, such as for example traumatic brain injuries (e.g., Azouvi et al., 1996, 2004; Vallat-Azouvi et al., 2007). Hence, to address knowledge domain-dependent characteristics, it is necessary to investigate these different WM sub-systems using designated tasks and stimuli.

5.3 The Role of Working Memory in Divergent and Convergent Thinking

WM, WMC and other related cognitive control processes (e.g., inhibition or shifting; Cancer et al., 2023), can be assumed to be involved in both, divergent and convergent thinking processes. Prior research further indicates that the type of stimuli presented during a creative thinking task may also influence the applied memory strategies (Chrysikou et al., 2016; Sunavsky & Poppenk, 2020) and thus, the role of WM during these tasks. For example, in creative cognition it is necessary to keep information in an active state in order to evaluate and compare generated ideas (Benedek et al., 2011; De Dreu et al., 2012). However, there are only few studies that investigate the underlying relationship between divergent thinking and WM. Additionally, the reported strength of observed correlations differed vastly across these studies, from strong (e.g., Lee & Therriault, 2013; Takeuchi et al., 2011) to no correlations (e.g., Lin & Lien, 2013; Smeekens & Kane, 2016) across different knowledge domains and tasks. Hence, from an experimental standpoint it is essential to investigate different knowledge domains by contrasting tasks that contain highly similar stimulus material, as the exact role of WM for divergent and convergent thinking remains to be established.

Regarding the visuo-spatial knowledge domain, a strong correlation between WM (especially WMC) and convergent thinking has been observed (e.g., Chuderski et al., 2012; Domnick et al., 2017). A study by Fukuda and colleagues (2010) specifically reported that WM was associated with solving geometric matrices (similar to what is done during APM). WM-related subprocesses that underlie this convergent thinking process specifically have been described by Carpenter and colleagues (1990) as perceptual analysis (i.e., encoding, finding correspondences, and pairwise comparison), conceptual analysis (i.e., row-wise rule introduction, and generalization), and finally response generation and selection. However, it is reasonable that these or at least similar processes are active during the creation of geometric matrices, as it is required during CRT. Hence, we assume that both tasks (APM and CRT) that we used to assess divergent and convergent thinking in the visual knowledge domain require WM and related processes.

Regarding the verbal knowledge domain, Benedek and colleagues (2011) as well as Cancer and colleagues (2023) observed that WM and associated cognitive control process (i.e., inhibition and shifting) were present during divergent and convergent thinking, respectively. However, a more refined analysis revealed that those associations are not identical for both thinking processes. For example, Gerver and colleagues (2023) as well as Lee and Therriault (2013) observed that WMC predicted performance of convergent, but not divergent thinking (see also Rodriguez-Boerwinkle et al., 2024). The latter, however, was in turn correlated with associative fluency (Lee & Therriault, 2013) or was enhanced when participants were less focused on the task (‘diffuse attention’; Takeuchi et al., 2011). Moreover, Cancer and colleagues (2023) discuss the possible benefit of reduced cognitive control processes, which could be beneficial during divergent, but not convergent thinking. Very similar, in a study of Lin and Lien (2013), WM load enhanced divergent thinking performances. A similar phenomenon was also observed in other studies in regards to WMC (e.g., Lee & Therriault, 2013; De Dreu et al., 2012; Takeuchi et al., 2011). These observations indicate that WM might play a different role in divergent as opposed to convergent thinking. In regards to convergent thinking, De Dreu and colleagues (2012) observed that WMC was positively related to the performance of RAT.

It is, however, important to note that verbal and visual stimuli will evoke different cognitive processes also due to their semantic relations. Semantic associations between words can have different distances (see Chapter 10 for discussion), which in turn facilitate or impede their temporal storage or manipulation in working memory. At the same time, especially verbal tasks are oftentimes related to domain-specific prior knowledge (e.g., verbal fluency, vocabulary etc.) of participants, which is also the case for the tasks that were used in our studies (i.e., AUT and RAT). Hence, this might influence not only the performance, but also the cognitive processes activated during these tasks across participants. On the other hand, geometric shapes or related types of visual stimuli can also be ordered semantically (e.g., based on size or color), but tend to be less dependent on prior knowledge, language, and cultural background. Hence, this difference in semantic associations between these types of stimuli might evoke different ways of information processing.

In conclusion, in accordance with prior studies, I assume that the relationship between WM and divergent or convergent thinking might be influenced not only by the respective processes but also by the type of stimuli presented during tasks (such as geometric shapes or words) and with that, by the respective knowledge domain (i.e., visuo-spatial or verbal).

Chapter 6: NEUROCOGNITIVE MECHANISMS OF DIVERGENT THINKING, CONVERGENT THINKING AND WORKING MEMORY

In the following chapter, I will provide an overview on the neuroscientific investigation of divergent and convergent thinking. After a general introduction about specific challenges when studying creativity in a laboratory environment, I will summarize the most important and consisting findings in regards to divergent and convergent thinking, using both neuroimaging as well as electro-physiological techniques. Regarding the latter, I will focus on neuronal modulations in the alpha band. Lastly, neural correlates of WM and their implications for divergent and convergent thinking are discussed.

With the rise of neuroscientific methods and techniques, such as functional magnetic resonance imaging (fMRI) or electroencephalography (EEG), researchers also entered the field of creativity to study the underlying brain mechanisms of divergent and convergent thinking. These methods of cognitive neuroscience expand our view on divergent and convergent thinking, as they allow researchers to locate the brain area (fMRI) as well as the temporal dynamics (EEG) that underlie these processes. However, these methods also have certain characteristics which bring some challenges for the neuroscientific study of creativity in general (Abraham, 2018). These characteristics particularly concern the laboratory environments, which appear to contradict a typical creative environment and could also potentially influence the respective thinking processes. Firstly, participants have to lie in the scanner with their head completely still during an fMRI session. Secondly, fMRI creates a very noisy environment due to the sound of the switching magnetic field (up to 100 dB). Lastly, because movement disturbs the data quality, it is not easily possible for participants to speak (verbal tasks), nor to draw during scans (visuo-spatial tasks). In most of the conventional fMRI paradigms, responses are given using a few buttons that are pressed (creating a well-defined problem space), which is vastly different from the type of responses that are typical for most creativity tasks (i.e., ill-defined problem space). Very similar problems can be faced when using EEG, which is equally sensitive to participant’s movement. In addition, the fixed time limit for trials in most of these tasks restricts the natural flow of idea generation. Nevertheless, some researchers met these challenges by re-designing some of the creativity paradigms and adding different stages of idea generation and production, or idea evaluation for EEG (Fink et al., 2009; Ellamil et al., 2012; Rominger et al., 2018; Schwab et al., 2014; Jaarsveld et al., 2015; Jia & Zeng, 2021; Eymann et al., 2022) and fMRI (Fink et al., 2009; Abraham et al., 2012, 2018; Ellamil et al., 2012; Japardi et al., 2018). Despite these challenges mentioned above, research in the field has led to some major findings in recent decades. For instance, the neuroscientific investigation of creativity revealed that creative thinking does not depend on a single neural mechanism, but rather a variety of brain regions and neurocognitive processes (Cogdell-Brooke et al., 2020; Gonen-Yaacovi et al., 2013; see Dietrich & Kanso, 2010; Boccia et al., 2015 for overviews).

6.1 Neuroimaging Correlates of Divergent and Convergent Thinking

The idea of the right hemisphere as the ‘creative side of the brain’ gained popularity even outside of the neuroscientific community and can be seen as the most famous theory regarding the underlying neural structure of creativity in the general public (Dietrich & Kanso, 2010; Martindale et al., 1984). While hemispheric specialization has been demonstrated in other areas (e.g., preferential global processing of complex visual stimuli in the right hemisphere; Fink et al., 1997), a meta-analysis by Dietrich and Kanso (2010) revealed that neither EEG nor fMRI studies on divergent thinking could confirm this specialized role for the right hemisphere in creative thinking. Nevertheless, a hemispheric specialization was observed when contrasting high and less creative individuals (i.e., highly creative participants showed higher upper alpha synchronization in the right in contrast to the left hemisphere during AUT; Fink et al., 2009) or males and females (i.e., males displayed higher upper alpha synchronization in the right hemisphere than females during insight problem-solving; Fink & Neubauer, 2006). The meta-analysis of Dietrich and Kanso (2010) was the first systematic review on the existing neuroscientific data of divergent thinking, in which the authors used highly aggregated data across different paradigms and domains (for example verbal, figural, hypothesis generation, insight problem-solving, drawing). Furthermore, the authors included tasks such as RAT in their analysis, which can be used (depending on the instructions; ct. Chapter 4.3) to assess convergent thinking (see Chapter 4.4 for a discussion). A later meta-analysis of neuroimaging studies by Boccia and colleagues (2015) suggests that by accounting for domain-specific creativity, different involvements of both hemispheres can be observed. Verbal creativity was mainly located in the left hemisphere, whereas visuo-spatial creativity activated several regions in the right hemisphere. The authors concluded that creative thinking provokes activity in a variety of regions throughout the brain, with certain brain regions responsible for specific domains (Boccia et al., 2015), however there was no direct accounting for divergent and convergent thinking within the creative thinking process. Hence, in the following I aim to outline the current status of neuroscientific research regarding divergent and convergent thinking, respectively.

Neuroimaging provides different levels and qualities of data to study the brain during divergent thinking. In general, a distinction can be made between structural and functional data. While the former is used to identify differences in the structural organization of the brain, such as correlates of grey and white matter volume (*volumetry*) but also spontaneous fluctuations in neural activity (*resting state fMRI*; Lee et al., 2013), functional methods provide information about brain activation during a given task. These include fMRI, which estimates neural activity according to the local metabolic demand of the brain (i.e., blood oxygen level dependent; *BOLD*; Heeger & Ress, 2002) in response to experimental conditions as well as *functional connectivity*, which quantifies common patterns of neuronal activity of spatially distinct brain regions during a task (Rogers et al., 2007).

Only a small number of studies on creativity focus on brain volume and connectivity. Sunavsky and Poppenk (2020) conducted a whole brain exploratory analysis in their meta-analysis and concluded that both left and right inferior frontal gyrus (IFG) grey matter volume were reliable predictors for verbal divergent thinking. Visuo-spatial divergent thinking was in turn predicted by left ventromedial prefrontal cortex (PFC) volume. Furthermore, the cerebellum grey matter density and white matter integrity were both positively correlated to verbal as well as visuo-spatial divergent thinking, respectively. Finally, white matter integrity of the basal ganglia was a predictor for general creativity performance in both domains. The same authors found that IFG-IPL (inferior parietal lobe) functional connectivity was linked to greater divergent thinking performance in the verbal domain (Sunavsky and Poppenk, 2020). In a study of Chen and colleagues (2019) using resting state fMRI, verbal divergent thinking performance was predicted by the functional connectivity of regions such as the lateral temporal cortex and IFG, as well as the middle frontal cortex and the superior parietal lobule. On the other hand, visuo-spatial divergent thinking was predicted by several functional networks within the right hemisphere (e.g., the visual network, the fronto-parietal network, and default mode network; Chen et al., 2019).

The involvement of these networks during divergent thinking has also been reported by neuroimaging studies using event-related fMRI. Generally speaking, the majority of these studies found a variety of brain regions within both hemispheres activated during divergent thinking. For example, Beaty and colleagues (2016) proposed an involvement of the default mode network alongside with networks dedicated to executive control in an orchestrated, opposite coupling. Boccia and colleagues (2015) performed a meta-analysis to 45 fMRI studies using activation likelihood estimation (ALE) which revealed that creativity in general relies on the activation of different regions throughout all lobes and both hemispheres. More specifically, verbal divergent thinking was accompanied by activation in the IFG and middle frontal gyri (MFG), middle and superior temporal gyri (STG), IPL, postcentral and supramarginal gyri, middle occipital gyrus, as well as the insula, all of these activations within the left hemisphere. Furthermore, the authors found the right IFG and right lingual gyrus as well as the right posterior cerebellum to be activated during verbal divergent thinking (Boccia et al., 2015). On the other hand, the authors found visuo-spatial divergent thinking to reveal clusters of activation in the bilateral thalamus, as well as the IFG and MFG within the right hemisphere. Furthermore, the left precentral gyrus was activated during visuo-spatial divergent thinking (Boccia et al., 2015). Gonen-Yaacovi and colleagues (2013) concluded that different fronto-parietal regions are active during creative cognition in the verbal domain. In addition, activation in areas specialized to domain-specific task demands have also been observed (Sun et al., 2019; Chen et al., 2019), suggesting that creative cognition is mediated by increased activity in brain regions closely associated with the specific underlying task demands. However, not indicating such a distinction, Beaty and colleagues (2021), as well as Zhu and colleagues (2017), observed (among other regions) activation in the so called fronto-parietal control network (FPN; Vincent et al., 2008) in both, verbal as well as visuo-spatial creativity tasks (see also Gao et al., 2023). Hence, it remains to be established whether functional brain activity can be attributed to the knowledge domain (i.e., verbal or visuo-spatial). In another meta-analysis of 20 fMRI studies on verbal and visuo-spatial divergent thinking using ALE, Cogdell-Brooke and colleagues (2020) identified four clusters within the semantic network, namely the left IPL, the left IFG and the left precentral gyrus, the MFG and superior frontal gyrus as well as the right cerebellum. The authors concluded that activity in these regions played a major role during divergent thinking, implying a specialization of these regions for the flexible retrieval of knowledge as well as online mental manipulation of objects (Cogdell-Brooke et al., 2020).

Looking more specifically at the processes of idea generation (i.e., divergent thinking), Ellamil and colleagues (2012) employed an fMRI paradigm where participants were asked to generate, sketch and subsequently evaluate their design of a book cover. When contrasting both conditions, the authors observed stronger activation in the medial temporal lobe (MTL) as well as the hippocampus and parahippocampus during idea generation in comparison to idea evaluation. The authors hence argue for a central role of the MTL, which has previously been linked to memory formation and retrieval as well as associative processing, for divergent thinking and creative idea generation (see Ellamil et al., 2012 for overview). On this basis, the authors conclude that the MTL might be relevant for the association and recombination of new and old ideas. Furthermore, other studies (e.g., Abraham et al., 2012, 2018; Fink et al., 2009) found certain areas in the posterior parietal lobe, such as the left IPL to be related to the originality of ideas. Regarding the two main components of creativity (i.e., novelty and usefulness, ct. Chapter 2.2), Ren and colleagues (2020) observed that hippocampus and medial temporal lobe (MTL) are critical regions regarding the novelty and usefulness aspect during creative designing, as these regions have been linked to forming of novel associations, integrating new information into existing knowledge, as well as processing of novel associations during divergent thinking (see Ren et al., 2020 for overview) .

In contrast to divergent thinking, only few fMRI studies have focused or even considered convergent thinking in the context of creativity. In addition, most of these studies compared a divergent thinking task to a task that does not require divergent thinking (e.g., n-back task; e.g., Abraham et al., 2012, 2014, 2018; Gonen- Yaacovi et al., 2013), but oftentimes not specifically to convergent thinking tasks. In the case of APM, a few studies investigated brain connectivity using resting state fMRI (Chen et al., 2017) or event-related fMRI (e.g., Prabhakaran et al., 1997; Christoff et al., 2001; Perfetti et al., 2009). Using global brain connectivity analysis in resting-state fMRI data, Chen and colleagues (2017) observed distinct neural correlates for visuo-spatial and verbal reasoning when solving APM items. They reported that performance of visuo-spatial items was correlated to specific functional connectivity in the left middle and inferior temporal gyri, cuneus and precuneus. On the other hand, verbal-analytic scores of APM were correlated with right IFG and temporoparietal junction (TPJ; both associated with cognitive control functions), right angular/supramarginal gyrus (responding to integration and abstracting of sensory information) as well as dorsal anterior cingulate cortex (ACC; response selection) and supplementary motor areas (Chen et al., 2017), revealing different reasoning strategies that participants applied for the different subsets and the corresponding cognitive demands. In regards to fMRI, Prabhakaran and colleagues (1997) observed different domain-specific WM-related brain regions to be activated during visuo-spatial (involving right frontal regions, such as right MFG and bilateral parietal regions) and verbal-analytical reasoning (involving mainly left hemispheric activation for example in the IFG and MFG as well as premotor cortex; Prabhakaran et al., 1997). Furthermore, when solving APM items, bilateral rostro-lateral PFC activation was linked to relational integration (Christoff et al., 2001) and bilateral fronto-parietal network to complex reasoning, respectively (Perfetti et al., 2009).

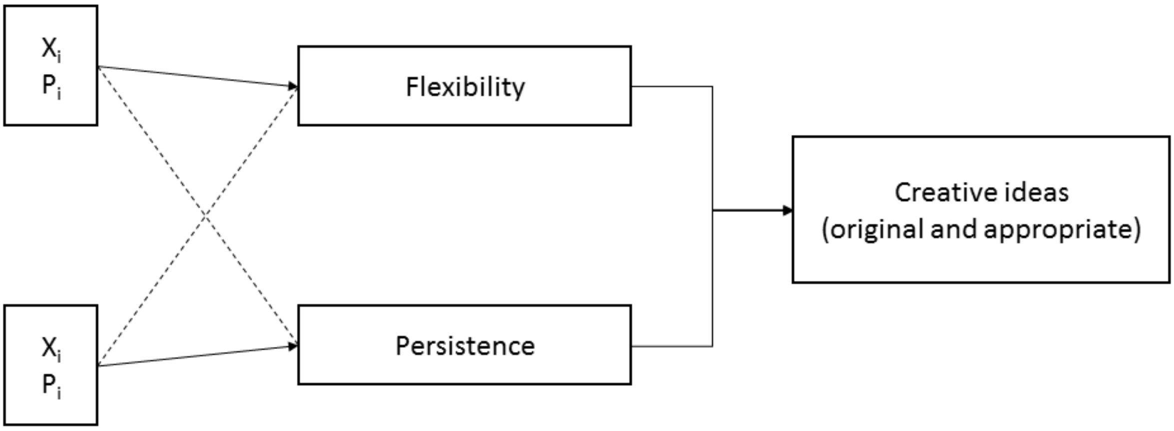
A meta-analysis of 34 fMRI studies (Gonen- Yaacovi et al., 2013) revealed that divergent and convergent thinking (here: idea generation vs. combination task) showed overlapping activity in several regions, such as the inferior frontal junction, the IFG, the posterior MFG, the parieto-occipital cortex, as well as the medial wall. However, the authors found that rostral PFC showed higher activation during the convergent thinking task, which has also been associated to analogical reasoning and abstract thinking, while at the same time, right IFG showed higher activation during idea generation (Gonen-Yaacovi et al., 2013). Hence the authors concluded that these regions hold a special role for the distinction of both thinking modes (Gonen- Yaacovi et al., 2013). In the already mentioned study of Ellamil and colleagues (2012), participants showed enhanced activation in several regions of the executive network (including the dorsolateral PFC as well as the dorsal ACC) as well as in the default network (including the medial PFC, the posterior cingulate cortex, and the TPJ) when evaluating their ideas. Hence, the authors concluded a central role of this co-activation for deliberate and analytical idea evaluation processes (i.e., convergent thinking; Ellamil et al., 2012).

Looking specifically at the brain activation during AUT and RAT, a few fMRI studies compared those two tasks directly, instead of simply contrasting divergent thinking to a non-divergent task. Please note again that for CRT as of today there has not been any neuroimaging study published. Fink and colleagues (2009) observed strong activation in the left IFG and left angular gyrus during AUT performance. In a study of Abraham and colleagues (2012), divergent thinking assessed with AUT was associated with activation in the hippocampal formation, the amygdala, the posterior cingulate cortex, the dorsal medial PFC, ventral medial PFC, as well as the angular gyrus (Abraham et al., 2012; see also Abraham et al., 2018 for a replication of these results). Note that these enhanced activations are reported relative to a WM task, as convergent thinking (e.g., RAT) was not assessed. Japardi and colleagues (2018) directly contrasted divergent and convergent thinking in Big-C individuals using AUT and RAT, respectively. Although this study focuses predominantly on specific brain characteristics between exceptionally creative participants and control groups (cf. Big-C vs. little-c creativity, see Chapter 2.2), the authors still provided results regarding the congruent and overlapping activation patterns during divergent and convergent thinking across both groups. They found left frontal and bilateral occipital cortex activation during AUT, as well as strong left-hemisphere activation patterns during RAT performance (Japardi et al., 2018). However, the authors also discuss the problem of limited validity due to transforming these tasks into MRI compatible procedures (see also discussion in Chapter 4.4 about these limitations). For example, both tasks were strictly timed (AUT: 10 minutes; RAT: 14 minutes) with rather short presentation time for each item (20 seconds in AUT, 14 seconds in RAT). The concern of limited validity has also been supported as the authors observed only moderate correlations between in-scanner and outside-scanner performance in both tasks (see Japardi et al., 2018 for discussion).

Zhang and colleagues (2020) reviewed different neuroimaging studies specifically investigating AUT and RAT and illustrate that divergent and convergent thinking are characterized by qualitatively different activation patterns. The authors identified mainly three cortical regions that can be observed during divergent (assessed with AUT) and convergent thinking (assessed with RAT), respectively. These regions are the left IFG, as well as the left dorsolateral PFC, and most parts of the right hemisphere (including the posterior parietal cortex; PPC and closely related areas; Zhang et al., 2020). Divergent thinking (as measured by the AUT) was associated with strong activation in the left IFG together with a weak association in the left dorsolateral PFC, as well as the right PPC and STG (Zhang et al., 2020). On the other hand, convergent thinking (as measured by the RAT) is characterized by weak activation in the left IFG together with high activation in left and right dorsolateral PFC as well as right PPC and STG. The authors hence interpret these findings as evidence for a distinguished activation pattern which implicates that divergent and convergent thinking are modulated by two different meta-control states, namely a flexibility and a persistence pathway (Zhang et al., 2020). This interpretation fits nicely with the proposal of Nijstad and colleagues (2010) regarding a *Dual pathway to creativity model*, where creativity (i.e., divergent and convergent thinking) is described as a function of cognitive flexibility and cognitive persistence (see Figure 9). Cognitive *flexibility* describes the ability to switch from the current task to the next by inhibiting the previously relevant task set and activating the new task-set (Egner & Siqi-Liu, 2024; Monsell, 2003), while *persistence* (or stability) describes the ability to allocate maximum control towards the task that is currently performed in order to minimize distraction (Musslick et al., 2018). It is assumed that the creative process relies on these two routes but to different degrees, depending on the product (e.g., highly creative products might require more flexibility) and the state within the creative process (e.g., in order to evaluate and find the final solution, persistence might be prioritized; Nijstad et al., 2010). Hence, both pathways can be influenced by both, situational (X_i) as well as dispositional factors (P_i) to different degrees (Nijstad et al., 2010; see Figure 9). According to this model, the flexibility and stability pathway both can result in creative outcomes, as both emphasize the role of cognitive control processes for creative cognition (Nijstad et al., 2010). Additionally, Zhang and colleagues (2020) argue that these two pathways interact differently in divergent and convergent thinking, respectively: divergent thinking relies mainly on flexibility, whereas convergent thinking relies mainly on persistence (Zhang et al., 2020).

Figure 9

Dual pathway to creativity model (Nijstad et al., 2010)



Note. The model describes creativity as a function of cognitive flexibility and persistence, which in turn are influenced by both, situational (X_i) and dispositional factors (P_i). Adapted from Nijstad et al., 2010.

This model has received empirical support, specifically from neuroscientific studies that investigate neurotransmitters such as dopamine in creative cognition. Here, there is evidence that creativity relies on dopaminergic modulations in fronto-striatal brain circuitries that modulate both, flexibility and persistence (see Zhang et al., 2020 for systematic overview). As these and other prior findings already imply (e.g., Zhu et al., 2017, Sunavsky & Poppenk, 2020; Fink et al., 2009), it can be assumed that further processes, such as cognitive control, WM, attention, and similar processes are involved in creative cognition and thus elicit specific activation patterns during the performance of divergent and convergent thinking. With that, distinguishing which specific neural activation mirrors which specific process still remains to be established.

On the flipside, there are various regions involved in creativity tasks that are also activated in the aforementioned processes when measured by tasks designated to assess these cognitive processes per se. For example, Gonen-Yaacovi and colleagues (2013) found different types of executive processes (such as cognitive control and WM) to be involved in different divergent thinking and music improvisation tasks. Those regions include the caudal part of the lateral PFC, both ventrally and dorsally, the medial and lateral portion of the left rostral PFC, the IPL, as well as the lateral temporal gyrus (Gonen-Yaacovi et al., 2013). The authors concluded that the networks related to divergent thinking and music improvisation include brain regions that are typically associated with cognitive rather than affective processing (Gonen-Yaacovi et al., 2013). Sunavsky and Poppenk (2020) still observed the involvement of other regions, such as for example the cerebellum or the parahippocampal gyrus in divergent thinking, which aligns with the proposal of the importance of WM for divergent thinking. In fact, in the already mentioned study of Fink and colleagues (2009) certain cortical areas were significantly activated during the AUT that are specifically linked to verbal WM (i.e., IPL and superior parietal lobe; Fink et al., 2009), further indicating an important role of domain specific information storing, maintenance and rehearsal during divergent thinking (i.e., verbal and visuo-spatial WM).

6.2 Electro-physiological Correlates of Divergent and Convergent Thinking

Similar to fMRI research, numerous EEG studies assessing divergent thinking have been published over the last 30 years, while convergent thinking (specifically assessed with designated tasks) has not quite received the same attention in empirical research. Nonetheless, the high temporal resolution of EEG has been particularly useful to investigate the temporal course of electrical activity in the brain during divergent and convergent thinking.

As already discussed, the specific dynamics of the creative process oftentimes require modifications and adjustments in the EEG protocol, especially to account for individual differences amongst participants (such as individual differences in response time). Hence, some researchers accommodated the potentially time sensitive processes of divergent and convergent thinking by analyzing EEG data in consecutive time points or time intervals during the thinking phases (e.g., Schwab et al., 2014, Jaarsveld et al., 2015; Camarda et al., 2018; Mastria et al., 2021; Eymann et al., 2022, 2024; see Rothmaler et al., 2017 for insight problem-solving). These approaches allow a more fine-tuned observation of the interplay between divergent and convergent thinking during creative cognition, but also to observe changes in activation due to specific events within the creative process (for example the "Aha! moment"; Stevens & Zabelina, 2019 in the case of insight problem-solving).

Generally speaking, EEG studies on divergent and convergent thinking report their findings in terms of power and synchrony (i.e., event-related de-/synchronization; Dietrich & Kanso, 2010; Benedek et al., 2011) in different EEG frequency bands using time-frequency analysis. Here, the stimulus-induced activation is contrasted to a pre-stimulus reference interval to observe changes (i.e., increase or decrease) in event-related synchronization and desynchronization (see Chapter 7 and Chapter 8 for details on this method). EEG studies using time frequency analysis investigate different EEG frequency bands. However, there is a main focus on the alpha band (8-12 Hz) and its significance for creativity is one of the most consistent findings regarding the cognitive neuroscience of creativity (Fink & Benedek, 2012; Jauk et al., 2012; Fink et al., 2011; Martindale & Hasenfus, 1978; see Dietrich & Kanso, 2010; Fink et al., 2007; Stevens & Zabelina, 2019 as well as Srinivasan, 2007 for overview). For the scope of this thesis, I will hence focus on the evidence in regard to alpha band, especially upper alpha band (10-12 Hz) as it is also the focus in our studies.

Activity in the alpha band, sometimes divided more specifically into upper (10-12 Hz) and lower (8-10 Hz) alpha, has been related to creative thinking in several studies over the last years, as it shows specific modulations in regards to specific requirements of the tasks (e.g. switching between semantic categories; Mastria et al., 2021), indicating that alpha is especially sensitive to creativity-related task demands (Fink & Benedek, 2012; Perchtold-Stefan et al., 2023). For example, several studies reported increased alpha power to be associated with the generation of more original ideas (e.g., Agnoli et al., 2020; Jauk et al., 2012; Fink et al., 2011; Fink et al., 2007; Martindale et al., 1984). Furthermore, solving ill-defined problems was found to be related to higher alpha power in contrast to problem-solving in well-defined problem spaces (Jaušovec, 1997; Mölle et al., 1999), indicating that divergent thinking is associated especially to upper alpha (10-12 Hz) synchronization over frontal and parietal regions (see also Jauk et al., 2012; Fink and Benedek, 2014). Moreover, some studies reported that highly creative individuals (as well as professional dancers; see Fink et al., 2009a) showed significantly higher synchronization in upper (Fink et al., 2009a; Fink et al., 2009b) or upper and lower alpha band (Fink & Neubauer, 2008; Jaušovec & Jaušovec, 2000) during the performance of a divergent thinking task (or the imagination of dance improvisations; Fink et al., 2009a). Lastly, Jaušovec and Jaušovec (2000) reported findings on upper alpha (here: 10.1-12.9 Hz) synchronization being related to the form of problem presentation (i.e., knowledge domain). Here, upper alpha was systematically more synchronized during verbal than visuo-spatial divergent thinking (Jaušovec & Jaušovec, 2000). In conclusion, it seems that both, lower and upper alpha band show distinct modulations within creative thinking. Hence, it is necessary to take these observations into consideration by investigating both bands separately.

There are several approaches to explain the functional significance of synchronization in the upper alpha band during creative thinking. Dietrich and Kanso (2010) suggest that the increase in synchronization should be interpreted as an efficient transfer of information accompanied by an increase in intra- and interhemispheric communication of brain areas, especially frontal and parietal areas (Fink & Benedek, 2014). Further explanations were offered by Fink and colleagues (2007). The authors concluded that the increase especially in upper alpha synchronization reflects an active inhibition process, by shielding the internal information processing during creative thinking from external, environmental disturbances (Fink et al., 2007). An alternative interpretation is that the production of original ideas requires a reduced or lower activity level in certain brain areas (also known as "cortical idling"; Fink et al., 2007; Pfurtscheller et al., 1996), which is reflected by alpha synchronization.

While alpha synchronization is consistently observed during divergent thinking, researchers have also reported desynchronizations in lower and upper alpha (7.5–10.5 and 10.5–12.5 Hz; Jauk et al., 2012) during tasks which require convergent thinking (see also Mölle et al.,1999; Razoumnikova, 2000; Wang et al., 2017; Jaušovec & Jaušovec, 2012; Eymann et al., 2022). However, Benedek and colleagues (2011) observed frontal upper alpha synchronization during both divergent and convergent thinking but only for certain internal processing demands (in this case: exclusively top-down control processes; Benedek et al., 2011). Thus, upper alpha synchronization can potentially be observed in both divergent and convergent thinking, leaving room for conjecture whether the distinction divergent thinking - synchronization and convergent thinking – desynchronization is as sharp as previously assumed (Benedek et al., 2011).

6.2.1 Divergent Thinking and Alpha Synchronization

In the following, I will provide an overview on research specifically for the visuo-spatial and verbal tasks used in Study 1 and 2 (i.e., CRT, APM, AUT, and RAT) with regard to synchronization in the alpha band. Please note that as the CRT provides measures for both divergent and convergent thinking, these results are discussed separately within the next two chapters. Therefore, I will summarize and discuss these tasks under the notion of divergent thinking, encompassing the divergent part of the CRT (Toolbox, Row1; see Chapter 6.2.1) and AUT, as well as convergent thinking, encompassing APM, RAT, and the convergent part of the CRT (Row 2, Row 3; see Chapter 6.2.2), respectively.

As of today, there are only two EEG studies investigating upper alpha during the CRT, which is one study by Jaarsveld and colleagues (2015) and the other by Eymann and colleagues (2022). Hence, to avoid repetition I will mostly focus on the study conducted by Jaarsveld and colleagues (2015), as the results of Eymann and colleagues (2022) are discussed in great detail in Chapter 7 of this thesis. Jaarsveld and colleagues (2015) investigated upper alpha (10-12 Hz) synchronicity by assessing each stage of the CRT individually and subdivided into three consecutive time intervals. This approach accounts for the specific requirements of the EEG (i.e., to minimize movement artefacts and to take participants-specific processing speed into consideration). The performance of the CRT task was generally associated with upper alpha (10–12 Hz) synchronization at frontal sites, while at the same time upper alpha desynchronized slightly over the posterior cortex (Jaarsveld et al., 2015). The authors further observed that divergent thinking (i.e., Toolbox and Row1) was accompanied by upper alpha desynchronization, whereas convergent thinking (i.e., Row2 and Row3) was accompanied by upper alpha synchronization, especially at pre-frontal electrode sites. Investigating the temporal course of activation within each thinking stage (i.e., Toolbox, Row1, Row 2, and Row 3), upper alpha was most synchronized at the beginning of each stage and just before response at the end of each stage (Jaarsveld et al., 2015). The observations of Jaarsveld and colleagues (2015) as well as by Benedek and colleagues (2011) emphasize the importance to further investigate the specific role of alpha synchronization and desynchronization in both, divergent and convergent thinking as their results provide evidence for an opposite pattern.

During divergent thinking using AUT, several studies reported alpha synchronization (e.g., Agnoli et al., 2020; Mazza et al., 2023; Stevens & Zabelina, 2020; Jauk et al., 2012; Fink et al., 2007). In their study, Jauk and colleagues (2012) adapted the AUT by systematically varying the instructions to probe common vs. uncommon responses (i.e., convergent vs. divergent thinking processes). The authors observed that divergent thinking (i.e., thinking about uncommon responses) was accompanied by task-related synchronization upper and lower alpha (7.5–10.5 Hz and 10.5–12.5 Hz), in contrast to the generation of common responses (i.e., convergent thinking) which was accompanied by desynchronization in both alpha bands (Jauk et al., 2012). These findings were supported by Mazza and colleagues (2023) using the same methodological approach, indicating that both divergent and convergent thinking can be assessed within the AUT using designated instructions. Furthermore, Jauk and colleagues (2012) concluded that alpha band synchronization can be specifically attributed to divergent thinking, rather than general tasks characteristics, such as stimulus material. In a study of Fink and colleagues (2011), divergent thinking assessed with the AUT was accompanied by significant upper alpha (10-12 Hz) synchronization relative to the pre-stimulus reference period, especially in prefrontal cortex and throughout the right hemisphere. This pattern was even more emphasized when participants were exposed to cognitive stimulation during the item presentation (i.e., presentation of two highly original answers for the stimulus word; Fink et al., 2011). In a study of Agnoli and colleagues (2020), alpha band (8-12 Hz) synchronization was observed during the generation of four alternative uses in a structured version of the AUT. While a serial order effect was observed on a behavioral level (increase in originality along with an increase in response time), alpha synchronization over frontal, central and temporal regions predicted originality in the beginning and alpha synchronization over centro-parietal areas predicted originality throughout each item (Agnoli et al., 2020). Further investigating the temporal course of the divergent thinking process in AUT, Schwab and colleagues (2014) as well as Jauk and colleagues (2012) reported alpha was most synchronized at fronto-parietal regions in the beginning of each AUT trial, then decreased and increased again towards the end of each trial. Lastly, Mastria and colleagues (2021) observed distinct modulations of lower alpha (8-10 Hz) in regards to category switching (associated with bilateral posterior parietal synchronization) and category clustering (i.e., staying in the same category), which was associated with in right posterior parietal areas during AUT. This observation was interpreted as an indicator of an increase utilization of cognitive resources when switching categories during idea generation.

6.2.2 Convergent Thinking and Alpha Desynchronization

In contrast to alpha synchronization, which is mainly related to creative problem solving, alpha desynchronization is oftentimes observed during analytical problem solving (Wang et al., 2017). In their meta-analysis, Dietrich and Kanso (2010) concluded that alpha decrease in synchrony or desynchronization associated with convergent thinking cannot be interpreted as 'inefficient' information processing of the brain but instead, as a marker of conflict resolution or remote association formation (Dietrich & Kanso, 2010). Furthermore, Klimesch (1999) suggested that desynchronization in the upper alpha band (10-12 Hz) is associated with semantic memory performance. Razoumnikova (2000) observed upper (10-13 Hz) and lower alpha (8-10 Hz) desynchronization, especially in the left hemisphere during convergent thinking in a mental arithmetic task, in contrast to a resting condition. Furthermore, upper alpha intrahemispheric coherence was significantly lower during convergent in contrast to divergent thinking. Similarly, Sviderskaya (2011) presented participants with a verbal divergent vs. convergent thinking task (i.e., participants are asked to create words out of letter pairs vs. add missing letters in words) and a non-verbal divergent vs. convergent thinking task (create visual images using two simple geometric figures vs. determine the matching fragment for a picture). The authors observed changes within the alpha band frequency (here at 9.75-11 Hz), however convergent thinking was accompanied by less synchronization as opposed to divergent thinking. In the same study, the authors compared the strength of association between nonverbal divergent, verbal divergent, nonverbal convergent, and verbal convergent thinking. Here, verbal divergent and verbal convergent thinking performances showed strongest correlations coefficients (.78), while smaller correlations were observed between nonverbal and verbal divergent thinking (.42) as well as between nonverbal and verbal convergent thinking (.38, all p's $< .05$; Sviderskaya, 2011). No correlation was observed between nonverbal divergent and nonverbal convergent thinking though. These observations indicate that the relationship between divergent and convergent thinking also depends on the knowledge domain and the associated mental processes that are required by the knowledge domain (e.g., semantic relations in the verbal knowledge domain).

In case of the APM, the majority of studies do not directly assess EEG while participants perform the APM. Usually, the APM is rather assessed outside of the EEG as a co-variable to distinguish individual differences in Gf. One of the few studies that quantifies APM using EEG is by Jaušovec and Jaušovec (2012). In this study, upper alpha desynchronized during APM performance and this pattern was even more pronounced after participants completed a training to improve visual WM performance as well as executive functions (for example control of attention; Jaušovec & Jaušovec, 2012).

As already discussed, the CRT also requires convergent thinking (i.e., towards the end of the task in Row 2 and Row 3; Jaarsveld et al., 2015). Hence, for the sake of completeness, I will mention these results here. Jaarsveld and colleagues (2015) observed upper alpha (10-12 Hz) synchronization during Row 2 and particularly Row 3, most pronounced at prefrontal and frontal electrodes, while upper alpha desynchronized to a small extent. Furthermore, within each stage of the CRT (i.e., Toolbox, Row 1-3) the time-course of upper alpha followed a U-shaped function, where alpha was most synchronized at the beginning and the end, while in between alpha desynchronized slightly, regardless of the CRT-stage (Jaarsveld et al., 2015).

In the case of verbal convergent thinking assessed using RAT, Razoumnikova (2007) observed alpha (8-10 Hz and 10-13 Hz) desynchronization during RAT performance. This pattern was even more pronounced when participants were confronted with highly original verbal associates in contrast to less original ones (Razoumnikova, 2007). Other researchers used time frequency analysis to assess differences due to specific instructions for the RAT. In order to solve the RAT items, there are at least two strategies that participants can apply. Furthermore, these strategies can be prompted by specific instructions of the tasks (Landmann et al., 2014). These include 1) an analytical, trial-and-error approach or 2) an insight-driven strategy ("Aha! moment"; Stevens & Zabelina, 2019). In a study by Rothmaler and colleagues (2017), the authors observed that alpha power (especially in the right parietal hemisphere) increased when participants generated solutions in the RAT via insight in comparison to solutions that were reached analytically.

To conclude, different patterns of alpha synchronization and desynchronization demonstrate that these patterns of activation are not only dependent on the task (i.e., divergent or convergent task), but also on the cognitive strategy that is applied (i.e., insight vs. analytical problem solving). It is conceivable that the stimulus material as well as task specifications (see for example verbal tasks in Sviderskaya, 2011 vs. Razoumnikova, 2007) may also play a role in modulating alpha band activity.

6.3 Neural Correlates of Working Memory

As discussed in Chapter 5.3, WM plays an important role in both divergent and convergent thinking from a theoretical and behavioral perspective. Hence, it can be assumed that neural correlates of WM can also be observed during divergent and convergent thinking in both, fMRI and EEG.

Using brain imaging methods, it has been demonstrated that WM is associated with activity in several regions of the brain. These brain regions include cortical structures (e.g., bilateral frontal areas, anterior insula, posterior superior frontal gyrus and IFG, intraparietal sulcus and the superior parietal lobule) as well as sub-cortical structures (e.g., bilateral thalamus, and left basal ganglia; see Rottschy et al., 2012; Harding et al., 2015 for systematic overviews). Especially activity in the frontoparietal network have been of particular interest in regard to WM. For example, during a visual delay item match to categories task, Braunlich and colleagues (2015) observed two frontoparietal networks (i.e., the frontoparietal salience network and the frontoparietal central-executive network) were activated in different stages of the WM process (i.e., orientation, and complex stimuli processing vs. decision-making). More specifically, in a recent meta-analysis of Li et al. (2022) including 30 fMRI experiments and over 500 participants in total, visual WM was found to be associated with activity in the frontoparietal network including bilateral superior and MFG, IFG, left inferior parietal gyrus and bilateral superior parietal gyri among others, as well as the right inferior temporal cortex. By contrast, in a meta-analysis of 42 fMRI studies, Emch and colleagues (2019) found verbal WM to be associated with frontoparietal areas, right cerebellum, and basal ganglia structures. The authors further reported a bilateral frontal activation, a left-lateralization of parietal regions and a right-lateralization of the cerebellum during verbal WM consolidation (Emch et al., 2019).

Regarding oscillatory brain activity, WM has been observed to be related to activation in the theta band (4-7 Hz; see for example; Riddle et al., 2020; De Vries et al., 2020; Freunberger et al., 2011; Klimesch, 1999). More specifically, the latter reported an increase in theta amplitude with increasing

WM load and further, specific theta band modulations to be related to WM maintenance, retrieval processes and attention direction (Klimesch, 1999; see also Freunberger et al., 2011 for results on WM maintenance). Other researchers further reported theta band modulations associated to new information encoding, control processes, and cognitive load (Riddle et al., 2020; Schack et al., 2005). Regarding the topographical organization of this activation, fronto-parietal regions have been of particular importance (Wallis et al., 2015; Rutishauser et al., 2010; Sauseng et al., 2005), supporting the significance of the fronto-parietal network for WM-related processes (Harding et al., 2015). Lastly, there is evidence for a coupling of theta and alpha oscillations when prioritizing relevant and suppressing irrelevant information during a WM-task (Jaušovec & Jaušovec, 2012; see Riddle et al., 2020 for overview).

Although there are neuroscientific implications for the involvement of WM in divergent and convergent thinking (e.g., Sunavsky & Poppenk, 2020; Fink et al., 2009), there is only a limited amount of studies that investigate or directly compare neuronal activity in divergent or convergent thinking with WM. This is mainly because these tasks are very different in terms of task procedure (i.e., instructions and presentation) and in particular the stimulus material (Abraham et al., 2012). Hence, the specific interplay between divergent and convergent thinking with WM, especially their underlying brain or neurophysiological correlates remains a subject of debate. Furthermore, the specific association between divergent thinking, convergent thinking, and WM has previously not been assessed in regards to their underlying mechanism on a neuronal level.

Several EEG studies, however, investigate divergent thinking and its potential association to executive functions. For example, Jia and colleagues (2021) observed that changes in alpha power (8-12 Hz; besides other frequency bands) indicated different phases in the creative process, such as idea generation, and idea evaluation. In addition, the authors observed that self-reported cognitive load via NASA Task Load Index was highest, while self-reported cognitive control was lowest during idea generation phase (Jia et al., 2021). In another study, Benedek and colleagues (2014) investigated the relations of executive functions (i.e., updating, inhibition, and shifting) to divergent thinking performance on a behavioral level using a latent variable model. They found creative performance to be predicted by updating and inhibition, however this association was not found for shifting (Benedek et al., 2014). Also, Frith and colleagues (2021b) found that executive control processes (i.e., attentional control) significantly predicted divergent thinking originality during AUT. In a related line of research, but investigating EEG oscillatory activity, Benedek and colleagues (2011) observed that frontal alpha (8-12 Hz) synchronization in both divergent and convergent thinking was linked to high internal processing demands (i.e., top-down control), whereas the low internal processing condition did not elicit the same pattern. However, as already mentioned, most of these investigations focused exclusively on executive functions rather than the WM-related processes. Hence, the underlying relationship between divergent and convergent thinking and WM is still under debate (Frith et al., 2021b).

In conclusion: both, oscillatory activity and fMRI data provide evidence for WM (including distinct WM-subprocesses) being associated to specific fronto-parietal brain regions and further, to specific oscillatory activity in the theta band. At the same time, there is a lack of scientific evidence regarding the specific role and impact that WM processes have in both divergent and convergent thinking. This specific association between divergent thinking, convergent thinking, and WM has previously not been assessed using a designated study design that allows to separate WM-related oscillatory activity from both processes. Hence, in the following studies (Study 1 and 2) we aim to close this research gap by directly contrasting neuronal activity associated with each of these processes.

Chapter 7: STUDY 1

The following chapter includes the first study. It describes the investigation of divergent and convergent thinking beyond the influence of WM in the visuo-spatial knowledge domain. This study has been published[1] as part of the cumulative dissertation.

Alpha oscillatory evidence for shared underlying mechanisms of creativity and fluid intelligence above and beyond working memory-related activity

7.1 Abstract

Although the relationship between creativity and fluid intelligence has been studied extensively with divergent and convergent thinking tasks, the underlying neural mechanisms of this relationship are still under debate. As both have been associated to working memory (WM), the question arises if there are shared underlying mechanisms for creativity and fluid intelligence other than WM-related activity. The present study examined how creativity and fluid intelligence, as measured by the creative reasoning task (CRT) and Raven's Advanced Progressive Matrices (APM), respectively, are characterized by modulations in the upper alpha band (10–12 Hz) and if they share common mechanisms beyond the requirement to maintain information in WM. Hence, we subtracted WM-related activity, measured within the same knowledge domain and by using highly comparable stimulus material, from both divergent and convergent thinking activity. Furthermore, to account for the temporal variability in the creative process, we investigated divergent and convergent thinking at early, intermediate and late stages. By introducing this methodological approach, we provide evidence for a higher fronto-parietal alpha synchronization in divergent relative to convergent thinking, especially towards the end of the thinking phase. Furthermore, we provide evidence that creativity

---

[1] Eymann, V., Beck, A. K., Jaarsveld, S., Lachmann, T., & Czernochowski, D. (2022). Alpha oscillatory evidence for shared underlying mechanisms of creativity and fluid intelligence above and beyond working memory-related activity. *Intelligence*, *91*, 101630.

and fluid intelligence share underlying mechanisms above and beyond task demands that rely on WM processes.

7.2 Introduction

Creativity involves innovation and is defined as the ability to move beyond what is already known (Wertheimer, 1945/1968; Ghiselin, 1952). Furthermore, creativity can be defined as the ability to generate an idea for an open-ended problem (Guilford, 1967; Getzels & Csikszentmihalyi, 1976).These processes also relate to divergent thinking (Dietrich & Kanso, 2010; Benedek et al., 2011; Jaarsveld et al., 2012; Fink & Benedek, 2014), as characterized by generating multiple solutions or ideas for an open-ended problem (i.e., problem solving in an ill-defined problem space; Guilford, 1965; Getzels & Csikszentmihalyi, 1976; Benedek et al., 2014). Hence, creative thinking is typically assessed using divergent thinking tasks, in which participants are asked to come up with as many and as creative solutions as possible (e.g., the Alternate Uses task; AUT; Guilford, 1978) or the Torrance Test of Creative Thinking (TTCT; Torrance, 1974). These solutions are then scored in terms of fluency, flexibility, and originality (Guilford, 1967; Dietrich & Kanso, 2010; Lee & Therriault, 2013).

In contrast, general intelligence, in particular fluid intelligence defined as the ability to perceive relationships independent of previously accumulated knowledge (Horn & Cattell, 1967), is typically assessed using convergent thinking tasks, in which participants are asked to find the one correct solution for a given problem (i.e., well-defined problem space). A standard test for fluid intelligence that requires convergent thinking is Raven’s Advanced Progressive Matrices test (APM; Raven et al., 1998a). In the APM, participants are presented with a series of items, where each item consists of nine geometric patterns arranged in a 3 x 3 matrix. Eight cells contain a figure composed of one or several geometric components. These eight figures form a logical pattern (relations). The ninth cell of the matrix is empty and participants are asked to choose the one correct solution that completes the logical pattern. That means, in the case of the APM, convergent thinking occurs within a well-defined problem space, in which participants have to infer logical relations of a set of geometric figures.

The association between creativity and divergent thinking as well as between fluid intelligence and convergent thinking, however, is oversimplified, especially when looking at the intermediate steps of the creative process itself. The creative process starts with the generation of several ideas, which need to be selected and evaluated later based on their “fitting” to the desired outcome (Campbell, 1960; Jaarsveld & van Leeuwen, 2005; Ellamil et al., 2011). This means that creativity does not only involve divergent thinking (i.e., idea generation), it also requires convergent processes to fulfill the demands of creative problem solving (i.e., evaluation and selection; see also Getzels & Csikszentmihalyi, 1976; Smilanski, 1984; Smilanski & Halberstadt, 1986).

In order to understand the relationship of processes associated with creativity and fluid intelligence, cognitive neuroscientists investigate their underlying neural functions with various methods such as functional magnetic resonance imaging (fMRI) or Electroencephalography (EEG). Over the last decade, some researchers have compared brain activity during divergent thinking tasks (for example the AUT) with brain activity during tasks which do not require divergent thinking (for example n-back task) using fMRI (e.g., Abraham et al., 2012; Abraham et al., 2014; Japardi et al., 2018; Abraham et al., 2018) or EEG (e.g., Mölle et al., 1999; Razoumnikova, 2000; Danko et al., 2009; Benedek et al., 2011; Jauk et al., 2012). Other research focused on the divergent thinking process itself, focusing on distinct phases of creative idea generation and evaluation (e.g., Fink et al., 2009; Ellamil et al., 2012; Schwab et al., 2014; Rominger et al., 2018), or different stages of production and drawing (Jaarsveld et al., 2015; Jia and Zeng, 2021) assessed.

Considering that the creative process consists of at least two phases (idea generation and evaluation, i.e., divergent and convergent thinking), the high temporal resolution of EEG is especially useful to distinguish between these (see Srinivasan, 2007 as well as Dietrich & Kanso, 2010 for overviews). Time-frequency analysis shows temporal fluctuation of activation in different EEG frequency bands (e.g., alpha and theta) during cognitive processes. Temporal fluctuations of activation following a stimulus compared to a pre-stimulus reference interval is referred to as increase or decrease in event-related synchronization and was already assessed during creative thinking (see

Benedek et al., 2011 for overview). In this regard, upper alpha (10-12 Hz) synchronization has been linked to divergent thinking, observed over frontal and parietal regions (Jauk et al. 2012; for overview see Fink and Benedek, 2014), whereas desynchronization was observed in convergent thinking tasks in upper and lower alpha (7.5 – 10.5 and 10.5 – 12.5 Hz; Jauk et al., 2012). Jaarsveld and colleagues (2015) investigated synchronicity related to both, convergent and divergent thinking, during the creative reasoning task (CRT) by assessing alpha fluctuation during consecutive time intervals. For this study, the CRT was adapted for the requirements of EEG. In this version, participants are asked to create and sketch geometric patterns in subsequent thinking and drawing phases. Their data showed that divergent thinking (i.e., the beginning of each trial) was accompanied by upper alpha (10 – 12 Hz) desynchronization, whereas convergent thinking (i.e., the end of each trial) was related to upper alpha synchronization, especially at pre-frontal electrode sites. Additionally, when comparing different time intervals within the thinking phase, alpha was most synchronized in the first and the last interval of the creative process (i.e., prior to responding; Jaarsveld et al., 2015).

Fink and colleagues (2007) offered possible explanations for the functional significance of synchronization in the alpha frequency band. One is that in order to produce original ideas during creative thinking the brain is in a reduced or lower activity level, and this is reflected in enhanced alpha synchronization also known as “cortical idling” (Pfurtscheller et al., 1996; Fink et al., 2007). Another idea is that alpha synchronization reflects an active inhibition process, where cognitive, internal information processing is shielded from environmental, external information in creative operations (Fink et al., 2007). More specifically, Benedek and colleagues (2011) argued that frontal upper alpha synchronization is more influenced by specific tasks requirements (namely top-down control processes) and thus is common to both, divergent and convergent thinking. In sum, it might be necessary to differentiate alpha frequency bands when investigating divergent and convergent thinking. While upper and lower alpha show different activation patterns for these cognitive processes, upper alpha seems to be of particular relevance in this context. Furthermore, it seems relevant to consider timing, because the pattern of alpha activation changes over the time course of the creative process (as reported by Jaarsveld et al., 2015). Finally, it is still under debate whether there is a specific link between an increase or decrease in alpha synchronization and convergent or divergent thinking (Benedek et al., 2011), respectively.

The role of problem space and knowledge domain

When comparing fluid intelligence and creativity using convergent and divergent thinking tasks, respectively, there is one constraint: These tasks are based on entirely different experimental designs. Convergent thinking tasks require participants to identify logical relations (as in APM), whereas divergent thinking tasks involve the generation of ideas (as in AUT). Hence, these convergent and divergent thinking tasks operate neither within the same problem space nor the same knowledge domain. Jaarsveld and colleagues (2010) as well as Jauk and colleagues (2012) emphasized that both processes should, at least, be measured within the same knowledge domain and by the use of comparable stimulus material, and ideally by using the same paradigm.

One of the first attempts to measure creativity and fluid intelligence within the same task was done by Smilansky (1984), who asked participants to generate Raven-like matrices. Later, following the same idea, Jaarsveld and colleagues (2010; 2012; 2015, see Jaarsveld & Lachmann, 2017, for an overview) developed the creative reasoning task (CRT) encompassing both divergent and convergent thinking processes within the same open problem space. The CRT requires participants *to create* a 3 x 3 matrix of logically connected geometrical patterns, hence, participants generate a well-defined problem space rather than *solving* a well-defined problem as required in the APM (for more details see Methods section). Both CRT and APM are operating in the same knowledge domain, which is logical relationships between geometric components (Jaarsveld et al., 2015). Creating these matrices in the CRT involves generating the components of the geometrical figures as well as thinking about the logical relations of the patterns (Jaarsveld et al., 2012; 2015). The beginning of each trial (Toolbox, Row 1) requires mostly divergent thinking (i.e., creation and idea generation), whereas towards the end of each trial (Row 2, Row 3), the task requires more convergent thinking (i.e., assembling components based on logical relations). Therefore, the CRT can be regarded as a measurement for both divergent and convergent thinking within the same open problem space. Due to the strong similarities between CRT and APM it is possible to compare EEG alpha band activity in CRT and APM without any constraints regarding the format or requirements of the test.

The role of working memory

Prior research shows a strong correlation between working memory (WM; mainly working memory capacity) and fluid intelligence (e.g., Fukuda et al., 2010; Chuderski et al., 2012; Domnick et al., 2017). The latter study suggests that WM plays an important role specifically in solving geometric matrices, as required in the APM. In more detail, the cognitive process to solve geometric matrices involves further sub-processes. Those were described by Carpenter and colleagues (1990) as perceptual analysis (i.e., encoding, finding correspondences, and pairwise comparison), conceptual analysis (i.e., row-wise rule introduction, and generalization), and finally response generation and selection. Similarly, the cognitive sub-processes of *creating* geometric matrices, as required in the CRT, starts with generating possible components (divergent thinking) and evaluating their logical relations (convergent thinking; Jaarsveld et al., 2012). Hence, WM might play a crucial part for both solving and creating geometric matrices (i.e., APM and CRT, respectively).

Following this line of argumentation, WM related processes can be assumed to underlie both, convergent and divergent thinking, since it is necessary to keep information in an active state in order to compare and evaluate possible solutions or ideas (Benedek et al., 2011; De Dreu et al., 2012). Thus, we assume that WM is required in both, solving and creating geometric matrices (i.e., APM and CRT). There have been few studies investigating the underlying relationship between creativity and WM by comparing performance of creative thinking and WM tasks so far. However, these results are inconsistent as some reported strong correlations (Takeuchi et al., 2011; Lee & Therriault, 2013), whereas others did not observe any correlation between divergent thinking performance and WM (Lin & Lien, 2013; Smeekens & Kane, 2016), or only after controlling for participants’ general intelligence (De Dreu et al., 2012). One of the few studies that directly compared neuronal (fMRI) activity in divergent thinking (i.e., AUT) with WM-related activity (i.e., n-back task) indicates that the explanatory power is limited because of strong qualitatively differences between the tasks, especially in terms of stimulus material, as well as task instructions and presentation (Abraham et al., 2012).

In a related line of research, several investigations have focused on a potential association between executive functions and creative thinking. For example, Benedek and colleagues (2014) found that creative performance was predicted by updating and inhibition, but not shifting. Frith and colleagues (2021b) found that executive control mechanisms predict the output originality of divergent thinking. Also, the same authors observed that the strong relationship between fluid intelligence and divergent thinking was explained by attentional control (i.e., one of the core components of executive function; Frith et al., 2021b). However, as most of these investigations focused on the performance of various executive functions rather than the WM process per se, the *specific* relationship between creativity and WM is still under debate (Frith et al., 2021b). To the best of our knowledge, the specific association between creativity, fluid intelligence, and WM has previously not been assessed by directly contrasting neuronal activity associated with each of these processes.

7.3 The present study

Our goal is to investigate the neurophysiological mechanisms underlying creativity and fluid intelligence beyond the shared requirement to hold information active in WM. For this purpose, the WM task should operate within the same knowledge domain (i.e., domains that are organized by general principles; Jaarsveld & Lachmann, 2017) and use the same stimulus material as CRT and APM in order to keep the resulting cognitive processes comparable. Therefore, we designed a WM-version of CRT: CRT-WM. This newly designed task meets two requirements: First, the stimulus material is similar to the one in the original CRT and APM (i.e., recombined geometric patterns presented in matrices), referring to a shared visuo-spatial knowledge domain. Second, these geometric patterns do not have any logical relations, therefore participants cannot use specific strategies to encode and recall the stimuli but rather need to rely on their WM capacity.

As the outcome of creative performance is necessarily the result of several interleaved cognitive sub-processes, neurophysiological measures of the underlying mechanisms are optimally suited to dissociate component processes and shed light on their temporal course. Therefore, we collected EEG data while participants performed all three tasks. Since we expect WM to play an important role in both APM and CRT, this task demand may overestimate the commonalities in these particular tests of intelligence and creativity. For this reason, we compare both processes above and beyond the shared requirement to maintain information in WM. First, we evaluate whether WM related brain activity can be observed during the new CRT-WM paradigm. Hence, we analyze theta band (4 – 7 Hz) oscillatory activity serving as an indicator of WM-related activity (for example Schack et al., 2005; Freunberger et al., 2011; Riddle et al., 2020; Klimesch, 1999 for review). Additionally, we evaluate whether there is a systematic difference in upper alpha band (10 – 12 Hz) activation regarding the specific timing. We differentiate between divergent and convergent thinking by taking advantage of the four stages of the CRT (Toolbox, Row 1, Row 2, and Row 3). In the beginning of each trial (stages: Toolbox and Row 1), we expect mainly activity related to divergent thinking, but with proceeding stages (stages: Row 2 and Row 3) we expect an increase of activity related to convergent thinking (see Jaarsveld et al., 2015).

Our first research question focuses on how upper alpha band (10 – 12 Hz; Jaarsveld et al., 2015) oscillatory activity reflects divergent and convergent thinking, above and beyond the shared requirement to maintain information in WM. In order to do that, we subtract WM-related upper alpha band oscillatory activity observed during the performance of the CRT-WM from the convergent- and divergent-thinking-related upper alpha band observed during the performance of the APM (i.e., convergent thinking) and CRT (i.e., divergent and convergent thinking). Our second research question focuses on the temporal course of this activation. Hence, we examine whether there is a temporal change in activity during CRT and APM beyond WM related activity. It is important to investigate upper alpha activity at different intervals in time within each stage of the CRT, as the cognitive process to create and to solve geometric matrices consists of sub-processes likewise. We investigate upper alpha activity in three intervals: at the beginning, the middle and the end of each trial (or CRT stage, respectively) related to divergent and convergent thinking in the CRT (similar to Jaarsveld et al., 2015) and the APM.

7.4 Methods

Participants

All participants were undergraduate students from the University of Kaiserslautern, and, according to self-reports, were right-handed, had normal or corrected-to-normal vision, had no diagnosis of psychological or neurological disorders, and did not consume medication affecting the central nervous system. Every participant provided written informed consent after being informed about the procedure and having had the possibility to ask questions. The study was conducted according to the Declaration of Helsinki (World Medical Association, 2013) and approved by the ethical review board of the Faculty of Social Science of the University of Kaiserslautern. We recorded EEG data from 21 students who received course credit or monetary compensation. After initial data preprocessing, we excluded participants with an insufficient number of artifact free segments in the CRT Row 3 ($n = 2$) and Row 1 ($n = 1$), and technical difficulties ($n = 1$). Thus, EEG data from 17 students were analyzed (7 female; M_{age}: 22.41 years, $SD = 2.03$ years, range: 18 – 25 years).

Materials and procedure

In the following, we describe our stimulus material. First, we introduce CRT and APM with respect to the material and their rationale. Subsequently, we will introduce the CRT-WM, a WM version of CRT, that was developed specifically for this study.

For measuring creativity, we used the EEG adaptation of the CRT from Jaarsveld and colleagues (2015). In this task participants are asked to generate a 3x3 matrix of geometric figures with a logical connection. Notably, distinct phases of subsequent thinking and drawing in each CRT trial were self-paced. Each trial consisted of four stages (i.e., Toolbox, Row 1, Row 2, Row 3). Participants were given separate answering sheets (see Figure 10) for the 10 CRT trials that were performed. During the task, participants saw instructions on the computer screen helping them to navigate through the task. Each trial started with a thinking phase, in which participants were asked to come up with the geometric figures they want to use for the matrix (i.e., Toolbox). As soon as participants generated an idea, they were asked to press a key on the PC keyboard to enter the drawing phase of the Toolbox. As soon as they were done drawing, participants pressed another key to enter the thinking phase and the subsequent drawing phase of Row 1. This procedure was repeated until the end of Row 3. Within the stages of Row 1, Row 2, and Row 3 participants were required to think about how to put together the components of the Toolbox in such a way that the final matrix contained figures with a logical relation. Hence, the CRT Toolbox requires mostly divergent production, whereas subsequent Rows require additional convergent operations. Participants were instructed to design their matrix as original and creative as possible, but also to make sure that another person would be able to understand the connections within these figures.

For measuring fluid intelligence with a convergent thinking task, we used the Advanced Progressive Matrices Test (APM; Raven et al., 1998a). The APM is a non-verbal assessment of higher-order cognitive abilities designed for adults with above average intelligence (Arthur & Day, 1994). It consists of 36 items that gradually increase in difficulty. It requires the participant to complete a 3x3 matrix by adding a correct figure out of eight options. Choosing the correct figure can be seen as logical reasoning since the matrix is a closed problem space and the figures have logical relations. The task was self-paced, which means that participants had no time restrictions to solve each item. Overall, participants had 15 minutes to complete the task and they were instructed to work as fast and accurate as possible.

For measuring WM, we used the figures of 20 CRT matrices that were designed by participants of a prior CRT study (manuscript in preparation). All figures of the CRT matrices were randomly put together in a set of three cells, controlling for the number of components in each cell (see Figure 10). The resulting items were digitalized to be presented on a computer screen. For each CRT-WM trial, one item was presented for 30 seconds. After that, participants were asked to draw the figures on a sheet with an empty 3x1 cell matrix. In total, the CRT-WM consists of 30 items. The duration of the drawing phase is self-paced.

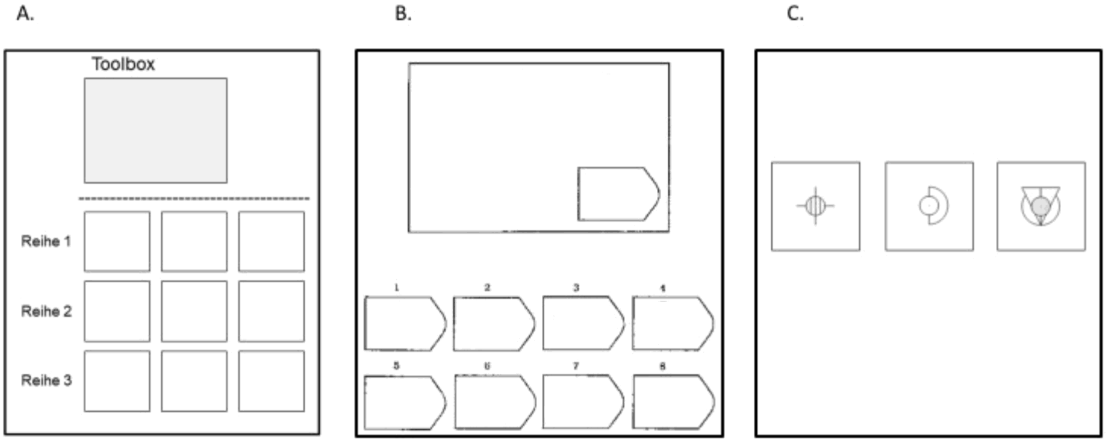


Figure 10. Stimulus Material. We used the CRT to assess divergent and convergent thinking within the same task (A). Participants are asked to create components (Toolbox) and use them to generate a logically coherent pattern of geometrical figures during subsequent stages (Row 1 – Row 2). Raven's APM was used to assess convergent thinking (B). Participants are asked to complete the geometric pattern in a logical way, using one of eight figures on the bottom. Original APM items are not printed due to copyright concerns, hence this figure only illustrates the layout of the items. The CRT-working memory (CRT-WM) was used to assess working memory (C). It requires participants to encode three geometric figures (consisting out of different geometric components) within 30 s and subsequently recall and draw them into a form sheet.

We performed the same experimental order of tasks for all participants, which was CRT, APM and lastly, CRT-WM (see Figure 11). We decided against a counterbalanced order to ensure that the performance of CRT was not confounded by a prior presentation of the stimulus material in APM and CRT-WM. As the stimulus material is highly comparable, operating with the same stimuli before might influence their creative outcome and hence influence the use of their full creative potential in this task.

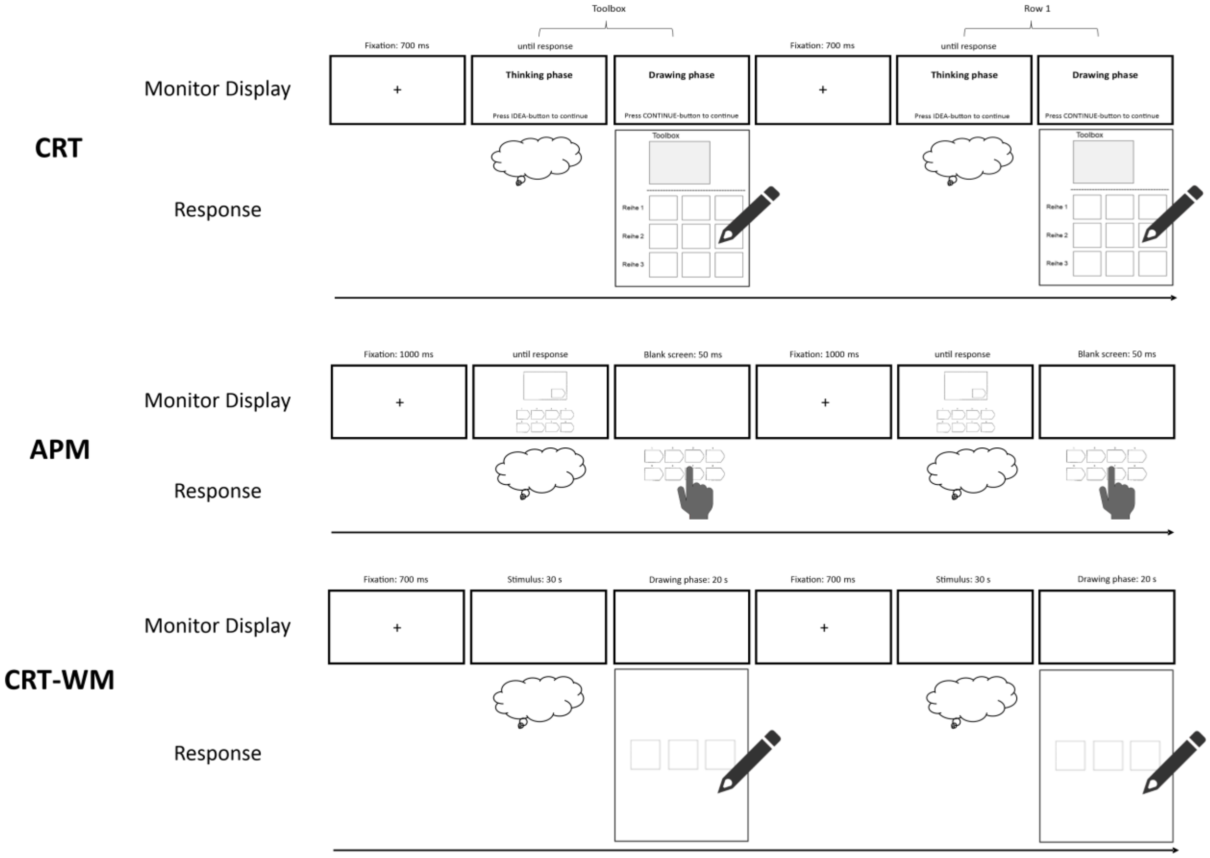


Figure 11: Overview of task procedure and measurement intervals. Each trial of the CRT (top) started with a fixation cross of 700 ms. Next, participants started with the self-paced thinking phase for the Toolbox. As soon as they generated components for the subsequent geometrical figure, they pressed the IDEA-button and the drawing phase started. As soon as participants finished drawing the components, they pressed the CONTINUE-button and they entered the same procedure for Row 1, then Row 2, and finally Row 3. Each trial of the APM (middle) started with a fixation cross of 1000 ms. In the following, participants were presented with the geometric pattern. As soon as participants chose the corresponding figure (one of eight figures on the bottom), they were asked to indicate their choice by pressing a corresponding button. The CRT-working memory (CRT-WM; bottom) started with a fixation cross of 700 ms. Subsequently, the stimulus was presented for 30 s and participants were asked to remember the three geometric figures. After the stimulus disappeared, participants were asked to draw the figures into a form sheet within 20 s.

EEG recording

EEG was recorded with 27 Ag/AgCl cap-mounted electrodes (EasyCap GmbH; Gilching, Germany) positioned on an extended 10 – 20 system (Jasper, 1958), plus two electrodes placed at the mastoids and four electrodes around the eyes, with the BrainVision Recorder (BrainProducts GmbH; Gilching, Germany). We used the electrodes around the eyes (above and below the right eye, and beside the right and left eye) to record eye-movements. The ground electrode was placed at the electrode site AFz. The electrode positioned at electrode site FCz was used as online reference. The signal was recorded with electrode impedances lower than 10 KΩ. The sampling frequency was 500 Hz. Processing of the EEG data was performed by using Brain Vision Analyzer 2.1 (Brain Products, Gilching, Germany). Only for one participant, we used a spline interpolation on one electrode (F3) with many artifacts. The signal was re-referenced offline to the average of all electrodes except for eye electrodes. We used a bandpass filter (zero phase shift Butterworth) from 0.5 Hz to 30 Hz (with 12 dB/oct). We performed a manual artifact rejection to remove artifacts based on body movements occurring during the drawing phase of CRT and CRT-WM. We corrected for eye movement artifacts by using an independent component analysis (ICA) with the infomax restricted algorithm (Jung et al., 1998). For the ICA, we selected an artifact free interval as a training data set for computing the unmixing matrix. ICA components were automatically identified by picking up blinks and saccades, as evidenced by their characteristic shape and location (at frontal electrode sites). After removing components semi-automatically (on average 2.1 per participant; ranging between 2 and 3 deleted components), the EEG signal was reconstructed.

The self-paced speed in both APM and CRT resulted in different lengths in reaction times of the thinking phase; hence, segment lengths differed for each participant in each trial. We excluded segments of thinking phases that were shorter than eight seconds (see below), as we analyzed the data in three intervals (beginning, middle and end of the task). Each of these intervals has a length of 2000 ms, resulting in 6000 ms for each thinking phase. Furthermore, to account for smearing effects of frequency filters, we removed the first and last 1000 ms of each thinking phase (see for example Cohen, 2014), which leads to a minimum length of 8000 ms for each thinking phase. For CRT, this resulted in an average of 32 segments for each participant (*SD* = 5; range between 22 and 38 segments). For APM, we only included correctly solved items longer than eight seconds in our oscillatory analysis; due to this criterion we excluded nine APM segments for the whole sample (ranging between 0 and 2 excluded segments per individual). The average number of segments retained for each participant in APM was 21 (*SD* = 3; range between 17 and 26 segments).

Artifacts were removed automatically when (1) a voltage step of 50 µV/ms was detected, (2) a voltage difference of 200 µV occurred in any 200 ms interval, or (3) a low amplitude of 0.5 µV occurred in a 200 ms interval. Due to the artifact rejection on average 0.15 % (*SD* = 0.23 %) of all trials were removed in CRT, on average 0.77 % (*SD* = 0.82 %) of all trials were removed in APM, and 0.46 % (*SD* = 0.40 %) of all trials were removed in CRT.

Spectral changes of oscillatory activity

Spectral changes of oscillatory activity in the time-frequency domain were calculated by the means of complex Morlet's wavelet transform, with wavelets of seven cycles between 1 and 30 Hz, in .5 Hz steps. Percent change of each trial was calculated by contrasting them to a baseline of 300ms (-400 to -100 ms pre-stimulus) where participants looked at a fixation cross. Thus, we obtained a relative increase and decrease (i.e., synchronization and desynchronization) in oscillatory activity. We analyzed three intervals of 2000 ms within each segment. The first interval starts 1000 ms after the beginning of the thinking phase (1000 – 3000 ms). The third interval ends 1000 ms before end of thinking phase. The second interval of 2000 ms was set in the middle of each segment. As both tasks were self-paced, the selection of the interval position (beginning, middle, end) is participant-specific, rather than fixed to an absolute interval of time across the full sample. This approach accounts for individual differences of processing speed and allows to observe the thinking processes more realistically. Spectral changes were averaged over all segments for each participant of APM and CRT-WM. For the CRT this was done for all stages separately. In CRT-WM we extracted the wavelet-layers for theta (4-7 Hz) and searched local maxima for individual peaks to extract values for the layer with the highest peak for each participant. As the final step, we extracted the wavelet-layers for upper alpha band (10-12 Hz), using the same method as for the theta band for each interval (in APM and CRT-WM) and for each interval in each stage in CRT for each participant.

Analysis of behavioral data

Behavioral data were analyzed with SPSS 25 (IBM Corporation, Armonk, NY). For CRT, we computed the total score that involves two sub-scores (cf., Jaarsveld et al., 2012). For CRT-WM, we counted the number of correctly recalled geometrical components within each cell (see Figure 10), retaining only items with at least two correctly recalled components (correct form and location). As a result, no items of CRT-WM needed to be excluded from further analysis. For APM, we only included correctly solved items that participants generated within the 15 minutes test time.

Analysis of oscillatory activity

The oscillatory activity was analyzed with SPSS 25. This analysis was performed by averaging seven electrode-pairs according to Jaarsveld and colleagues (2015) for each participant. These regions of interest (ROIs) were FP1/FP2, F3/F4, F7/F8, C3/C4, P3/P4, P7/8, and T7/T8. We decided against a data-driven approach in order to ensure comparability with the former EEG study (Jaarsveld et al., 2015). We analyzed theta oscillatory activity serving as empirical measure confirming WM activity during the newly developed CRT-WM task. Oscillatory activity for CRT-WM was analyzed using a repeated measurements ANOVA for 7 ROIs. Additionally, we analyzed alpha oscillatory activity serving as empirical measure for a differentiation between divergent and convergent thinking in the temporal course of each CRT stage. Oscillatory activity was analyzed using a repeated measurements ANOVA for the 4 stages of the CRT (i.e., Toolbox, Row 1, Row 2, Row 3). According to this analysis, we separated the four stages CRT into $\mathrm{CRT}_{\mathrm{div}}$ (containing predominantly divergent thinking during Toolbox and Row 1) and $\mathrm{CRT}_{\mathrm{con}}$ (containing predominantly convergent thinking during Row 2 and Row 3).

The main analysis was based on each of the three processes while removing WM activity by subtracting the activity of CRT-WM from $\mathrm{CRT}_{\mathrm{div}}$ ($\mathrm{CRT}_{\mathrm{div|WM}}$), $\mathrm{CRT}_{\mathrm{con}}$ ($\mathrm{CRT}_{\mathrm{con|WM}}$), and APM ($\mathrm{APM}_{\mathrm{|WM}}$), respectively. For statistical analyses, we performed a repeated measurements ANOVA on these upper alpha difference values, serving as dependent variable. As within subject factors, we compared PROCESS ($\mathrm{CRT}_{\mathrm{div|WM}}$, $\mathrm{CRT}_{\mathrm{con|WM}}$, and $\mathrm{APM}_{\mathrm{|WM}}$), INTERVAL (Int1, Int2 and Int3), and AREA (FP1/FP2, F3/F4, F7/F8, C3/C4, P3/P4, P7/8, and T7/T8). We report only those effects and interactions with p-values below the conventional significance value of .05. All recorded p-values were Greenhouse-Geisser corrected, when needed (Geisser & Greenhouse, 1958); for readability uncorrected degrees of freedom were reported. To clarify significant interaction effects, we used Bonferroni corrected post-hoc analysis.

7.5 Results

Results of behavioral data

For the CRT-WM, we computed a total score that includes the total number of correctly drawn components for each item. On average, participants reproduced over 80% of the components in the three cells of each item correctly (*M* = 82.21, *SD* = 20.71%) with a range between 11.76% and 100.00%. For the CRT, we computed a total score including one score for reasoning and one for creativity, according to the scoring method of Jaarsveld and colleagues (2012). Our participants' total scores ranged between 2 and 192 per Item (*M* = 53, *SD* = 20.77). For the APM, we only analyzed correctly solved items. Within 15 minutes, participants solved between 18 and 28 items correctly (*M* = 21.29, *SD* = 2.66).

Results of oscillatory activity

All results of oscillatory de-/synchronization are reported the percentage change relative to the baseline activity, which reflects the relative increase and decrease in oscillatory activity.

For the CRT-WM, we observed theta (4 – 7 Hz) synchronization for all electrodes throughout all three intervals (Int1 *M* = 29.37, *SD* = 2.66; Int2 *M* = 29.92, *SD* = 2.28; Int3 *M* = 34.14, *SD* = 5.51). No differences were observed between the intervals; all *p*s > .25 (see Figure 12). Hence, we interpret this result as good evidence that the new CRT-WM paradigm taps WM activity.

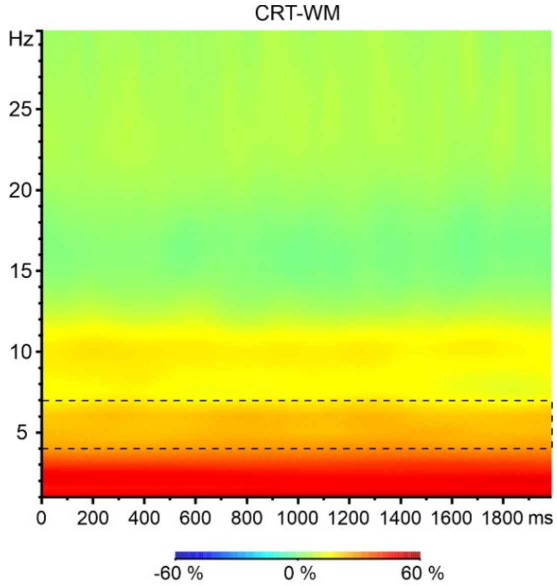


Figure 12. Theta band (4–7 Hz; dashed frame) oscillatory activity in CRT-WM.

As expected, for CRT, we observed upper alpha (10 – 12 Hz) synchronization for Toolbox and Row 1 as compared to Row 2 and Row 3. As expected, based on the task requirements, we did not find significant differences regarding oscillatory activity between CRT Toolbox and Row 1 (p = .23), neither between Row 2 and Row 3 (p = .29). Therefore, in further analysis we combined both consecutive stages and refer to Toolbox and Row 1 as $\mathrm{CRT_{div}}$ and Row 2 and Row 3 as $\mathrm{CRT_{con}}$. Hence, we confirmed that the four stages of the CRT need to be dissociated in terms of cognitive processes, i.e., convergent thinking following upon divergent thinking.

In our main analysis, where we used the subtracted values of WM related activity (measured by the CRT-WM) from $\mathrm{CRT_{div}}$ (i.e., $\mathrm{CRT_{div|WM}}$), $\mathrm{CRT_{con}}$ (i.e., $\mathrm{CRT_{con|WM}}$), and APM (i.e., $\mathrm{APM_{|WM}}$), we observed a threefold interaction effect between PROCESS, INTERVAL, and AREA, $F(24,384) = 2.88$, $p < .001$, $\eta_p^2 = .15$, using upper alpha activity as dependent variable. In line with our expectations, post-hoc tests revealed a significantly higher activation in $\mathrm{CRT_{div|WM}}$ in contrast to $\mathrm{APM_{|WM}}$. These differences were found only between Int2 and Int3 for the following electrodes: F3/F4 Int2 ($p < .05$), F3/F4 Int3 ($p < .005$), P3/P4 Int2 ($p < .05$), P3/P4 Int3 ($p < .01$), and P7/P8 Int2 ($p < .05$), P7/P8 Int3 ($p < .05$).

In the following, we report our interaction effects to further decompose our threefold-interaction. We observed an interaction effect between PROCESS and INTERVAL, *F*(4,64) = 6.19, *p* < .001, η_p^2 = .28 (see Figure 13). Post-hoc tests revealed a significantly higher alpha synchronization in CRTdiv|WM Int2 (*M* = 39.64, *SE* = 7.46, 95% CI [23.83, 55.46]) than CRTdiv|WM Int3 (*p* < .05; *M* = 9.32, *SE* = 5.61, 95% CI [-2.58, 21.23]). However, there was no significant difference between CRTdiv|WM Int1 and Int2, as well as no significant differences within CRTcon|WM and APM|WM. We observed an interaction effect between PROCESS and AREA, *F*(12, 192) = 9.25, *p* < .001, η_p^2 = .37. Post-hoc tests indicated a higher alpha synchronization in Fp1/Fp2 electrodes in CRTdiv|WM (*M* = 19.50, *SE* = 5.21, 95% CI [8.45, 30.53]) as compared to in Fp1/Fp2 electrodes in CRTcon|WM (*p* < .05; *M* = -10.50, *SE* = 5.66, 95% CI [-22.49, 1.49]), and Fp1/Fp2 electrodes in APM|WM (*p* < .005; *M* = -18.13, *SE* = 4.96, 95% CI [-28.64, -7.62]). In F3/F4 CRTdiv|WM (*M* = 19.88, *SE* = 3.88, 95% CI [11.65, 28.11]), alpha was significantly more synchronized in contrast to F3/F4 CRTcon|WM (*p* < .005; *M* = -12.46, *SE* = 4.56, 95% CI [-22.13, 2.80]) as well as in contrast to the APM|WM electrodes F3/F4 (*p* < .005; *M* = -13.03, *SE* = 5.93, 95% CI [-25.60, -.46]). For CRTdiv|WM parietal electrodes P3/P4 (*M* = 29.08, *SE* = 4.82, 95% CI [18.87, 39.29]), post-hoc tests indicated significantly higher activation than in CRTcon|WM electrodes P3/P4 (*p* < .01; *M* = -25.56, *SE* = 7.23, 95% CI [-41.30, -9.81]). For CRTdiv|WM electrodes P7/P8 (*M* = 24.05, *SE* = 4.92, 95% CI [13.62, 34.49]), post-hoc tests indicated a significantly higher alpha synchronization than in CRTcon|WM electrodes P7/P8 (*p* < .05; *M* = -16.65, *SE* = 5.42, 95% CI [-28.13, -5.16]) as well as significantly higher activated than APM|WM electrodes P7/P8 (*p* < .005; *M* = -39.40, *SE* = 6.21, 95% CI [-52.58, -26.23]). We also observed an interaction effect between INTERVAL and AREA, *F*(12,192) = 4.03, *p* < .001, η_p^2 = .20. Post-hoc tests indicated that regardless of the process (CRTdiv|WM, CRTcon|WM, and APM|WM), prefrontal electrodes Fp1/Fp2 in Int2 (*M* = .21, *SE* = 4.03, 95% CI [-8.34, 8.77]) were significantly less desynchronized in contrast to Fp1/Fp2 electrodes in Int3 (*p* < .05; *M* = -11.13, *SE* = 4.52, 95% CI [-20.72, -1.55]).

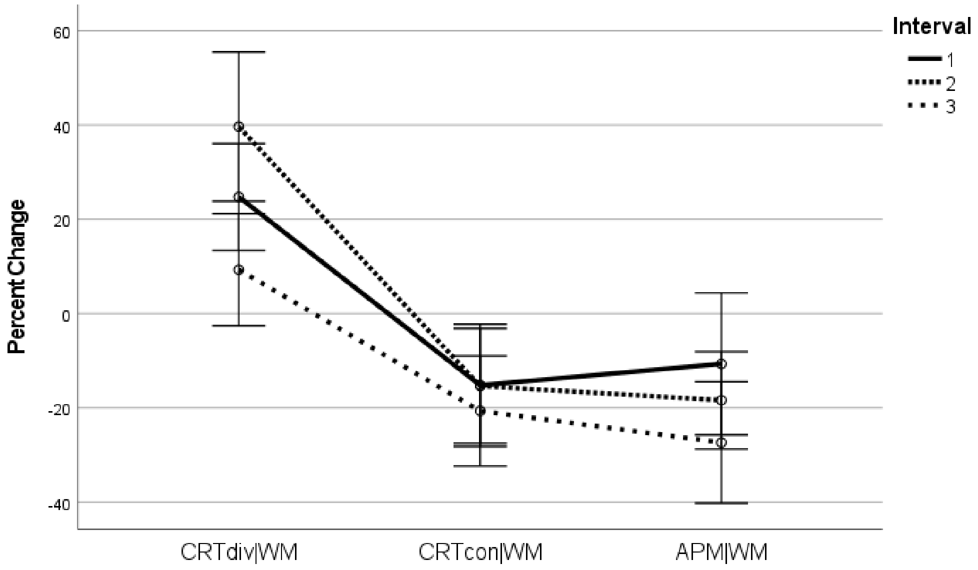


Figure 13. Results for upper alpha oscillatory activity over all electrodes for CRTdiv|WM, CRTcon|WM, and APM|WM. We observed significantly higher activation in CRTdiv|WM Int2 (dotted) in contrast to CRTdiv|WM Int3 (dashed). No significant differences were observed for CRTdiv|WM Int1 (black) and Int2, as well as within CRTcon|WM and APM|WM. Error bars indicate 95% confidence intervals.

As expected, we observed a main effect of PROCESS, *F*(2, 32) = 27.15, *p* < .001, η_p^2 = .63 with strong synchronization in CRT$_{div|WM}$ (*M* = 24.57, *SE* = 4.34, 95% CI [15.38, 33.77]) in contrast to CRT$_{con|WM}$ (*p* < .001, *M* = -17.07, *SE* = 5.49, 95% CI [-28.73, -5.41]) and APM$_{|WM}$ (*p* < .001, *M* = -18.79, *SE* = 5.43, 95% CI [-30.29, -7.28]), see Figure 14. We also observed a main effect of INTERVAL, *F*(2, 32) = 7.11, *p* < .005, η_p^2 = .31 where Int3 was stronger desynchronized (*p* < .05, *M* = -12.89, *SE* = 4.76, 95% CI [-22.98, -2.80]) in contrast to Int1 (*M* = -.37, *SE* = 4.56, 95% CI [-10.04, 9.30]) and Int2 (*M* = 1.97, *SE* = 2.93, 95% CI [-4.24, 8.18]). Furthermore, we observed a main effect of AREA, *F*(6, 96) = 5.74, *p* < .001, η_p^2 = .26), indicating that both parietal ROIs were most desynchronized (*M* = -14.05, *SE* = 4.92, 95% CI [-24.47, -3.63]) for P3/P4 and (*M* = -10.67, *SE* = 3.27, 95% CI [-17.60, -3.73]) for P7/P8, whereas the central ROI (C3/C4) was most synchronized (*M* = 8.01, *SE* = 4.98, 95% CI [-2.55, 18.56]).

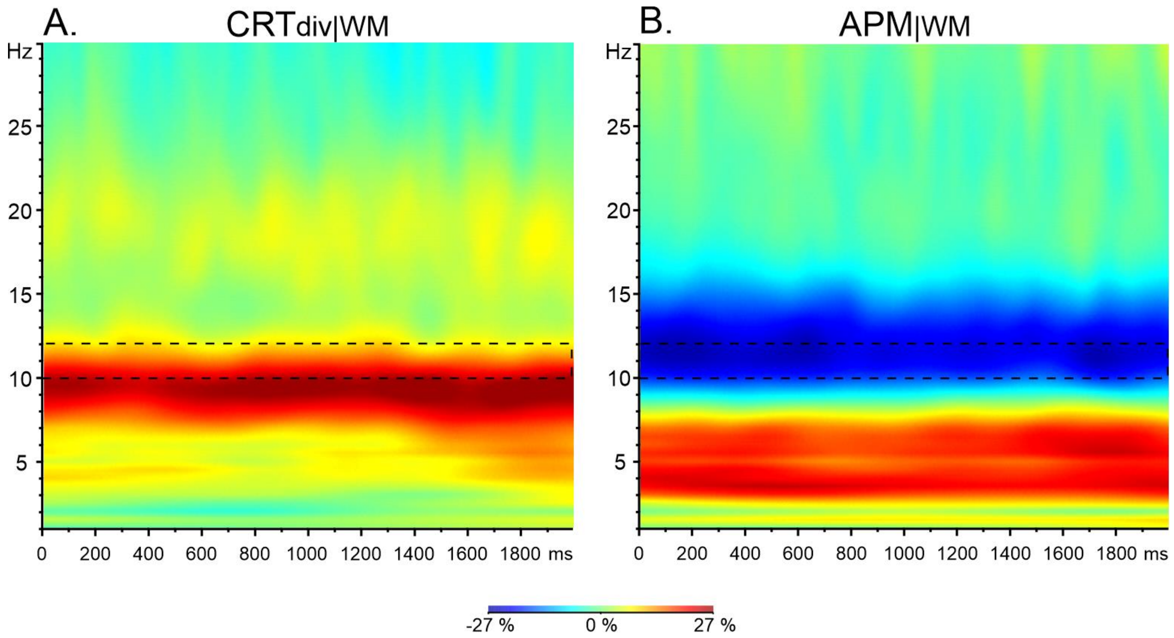


Figure 14. Upper alpha (10–12 Hz; dashed frame) oscillatory activity in CRTdiv|WM (A) and APM|WM (B). Grand averages for every task after subtracting oscillatory activity measured by CRT-WM. Grand averages include all electrodes and all participants to illustrate increase and decrease of upper alpha band oscillations analyzed here.

To summarize, when subtracting WM-related activity, we observed a higher synchronization of upper alpha in CRTdiv|WM in contrast to CRTcon|WM and APM|WM. While we did not observe differences in upper alpha between intervals during convergent thinking, higher synchronization during divergent thinking was most pronounced in Int1 and Int2 as compared to Int3 at frontal as well as parietal electrodes sites.

7.6 Discussion

In this study, we investigated the relationship between divergent and convergent thinking beyond the shared attributes due to WM requirements within the same knowledge domain and by using highly similar stimulus material. To our knowledge, this is the first attempt to separate WM-related oscillatory activity from divergent and convergent thinking related oscillatory activity in comparable tasks (APM, CRT, and CRT-WM). Hence, we subtracted WM-related activity from the activity related to divergent thinking (CRTdiv|WM) and convergent thinking (APM|WM and CRTcon|WM). We observed a synchronization in upper alpha band (10 – 12 Hz) oscillatory activity in divergent thinking ($\text{CRT}_{\text{div|WM}}$) as compared to convergent thinking ($\text{APM}_{\text{|WM}}$ and $\text{CRT}_{\text{con|WM}}$). Additionally, we examined activity during three subsequent intervals (beginning, middle, and end) during each trial. We observed a higher synchronization at the beginning and middle as compared to the end of the trial.

In a first step, we validated our new WM paradigm and found good evidence that CRT-WM measures WM by observing theta (4 – 7 Hz) synchronization. We observed sustained theta synchronization throughout the trials of the task. This is in line with prior studies that reported theta synchronization as an indicator of WM-related processes, such as encoding and prioritizing of new information, attention, control processes, increasing task demands, and cognitive load (Schack et al., 2005; Freunberger et al., 2011; Riddle et al., 2020; Klimesch, 1999 for review). Thus, we interpret this result as good evidence, as it is highly consistent with these prior studies. We conclude that the CRT-WM task is therefore, appropriate to distinguish between WM processes and divergent and convergent thinking.

The role of oscillatory alpha activity

In a second step, we replicated and extended the findings of Jaarsveld and colleagues (2015) regarding different stages of CRT (Toolbox, Row 1, Row 2, and Row 3). In line with prior research (see Fink et al., 2009; Jauk et al. 2012; Fink and Benedek, 2014), we observed upper alpha synchronization in the mainly divergent thinking stages of CRT (Toolbox and Row 1), whereas we observed upper alpha desynchronization in the predominantly convergent thinking stages of CRT (Row 2 and Row 3). On the first glance, this appears to contrast the results by Jaarsveld and colleagues (2015), as they observed divergent thinking accompanied by alpha desynchronization and convergent thinking accompanied by alpha synchronization. Furthermore, they reported significant differences between Toolbox and Row 2 as well as Toolbox and Row 3, with highest synchronization in Row 3 (Jaarsveld et al., 2015). For alpha synchronization observed in convergent stages, they suggested that it represents the “active maintenance of relevant information” (i.e., WM; Jaarsveld et al., 2015; p.177). They further concluded that alpha synchronization, especially at frontal sites, “reflects increasing working memory load in those stages” (Jaarsveld et al., 2015; p.177).

Removing WM-related activity

Introducing a new methodological approach, we subtracted WM-related activity from both CRT$_{\text{div}}$, CRT$_{\text{con}}$, and APM in the present study, thereby, removing those WM-related processes that explain, according to Jaarsveld and colleagues (2015), an upper alpha synchronization during convergent stages. Our first research question was how oscillatory activity in upper alpha band (10 – 12 Hz) is represented after removing WM-related activity. Our results show that the differences between divergent and convergent thinking cannot solely be explained by different degrees or timing of common WM-related activity. In contrast to Jaarsveld and colleagues (2015), we also observed desynchronization of upper alpha during convergent thinking (i.e., CRT$_{\text{con|WM}}$ and APM$_{\text{|WM}}$). This observation can also be a result of the subdivision of CRT in CRT$_{\text{div}}$ and CRT$_{\text{con}}$, which is different from Jaarsveld and colleagues (2015). The desynchronization of alpha has been linked to convergent thinking, more specifically fluid intelligence tests (Neubauer & Fink, 2003; Grabner, et al., 2004; Jauk et al., 2012). In line with prior research (see for example Fink et al., 2009; Jauk et al., 2012; Fink and Benedek, 2014), we observed upper alpha synchronization in the mainly divergent thinking stages of CRT (CRT$_{\text{div|WM}}$). Additionally, in line with prior research (Stipacek et al., 2003; Fink et al., 2005; Jauk et al., 2012), we observed upper alpha desynchronization during predominantly convergent thinking in the CRT (CRT$_{\text{con|WM}}$) and APM (APM$_{\text{|WM}}$). Thus, the pattern of alpha activation observed here is consistent with the literature, even in the absence of WM-related activity. At the same time, measuring creativity and fluid intelligence within the same knowledge domain demonstrates that these processes share characteristics above and beyond WM. Prior studies using different paradigms suggest that modulations in the upper alpha band are also observed irrespective of task requirements and the stimulus material. While we cannot dissociate between the proposed mechanisms of active inhibition (Fink et al., 2007) and top-down control (Benedek et al., 2011) in the present context, we provide further evidence that modulations in the alpha band are common to both, divergent and convergent thinking.

Regarding our second research question, we investigated if upper alpha activity differs within the thinking phases by analyzing the activity in three intervals. We observed significantly higher alpha synchronization in the second interval than in the third interval of the CRT$_{\text{div|WM}}$, suggesting more synchronization towards the end of divergent thinking phases. Furthermore, we did not find any significant differences between intervals within CRT$_{\text{con|WM}}$ and APM$_{\text{|WM}}$. This implies that increases in alpha activity reflect sub-processes of the cognitive process to create (but not to solve) geometrical matrices. Prior studies that investigated temporal patterns (in 3 versus 4 intervals) of alpha during creative thinking reported a U-shaped pattern as alpha synchronized in the first and last interval, but desynchronized in between (Schwab et al., 2014; Jaarsveld et al., 2015). One crucial difference between these paradigms and our approach is how individual thinking times are incorporated into neurophysiological analyses. A particular strength of our approach was that we accounted for the considerable variability of the temporal duration in each trial by assessing the beginning, middle and end based on individual thinking times in each trial. In addition, the pattern analyzed in our study reflects the difference between creative thinking and activity related to WM, and hence cannot be directly compared to prior findings. We conclude that there is a temporal course of alpha activity fluctuations even after the removal of WM-related activity. This implies that at least some inconsistencies in the findings regarding increases and decreases in alpha band synchronization during divergent and convergent thinking (Fink & Neubauer, 2006; Bendek et al., 2011; Jauk et al., 2012; see Dietrich & Kanso, 2010, for review), could be attributed to confounding WM-related processes.

Towards the end of the thinking phase (between interval 2 and 3), prefrontal electrodes sites (Fp1/Fp2) show a decrease in alpha synchronization. Although this effect was observed across all three processes (CRT$_{\text{div|WM}}$, CRT$_{\text{con|WM}}$, and APM$_{\text{|WM}}$) it was most prominent in CRT$_{\text{div|WM}}$. This observation is inconsistent with the findings of Jaarsveld and colleagues (2015), as they found highest prefrontal alpha increase in the first and the last interval, whereas both intermediate intervals decreased in alpha power. In the current study, the desynchronization in prefrontal alpha activity, in both the divergent and convergent thinking, occurs during the very last part of the problem-solving process. This process ends with participants pressing the response button. Hence, we can assume that the prefrontal alpha activity reflects some type of decision making or visuospatial attention shifting, as prefrontal regions have been shown to be involved in these processes using fMRI and Transcranial Magnetic Stimulation (TMS; Paulus et al., 2001; Sauseng et al., 2011). Because this effect is most pronounced in divergent thinking, it can also be due to a drop of high internal processing demands that are required during divergent thinking. As prefrontal alpha has been shown to increase during creative thinking and other tasks with high internal processing demands (Benedek et al., 2011; Schwab et al., 2014; Fink & Benedek, 2014; Jaarsveld et al., 2015), at this point it might decrease because this marks the transition to more convergent thinking processes. Note however that we cannot rule out that the decrease in alpha synchronization across all three tasks might be associated with our approach to remove WM-related activity (see Jaarsveld et al., 2015 for potential role of alpha modulation in WM).

In our study, higher synchronization occurred in divergent thinking ($\text{CRT}_{\text{div|WM}}$) as compared to convergent thinking ($\text{APM}_{\text{|WM}}$, and to a lesser degree in $\text{CRT}_{\text{con|WM}}$) only towards the end of the thinking phase (between interval 2 and 3). Note that this higher synchronization was observed at fronto-parietal electrode sites (F3/F4, P3/P4, and P7/P8), in line with the involvement of a network often referred to as the fronto-parietal control network (FPN; Vincent et al., 2008). The FPN is located at dorsolateral prefrontal cortex, middle frontal gyrus, and posterior parietal lobule (investigated using fMRI; Vincent et al., 2008) and has been associated with working memory, complex problem solving and executive functions, such as cognitive control (Niendam et al., 2012), but also divergent thinking (Gonen-Yaacovi et al., 2013; Zhu et al., 2017). Although using EEG does not allow firm conclusions about the origin of the electrical activity, it is reasonable to assume a higher synchronization of the FPN during divergent thinking ($\text{CRT}_{\text{div|WM}}$) in contrast to the convergent thinking task ($\text{APM}_{\text{|WM}}$). Note that the three-way interaction indicates a higher synchronization specifically towards the end of the trial (between interval 2 and 3), between the $\text{CRT}_{\text{div|WM}}$ and $\text{APM}_{\text{|WM}}$ at fronto-parietal electrode sites (F3/F4, P3/P4, and P7/P8). Hence, the synchronization of the FPN appears to be limited to the later phases of divergent thinking during creative problem solving.

7.7 Conclusion

Several limitations of our study need to be considered. One limitation concerns the sample size. We were able to observe considerable effect sizes. Nevertheless, we cannot exclude that a larger sample size might reveal additional or more subtle effects. Furthermore, this study should be seen as only a first attempt to shed light on mechanisms of divergent and convergent thinking beyond WM. As a second limitation, our sample is very homogenous regarding age, IQ, and cultural background, although there is evidence that these sample characteristics may influence cognitive processes (Posner & Rothbart, 2017), such as creativity (Dietrich & Srinivasan, 2007; Welter et al., 2017). On a behavioral level, we found large individual differences in both CRT and CRT-WM performance. In addition, we cannot rule out that participants employed qualitatively different strategies in solving our tasks. For instance, it is possible to solve the APM by generating a correct solution and then selecting the appropriate response option, or alternatively to verify whether each response option is correct or not (i.e., trial and error). Hence, in the future, it would be interesting to investigate potential moderating factors (such as response strategy, gender, or IQ) with a larger sample size.

Regarding our methodical approach, we want to emphasize that in the current study we analyzed “total power”, which consists of periodic (i.e., phase-locked power, evoked signal) and aperiodic (i.e., non-phase-locked power, induced signal) power (Cohen, 2014). Therefore, our results might be also influenced by aperiodic parameters (i.e., offset and exponent). Future studies should consider this limitation by using parametrization methods (for instance, see: Donoghue et al., 2020). Another interesting observation is an apparent increase in theta and delta band in the APM. As theta and delta band activity was not the focal point of interest in this study, we did not test effects in this regard. However, this finding should be more closely investigated in future studies. The last limitation of EEG studies is that there is no direct way to assess functional locations within the brain. The role of the FPN and potentially additional regions relevant for convergent and divergent thinking needs to be assessed in more detail, for instance by using fMRI.

To summarize, we provide evidence for the role of alpha oscillations in convergent and divergent thinking, assessing these functions within the same knowledge domain and using highly comparable stimulus material. Although this approach is new, our results constitute a first attempt in understanding this relationship beyond WM-related processes. In order to understand these processes more completely, the temporal course of this activity needs to be taken into account, specifically in light of the variable nature of the creative thinking process. After removing WM-related activity, we observed upper alpha synchronization within mainly divergent thinking phases, whereas we observed alpha desynchronization during convergent thinking phases. Thus, we provide evidence that creativity and fluid intelligence share underlying mechanisms above and beyond WM-related activity. Further research may explore the role of other executive functions in moderating the relationship between fluid intelligence and creativity.

7.8 Open Issues: The verbal Knowledge Domain

When comparing divergent and convergent thinking, the constraint has been oftentimes the lack of comparability between the tasks. Instead of comparing divergent thinking tasks with such tasks that assess different non-creative processes (such as for example WM, attentional control, convergent thinking), it is necessary to assess divergent and convergent thinking using designated tasks that are highly similar in stimulus material within the same knowledge domain. By contrasting divergent and convergent thinking using the CRT and APM, respectively, and at the same time accounting for their shared variance regarding WM, we provided a first attempt to understand these processes in a more purified way, also by restraining the influence of the factor knowledge domain. However, because of the quite recent proposal of the CRT task as well as the limitation to the visuo-spatial knowledge domain in Study 1, we expanded our new methodical approach to another knowledge domain using two traditional creativity tasks to assess divergent and convergent thinking. Both AUT and RAT are considered typical tasks to measure divergent and convergent thinking, respectively (Japardi et al., 2018). Furthermore, both assess these processes verbally, by using verbal stimuli and verbal response formats, hence defining a verbal knowledge domain. With the following study (Study 2), we aim to assess divergent and convergent thinking within the verbal knowledge domain while accounting for their shared variance due to WM related activity. Furthermore, this line of research enables us to gain insight into how divergent and convergent thinking differ within the same as well as across both knowledge domains.

Chapter 8: STUDY 2

The following chapter includes the second study. It describes the investigation of divergent and convergent thinking beyond the influence of working memory in the verbal knowledge domain. This study has been published[2] as part of the cumulative dissertation.

EEG oscillatory evidence for the temporal dynamics of divergent and convergent thinking in the verbal knowledge domain

8.1 Abstract

This study investigates neural mechanisms of divergent and convergent thinking in the verbal knowledge domain while taking into account activation related to working memory (WM). Divergent thinking was assessed using the Alternate Uses Task (AUT) and convergent thinking using the Compound Remote Associates task (RAT). We analyzed upper alpha band (10-12 Hz) oscillatory activity, in which we accounted for the temporal dynamics of both thinking processes by investigating three different time points during each trial for both tasks. We subtracted WM-related oscillatory activity measured by a serial recall task within the same knowledge domain and by using highly similar stimulus material as in both divergent and convergent thinking tasks. Our results show a strong upper alpha synchronization during divergent relative to convergent thinking, most pronounced at fronto-parietal electrodes. Moreover, we observed highest synchronization towards the middle (in contrast to the beginning and end) of each trial during both thinking processes. The results of the present study extend previous findings in the visuo-spatial knowledge domain, using a highly similar analytical approach to investigate divergent and convergent thinking. Together, these findings provide

---

[2] Eymann, V., Lachmann, T., Beck, A. K., & Czernochowski, D. (2024). EEG oscillatory evidence for the temporal dynamics of divergent and convergent thinking in the verbal knowledge domain. *Intelligence*, *104*, 101828.

theoretical implications on how divergent and convergent thinking interact beyond WM across different knowledge domains by emphasizing their complex interplay.

8.2 Introduction

Creativity, defined as the ability to generate a solution or an output that is both novel (original, unexpected) and appropriate (Sternberg & Lubart, 1996), is central for human civilization and innovation. Each of humanity's achievements roots in the fact that we are able to change our way of thinking permanently and thus to generate novel solutions for problems we face. This capability includes achieving significant improvements to prior solutions or approaching problems from a new perspective.

Creativity can be observed in different domains, for instance in verbal or visuo-spatial domains, for which researchers developed a variety of tasks that measure creative thinking in those domains without the requirement of domain-specific knowledge or expertise (Gerver et al., 2023). The most commonly used tasks related to creativity (Japardi et al., 2018) assess these cognitive processes within the verbal knowledge domain. Verbal creativity is defined as the generation of novel and useful solutions verbally (for example via oral responses or writing down ideas; Chen et al., 2019). Furthermore, verbal creativity tasks contain verbal stimuli (for example words or text) and with that define a verbal knowledge domain for these tasks. Visuo-spatial creativity, on the other hand, involves the production of novel and useful visual shapes (Dake, 1991), for example via drawing (Chen et al., 2019). Hence, creativity is assessed in a domain-specific format, depending on the knowledge domain in which the open problem space is presented (Lunke & Meier, 2016; Jaarsveld et al., 2010).

Prior research assumes that the quality of creative output can be predicted by other cognitive abilities within the same knowledge domain (e.g., verbal creativity by verbal intelligence, verbal logical reasoning, and/or verbal working memory); both in self-reports (Kaufman & Baer, 2004) or tested with creativity tasks (for example Palmiero et al., 2010; Gilhooly et al., 2007; Fink & Neubauer, 2006). However, the strength of these correlations seems to differ between knowledge domains. Moreover, creative abilities may be related across knowledge domains. For example, in the verbal domain the ability to solve open-spaced problems has been observed to correlate with verbal working memory (verbal WM), but not verbal intelligence. On the other hand, verbal creativity correlates with the corresponding creative ability in the figural domain. At the same time, the ability to operate in closed problem spaces in the verbal domain has been associated with verbal intelligence, but not with figural or verbal open problem solving or verbal WM (see Lunke & Meier, 2016 for overview).

Divergent and convergent thinking in creative cognition

The creative cognition approach suggests that creativity arises from the interplay of ordinary cognitive processes (Mastria et al., 2021), such as divergent and convergent thinking. Divergent thinking is defined as the production or generation of a set of solutions or ideas to a stimulus (Runco, 2007; Guilford, 1967). Typical divergent thinking tasks include the Alternate Uses Task (AUT; Guilford et al., 1978), in which participants are asked to generate unusual and original ideas for the use of an everyday-object, such as a shoe or a tire. Divergent thinking productions are scored in terms of three qualities: fluency, originality, and flexibility (Runco & Acar, 2010). From this perspective, the creative process first consists of the generation of several ideas. This is achieved by activating a maximum number of mental representations that only share weak associative connections to the given stimulus (Mölle et al., 1999). Wang and colleagues (2017) observed that a serial order effect can be observed during this first step of the generation of ideas. In this first idea generation phase, the number of ideas decreases over time, while the originality of ideas increases. Those ideas then are selected and evaluated later based on their 'fit' to the desired outcome (Ellamil et al., 2012; Jaarsveld & van Leeuwen, 2005; Campbell, 1960). Hence, creative cognition does not simply involve divergent productions (idea generations), it also requires a convergent process which involves the evaluation and selection of these generated ideas (see also Smilansky & Halberstadt, 1986; Smilansky, 1984; Getzels & Csikszentmihalyi, 1976). In this regard, divergent thinking can be seen as necessary condition, whereas convergent thinking corresponds to a sufficient condition of the creative thinking process.

According to Lee and Therriault (2013), the main focus of creative cognition research has been on characteristics of the divergent rather than convergent aspect of thinking.

Convergent thinking is often conceptualized as the counterpart of divergent thinking as it involves deductive processes to arrive at a final solution which is either correct or incorrect (Guilford, 1967; Mölle et al., 1999; Lee & Therriault, 2013). At the same time, convergent thinking tasks are typically used to assess fluid intelligence (i.e., Raven's Advanced Progressive Matrices; Raven et al., 1998a) in well-defined problem-spaces. Although convergent thinking is often conceptualized as the opposite of divergent thinking, Cropley (2006) as well as De Vries and Lubart (2019) highlighted that convergent thinking is always part of a former divergent process to fulfill the demands of the creative problem. This idea is plausible, as at least some amount of convergent thinking is necessary in a task such as the AUT to suppress common responses in favor of uncommon and novel responses during divergent thinking (Lee & Therriault, 2013) or to evaluate the appropriateness of the generated ideas (Cropley, 2006; Cortes et al., 2019). Convergent thinking is understood as the ability to create novel associations by connecting relatively remote ideas or concepts (Mednick, 1962), which is measured by convergent thinking tasks such as the Compound Remote Associates task (RAT; Mednick, 1962). However, as already mentioned, the link between convergent thinking and fluid intelligence leads to the phenomenon that tasks such as the RAT are highly related to measurements of fluid intelligence and less to divergent thinking (Cortes et al., 2019), which illustrates that convergent thinking is more than just a subcomponent of creative thinking.

Moreover, some authors suggest that divergent and convergent thinking "serve complementary functions in the creative process" (Lee & Therriault, 2013, pp. 307). Prior research assumes that in creative cognition, both processes are combined (*dual process models*; see Sowden et al., 2015 as well as Cortes et al., 2019 for overview) or seen as two sequential steps (Cancer et al., 2023). The first (divergent) phase involves the fast generation of a broad range of options that are ranked and narrowed down in a second (convergent) phase to find the best fitting solution (Cancer et al., 2023; Eymann et al., 2022). However, De Vries and Lubart (2019) observed that divergent and convergent performances were rather weakly correlated. The authors argued for a more complex underlying relation of both processes as being potentially influenced by individual factors such as personality traits as well as social and cultural background of participants (De Vries & Lubart, 2019).

The role of working memory in divergent and convergent thinking

Both, divergent and convergent thinking have been connected to WM performance and WM capacity (WMC) on an individual level (see for example Cancer et al., 2023; Lin & Lien, 2013; Lee & Therriault, 2013; De Dreu et al., 2012; Takeuchi et al., 2011; Vandervert et al., 2007). Lee and Therriault (2013) observed that WMC predicted convergent thinking performance (also Gerver et al., 2023) but not divergent thinking performance, which was in turn correlated with associative fluency (Lee & Therriault, 2013) or was supported by reduced exclusive focus on the task ('diffuse attention'; Takeuchi et al., 2011).

When it comes to verbal creative cognition, the processing of verbal stimuli during divergent and convergent thinking tasks requires WM (Benedek et al. 2011). However, because of the differences in the nature of divergent and convergent thinking, it can be assumed that WM and other cognitive control processes (such as inhibition and shifting; Cancer et al., 2023) serve different functions. For example, Cancer and colleagues (2023) argue that a decrease in inhibition and shifting might be beneficial during divergent thinking, while convergent thinking requires WM as well as inhibition (Cancer et al., 2023). Hence, there might be a stronger positive association of WM and verbal creativity during convergent thinking in contrast to divergent thinking. Moreover, Lin and Lien (2013) observed that WM load even enhanced divergent thinking performances while it hindered problem solving via insight. This mechanism is due to the fact that with high load, less cognitive resources are available for cognitive control (see Ferdinand & Czernochowski, 2018 for overview) which in turn allows more associative, heuristic processing (Lin & Lien, 2013). Other researchers observed WMC affecting divergent thinking performance (Lee & Therriault, 2013; De Dreu et al., 2012; Takeuchi et al., 2011) and also WMC to be related to verbal fluency (Daneman, 1991), which in turn promotes divergent thinking fluency. De Dreu and colleagues (2012) observed that WMC was positively related to creative performance also in a convergent verbal creativity task such as RAT. However, it is also possible that the relationship between WM and creative cognition is influenced by type of stimuli presented during the task (i.e., pictures vs. words; Chrysikou et al., 2016).

On a neuronal level, WM has been observed to be related to activation in specific electroencephalography (EEG) frequency bands, such as the theta band (4-7 Hz; see for example; Riddle et al., 2020; De Vries et al., 2020; Freunberger, 2011; Klimesch, 1999). More specifically, modulations in theta oscillatory activity have been observed to be related to encoding new information, control processes, recruiting attention, and cognitive load (Riddle et al., 2020; Freunberger, 2011; Schack et al., 2005; Klimesch, 1999); this activation has been observed mainly at fronto-parietal electrode sites (Wallis et al., 2015; Rutishauser et al., 2010; Sauseng et al., 2005).

Neural correlates of divergent and convergent thinking

The underlying neural functions of divergent and convergent thinking have been investigated with various tasks and methods, such as fMRI and EEG to identify brain correlates related to creative thinking.

Prior studies investigated which brain areas are involved in convergent and divergent thinking. According to Zhang and colleagues (2020), there are mainly three cortical regions that can be observed during divergent (assessed with AUT) and convergent thinking (assessed with RAT), respectively. These regions are the left inferior frontal gyrus (IFG), as well as the left dorsolateral prefrontal cortex (DLPFC), and most parts of the right hemisphere (including the posterior parietal cortex and closely related areas; Zhang et al., 2020). Beaty and colleagues (2021), as well as Zhu and colleagues (2017), observed (among other regions) activation in the so called fronto-parietal control network (FPN; Vincent et al., 2008**;** see also implications of the Parieto-Frontal Integration Theory; P-FIT by Jung & Haier, 2007) in verbal as well as the visuo-spatial creativity tasks. Zhu and colleagues (2017) explain that these brain regions are involved in cognitive control processes, which is central for creative cognition. Gonen-

Yaacovi and colleagues (2013) concluded that different fronto-parietal regions are active during creative cognition in the verbal domain. In addition, activation in areas specialized to domain-specific task demands are also observed (Sun et al., 2019; Chen et al., 2019).

Numerous EEG studies show evidence of the alpha band (8-13 Hz) frequency being related to creative problem-solving (see Dietrich & Kanso, 2010, as well as Fink & Benedek, 2014, for overview). Upper and lower alpha band (i.e., 10-12 Hz and 8-10 Hz) activity have been associated to creative thinking in several studies over the last years, as it shows specific modulations in regards to specific task requirements, indicating that alpha is especially sensitive to creativity-related task demands (Fink & Benedek, 2014). For example, several studies reported increased alpha power to be associated with the generation of more original ideas (for example Agnoli et al., 2020; Jauk et al., 2012; Fink et al., 2011; Fink et al., 2007; Martindale & Hasenfus, 1978). Furthermore, solving ill-defined problems was found to be related to higher alpha power in contrast to problem-solving in well-defined problem spaces (Jaušovec, 1997; Mölle et al., 1999), indicating that divergent thinking is associated specifically to upper alpha (10-12 Hz) synchronization over frontal and parietal regions (see also Jauk et al., 2012 as well as Fink and Benedek, 2014). For verbal divergent thinking tasks such as AUT, the alpha band has been reported to be synchronized (Mazza et al., 2023; Stevens & Zabelina, 2020; Jauk et al., 2012; Fink et al., 2007), which might also be due to upper alpha modulations in regards to semantic information processing (Klimesch et al., 1997; Klimesch, 1999). By contrast, the alpha band has been observed to desynchronize during verbal convergent thinking tasks, such as RAT (for example Mazza et al., 2023; Jauk et al., 2012). According to Stevens and Zabelina (2019), to solve the RAT items, there are at least two strategies that participants can apply, which can potentially influence the observed activation patterns: an analytical, trial-and-error approach or insight (“Aha! moment”; Stevens & Zabelina, 2019). For example, Rothmaler and colleagues (2017) observed that alpha power (especially in the right parietal hemisphere) increased when participants generated solutions in the RAT via insight in comparison to solutions that were reached analytically. This further shows how alpha synchronization is more related to creative problem solving, whereas alpha desynchronization is related mainly to analytical problem solving, as it is also required during tasks that assess intelligence (Wang et al., 2017). This means that the pattern of alpha de-/synchronization does not only depend on the type of task (i.e., divergent or convergent task, or open or closed problem spaces), but also depends on the type of reasoning that is probed by the instructions or applied to arrive at the solution (i.e., insight vs. analytical problem solving).

In order to dissociate distinct task requirements during creative cognition, the temporal course of cognitive processing can be of key importance. Comparing the temporal course of the divergent thinking process in detail, Jauk and colleagues (2012) as well as Schwab and colleagues (2014) observed that alpha synchronization at fronto-parietal regions was highest in the beginning of the AUT task, then decreased and increased again towards the end of each trial (see also Stevens & Zabelina; 2019 for overview). To account for these temporal changes in activity, some researchers investigate creative thinking processes using consecutive time points or time intervals during the thinking phases (i.e. Schwab et al., 2014, Jaarsveld et al., 2015; Camarda et al., 2018; Eymann et al., 2022). This approach allows a closer observation in terms of distinct component processes during creative thinking, or different activation patterns serving as an index for the associated cognitive process (for example right before the 'Aha' moment when solving insight problems; Rothmaler et al., 2017).

Motivation and Research Gap

When comparing divergent and convergent thinking tasks, it is of key importance to ensure a high similarity regarding the experimental design. This also includes to measure these processes within the same knowledge domain and by using highly comparable stimulus material (Jaarsveld et al., 2010; Jauk et al., 2012; Abraham et al., 2012). Furthermore, as already discussed, WM has been observed to underlie both divergent and convergent thinking, although their exact relationship needs to be established. Hence, any similarities between divergent and convergent thinking may at least to some extend be due to the common requirement to maintain information active in working memory.

However, the specific neural correlates of divergent and convergent thinking beyond the potential impact of WM have not directly been compared so far.

In a previous study (Eymann et al., 2022), we presented the first attempt to separate WM-related oscillatory activity from divergent and convergent thinking per se, using highly similar tasks within the same knowledge domain. We used highly comparable visuo-spatial stimulus material: Divergent thinking was assessed with the Creative Reasoning task (CRT; Jaarsveld et al., 2010; Jaarsveld et al., 2015; see Jaarsveld & Lachmann, 2017 for overview), in which participants are instructed to *create 3x3* matrices by sketching geometric components arranged in rows and columns according to a logical relationship, whereas convergent thinking was assessed with the Raven's Advanced Progressive Matrices (APM; Raven et al., 1998a), in which participants have to *complete* geometric matrices in a logical way by choosing the correct solution out of eight alternatives. Finally, WM was assessed using a newly developed visuo-spatial WM task (CRT- WM, Eymann et al., 2022), in which participants are asked to remember a compilation of geometric shapes. In a first step, we determined the oscillatory activity associated with WM (i.e., theta band synchronization), and subsequently subtracted this activity from EEG oscillatory activation during APM and CRT to rule out that common task requirements (i.e., to keep information active in WM) would mask the oscillatory signature of creative processing per se. We observed a synchronization in the upper alpha band (10-12 Hz) during divergent and a desynchronization of upper alpha band during convergent thinking. Furthermore, to account for temporal variability of both processes, we examined oscillatory activity during three subsequent intervals of 2000 ms (beginning, middle, and end of the thinking phase), which revealed higher synchronization at the beginning and middle, as opposed to the last interval during both, divergent and convergent thinking. Additionally, higher synchronization in divergent in contrast to convergent thinking was localized at fronto-parietal electrode sites (F3/4, P3/4 and P7/8; Eymann et al., 2022).

8.3 The present study

In the present study, we expand our previously presented methodological approach to the *verbal* knowledge domain. To do so, we employed the two most commonly investigated paradigms when it comes to (verbal) divergent and convergent thinking (Japardi et al., 2018), which are the AUT for divergent and the RAT for convergent thinking. Both tasks meet the criteria of verbal creativity tasks, as they not only present verbal stimuli (words) but also the response is given verbally (written format). Similar to our prior study, using tasks highly similar in stimuli and response format ensured that we considered the role of knowledge domain and comparability of different knowledge domains (Jaarsveld et al., 2010; Jauk et al., 2012; Abraham et al., 2012). Furthermore, with respect to WM-related activity, we used a serial recall task which also assesses WM within the verbal knowledge domain. We subtract upper alpha oscillatory activity measured during serial recall task from the activity measured during AUT and RAT to distinguish WM-related activity from the activity during divergent and convergent thinking. Additionally, to account for the temporal dynamics of the creative process itself (Stevens & Zabelina, 2019; Schwab et al., 2014), we investigate oscillatory activity at three different time points during the thinking phase.

8.4 Methods

Participants

We recorded EEG data from 35 participants who were undergraduate students from the University of Kaiserslautern-Landau. According to self-reports, participants were right-handed, had normal or corrected-to-normal vision, had no diagnosis of psychological or neurological disorder, and did not consume medication affecting the central nervous system. Participants provided written informed consent after being informed about the procedure and having the possibility to ask questions. Participants were compensated with course credits or monetary reward for their participation. The study was conducted according to the Declaration of Helsinki and approved by the ethical review board of the Faculty of Social Science of the University of Kaiserslautern-Landau. After initial data analysis, *n*

= 6 participants were excluded from further analysis due to less than 10 segments left in RAT (errors and movement) and *n* = 1 participant due to technical difficulties. Thus, EEG data from 28 students were analyzed (14 female; M_{age}: 22.29 years, *SD* = 2.12 years, range: 19 – 25 years). To verify that this sample size is appropriate to identify existing differences between conditions, we performed a post-hoc power analysis using G*Power version 3.1.9.6 (Faul, Erdfelder, Lang, & Buchner, 2007). For our repeated measures ANOVA (i.e., within-subject comparison), we confirmed an achieved power β = .796.

Materials and procedure

Our participants completed three consecutive tasks, that were presented in the same order for each participant. For measuring divergent thinking, we used the AUT (Guilford et al., 1978). In this task, participants are asked to generate as many alternate uses for a common object, such as for example shoe or brick. For the sake of our experimental design, we asked participants to provide only their most creative solution at the end of the thinking phase, since our aim was to investigate one thinking process at a time. We aimed to elicit participant's maximal originality and provoke a neural pattern according to that. Note that this part of the instructions is in contrast to the original instructions, which asks participants to generate as many uses as possible (fluency). Furthermore, this modification ensured that the instructions are as similar as possible for both AUT and RAT. We presented 30 items in total and participants had no time limit during each thinking phase, so they had enough time to generate their most creative solution for each item. Before each item, we presented a fixation cross for 1000 ms, which we later used as baseline to calculate the changes in oscillatory activity (see Figure 1).

To assess convergent thinking, we used a German version of the RAT (Mednick, 1962) adapted by Landmann and colleagues (2014). In this task, participants are shown a triad of seemingly unrelated words and are asked to find a fourth word that forms a compound that relates to all of the other three words (for example AGE – MILE – SAND, solution: STONE AGE, MILESTONE, SANDSTONE). Please note that in contrast to the original RAT, this German version only includes true compounds (i.e., without removing or adding additional letters in between, Landmann et al., 2014). Furthermore, RAT items vary in terms of abstractness and figurativeness (see Marko et al., 2019 for details), which in turn could influence activation patterns due to the consolidation of different cognitive systems. To avoid this possible confound, we only presented RAT items that include non-abstract, concrete words. This approach also ensured comparability to the exclusively concrete words that are presented in the AUT items. Lastly, in the RAT instructions, the insight-driven strategy is probed by specific instructions discouraging deliberation (Landmann et al., 2014), which we did not apply in our study. Hence, we assume that our participants followed a predominantly deliberate, analytical strategy to solve the task. In total, 30 RAT items were presented. Each trial started with a fixation cross for 1000ms, followed by the item that was presented without time restriction (thinking phase; see Figure 15). Thus, participants were able to answer in a self-paced manner. For the RAT there are specific instructions in term of font and font size due the three-word-stimuli presented horizontally in the center of the screen. To ensure comparability of stimulus presentation between RAT and the other two tasks, we adjusted stimuli for the AUT and WM task accordingly (Arial font, font size 50 pt, black font on a white background, words separated by three spaces from each other; Landmann et al., 2014).

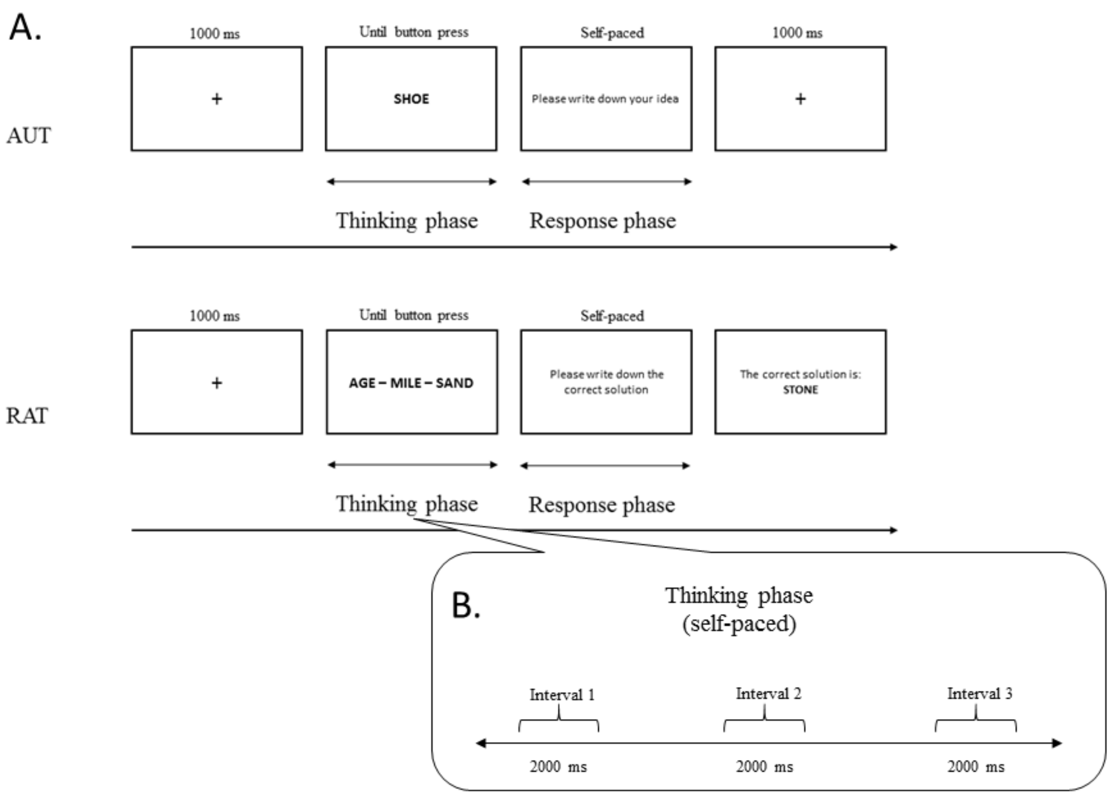


Figure 15. Overview of task procedure and placement of the recorded time windows (A.). Each trial started with a fixation cross of 1000 ms, which was used as a baseline for the oscillatory analysis. After 1000 ms, participants entered the thinking phase in which they were presented with the stimuli (one word in AUT, three words in RAT). The thinking phase was self-paced and participants had to press a button to indicate that they have generated their response (AUT) or they found the requested compound (RAT), respectively. Next, participants entered the response phase in which they had to write down their response. By pressing a button, participants terminated the response phase and continued with the next trial. Please note that the thinking phase (B.), used for data analysis was subdivided into three intervals of 2000 ms each, while the response phase was excluded since it is prone to motion-artifacts. Due to the self-paced processing speed of the thinking phase, the placement of interval 2 in the middle of each interval is participant-specific.

To be able to tell WM-related activity apart from divergent and convergent thinking activity, it was necessary to make sure our WM task is as similar as possible to the items used in RAT and AUT. Therefore, we used 20 word lists that were designed from items of the RAT and AUT and then presented on a computer screen for a serial recall. By using words that were all already presented to the participants during the prior tasks (RAT and AUT), we ensured that there was no effect of novelty in the activation during the list learning. For this reason, the WM task was presented last for all participants. Furthermore, we controlled these word lists for: word sound (no rhyming of words within the same list), the length of syllables (each list had exactly 12 syllables, word length varied between 1 and 3 syllables), first letter of the word (no two words with the same first letter within one list), semantic relations (e.g., words that are highly semantically related were not allowed within the same list, such as bread and butter), and words that can be compounded were not allowed within the same list (e.g., butter bread) to ensure that no other strategy other than WM was used. Also, only concrete words were used (not concepts like honesty, love, peace etc.). Words were presented in randomized order within the list, so that the first word was not always one with a same number of syllables. Each trial started with a fixation cross for 1000 ms, followed by 7 words. Each word was presented for 1000 ms and after each word there was a blank screen for 200 ms. Participants then recalled as many words as possible in their own pace during the response phase.

EEG recording

We recorded EEG using 27 Ag/AgCl cap-mounted electrodes (EasyCap GmbH; Gilching, Germany) positioned on an extended 10 – 20 system (Jasper, 1958). Additionally, two electrodes were placed at the mastoids and four electrodes around the eyes. We used the BrainVision EEG-System (BrainProducts GmbH; Gilching, Germany). The four electrodes around the eyes (above and below the right eye, and beside the right and left eye) were used to record eye-movements. Additionally, a ground electrode was placed at the electrode site AFz and an electrode positioned at electrode site FCz as online reference. The signal was recorded with electrode impedances lower than 10 KΩ and the sampling frequency was 500 Hz.

The EEG data was processed using Brain Vision Analyzer 2.1 (Brain Products, Gilching, Germany). The signal was re-referenced offline to the average of all electrodes except for the eye electrodes and filtered via a bandpass filter (zero phase shift Butterworth) from 0.5 Hz to 30 Hz (with 12 dB/oct). We performed a manual artifact rejection to remove artifacts based on body movements occurring during the response phase where participants wrote down their answers. Furthermore, eye movement artifacts were corrected by using an independent component analysis (ICA) with the infomax restricted algorithm (Jung et al., 1998). For the ICA, an artifact free interval was selected as a training data set for computing the unmixing matrix. ICA components were automatically identified by picking up blinks and saccades, as evidenced by their characteristic shape and location (at frontal electrode sites. After removing components semi-automatically (on average 2.9 per participant; ranging between 0 and 4 deleted components), the EEG signal was reconstructed. The segment lengths (i.e., time until response generation) differed for each participant in each trial because of the self-paced speed in both, AUT and RAT. This resulted in different lengths of the thinking phases for each trial and participant. For the thinking phases in AUT and RAT, segments shorter than eight seconds (see below) were excluded, as we analyzed the data in three intervals (beginning, middle, and end of the trial) to account for these variations in reaction times. Each of these three intervals has a length of 2000 ms, resulting in a total of 6000 ms of data extracted for each thinking phase. Additionally, we removed the first and last 1000 ms of each thinking phase to account for smearing effects of frequency filters (Cohen, 2014), which resulted in a minimum length of 8000 ms for each thinking phase. Hence, for RAT, we only included correctly solved items longer than eight seconds in our oscillatory analysis. Artifacts were removed automatically when (1) a voltage step of 50µV/ms was detected, (2) a voltage difference of 200 µV occurred in any 200 ms interval, or (3) a low amplitude of 0.5 µV occurred in a 200 ms interval. Due to the artifact rejection (on average 8.16 %, *SD* = 11.92 % of the remaining trials, after removing segments < 8000 ms) were removed in AUT for each participant, on average 3.68 % (*SD* = 7.01 %) were removed in RAT, and 1.46 % (*SD* = 3.02 %) in the WM task. The exclusion of segments with less than eight seconds and the consecutive artifact rejection resulted in an average of 27 segments remained for each participant (*SD* = 3.65; range between 16 and 30 segments) in AUT. The average number of segments retained for each participant in RAT was 14 (*SD* = 3.15; range between 10 and 24 segments). Lastly, for the WM task on average 17 segments were retained for each participant (*SD* = 2.49; range between 11 and 20 segments).

Spectral changes of oscillatory activity

Spectral changes of oscillatory activity in the time-frequency domain were calculated by means of complex Morlet's wavelet transform, with wavelets of 7 cycles between 1 Hz and 30 Hz, in 0.5 Hz steps. We calculated percent change of each trial by contrasting them to a baseline activity of 300 ms (-400 to -100 ms before stimulus onset), where participants looked at a fixation cross (at the beginning of each trial). Hence, we obtained a relative synchronization and desynchronization in oscillatory activity. Three consecutive intervals of 2000 ms within each segment were analyzed. As both tasks (AUT and RAT) were self-paced, the absolute interval position at the beginning, middle and end was specific for each participant to account for individual differences in processing speed. Furthermore, it allows to observe the temporal dynamics of the process more realistically for each participant. We placed the three intervals within each segment as follows: the first interval started 1000 ms and ended at 3000 ms after the beginning of the thinking phase; the second interval was set in the middle of each segment; the last interval ended 1000 ms before end of thinking phase. Again, all intervals had a length of 2000 ms each. Spectral changes were averaged over all segments of each interval for each participant. Using this method, oscillatory signals are composed of both evoked oscillations, i.e. locked to stimulus onset, and induced oscillations, i.e. with slight temporal jitter across trials (Herrmann et al., 2004). Percent change in the upper alpha band (10-12 Hz) relative to the 300 ms baseline period was obtained separately for each thinking phase (beginning, middle, end) and task (AUT, RAT, WM task). Subsequently, individual peak alpha frequencies were obtained by searching for local maxima within the extracted frequencies to extract values for the layer with the highest peak for each participant. For the WM task, we extracted the upper alpha (10-12 Hz) wavelet-layers and, additionally, the wavelet-layers for theta (4-7 Hz) for each interval, using the same method to extract the layer with the maximal peak for each participant. The last step of signal processing included the removal of WM-related oscillatory activity by subtracting the activity of the WM task from AUT (AUT|WM) and RAT (RAT|WM).

Analysis of behavioral data

For the AUT, we checked if the answers were relevant and applicable for the object and scored 1 if yes and 0 if not (maximum score = 30). For the RAT, we counted the number of correctly solved items as a total score (maximum score = 30). For the WM task, we counted the number of correctly recalled words (word and position) for each item (maximum score = 140).

Analysis of oscillatory activity

Oscillatory activity was analyzed using SPSS 29 (IBM Corporation, Armonk, NY). We performed the analysis by averaging seven electrode-pairs across both hemispheres for each participant according to Eymann and colleagues (2022). These regions of interest (ROIs) were FP1/FP2, F3/F4, F7/F8, P3/P4, P7/8, and T7/T8.

As the first step of our analysis, we analyzed theta oscillatory activity during the WM task using a repeated measurements Analysis of Variance (ANOVA) for the 7 ROIs with INTERVAL (Int1, Int2, and Int3) as within-subject factor. Here, theta band (4 to 7 Hz) was used as an indicator of WM-related oscillatory activity during the task to ensure that we were able to elicit theta synchronization with our task. We also analyzed upper alpha oscillatory activity to subtract this activity from the oscillatory activity we measured during AUT and RAT for our main analysis.

For our main analysis, we performed a repeated measurements ANOVA on the difference values we obtained by subtracting upper alpha activity of the WM task from AUT (AUT|WM) and RAT (RAT|WM), serving as dependent variable. Here, we compared PROCESS (AUT|WM and RAT|WM), INTERVAL (Int1, Int2, and Int3), and AREA (FP1/FP2, F3/F4, F7/F8, C3/C4, P3/P4, P7/8, and T7/ T8) as within-subject factors). We further formally tested interaction effects. In the following paragraph, only those effects and interactions with p-values below the conventional significance value of .05 are reported. All p-values were Greenhouse-Geisser corrected, when needed (Geisser & Greenhouse, 1958). We report uncorrected degrees of freedom for better readability. Lastly, to clarify significant interaction effects, we used Bonferroni corrected post-hoc analysis.

8.5 Results

Results of behavioral data

For AUT, we computed a total score. Our manipulation check showed that there were no incorrect (i.e., “non-creative” or obvious) or irrelevant (i.e., non-useful) answers given. For RAT, participants solved on average about 17 out of 30 items correctly (*M* = 17.15, *SD* = 3.29). For the WM task, participants recalled on average 5 out of 7 words correctly per item (*M* = 4.75, *SD* = 0.68). For each participant, we excluded responses with less than 4 correctly recalled words from our final analysis, in total 93 responses (corresponding to 16.61% of all responses).

Results of oscillatory activity

We observed an increase in low-frequency synchronization, including the theta band during the WM task (see Figure 16), but no differences between intervals (Int1 *M* = 61.31 %, *SE* = 3.06%; Int2 *M* = 59.81 %, *SE* = 2.59 %; Int3 *M* = 60.74 %, *SE* = 3.31 %; all *p*s > .71; see Figure 16). Hence, we interpret this result as good evidence that we were able to provoke WM-related oscillatory activity with our task.

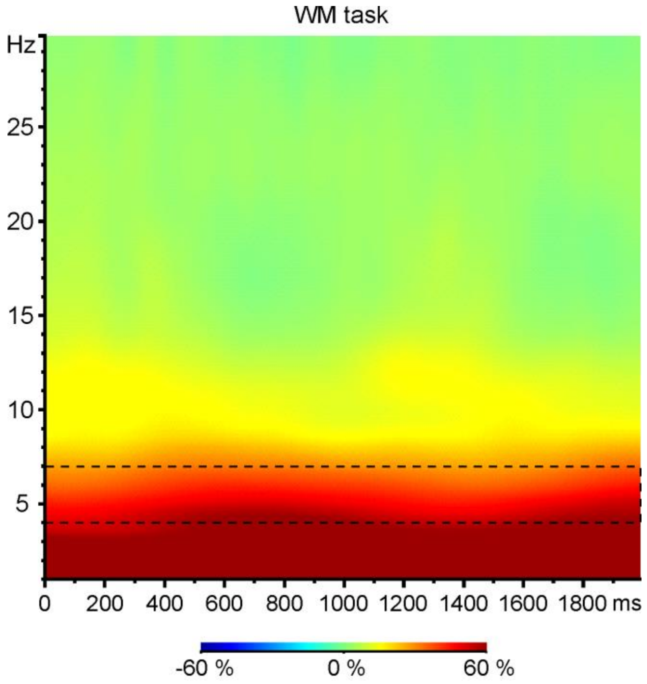


Figure 16. Theta (4-7 Hz) synchronization during the WM task. Results are reported as relative signal changes; percent change. Grand averages include all electrodes and all participants.

In our main analysis of upper alpha related activity for the AUT and RAT subtracted by WM-related activity, we observed a main effect in PROCESS $F(1, 27) = 29.09$, $p < .001$, $\eta_p^2 = .52$. Post-hoc tests revealed a strong synchronization in AUT|WM (*M* = 32.56 %, *SE* = 6.15 %, 95 % *CI* [19.92, 45.20]) in contrast to RAT|WM (*M* = 0.54 %, *SE* = 2.59 %, 95% *CI* [-4.79, 5.87]; see Figure 17).

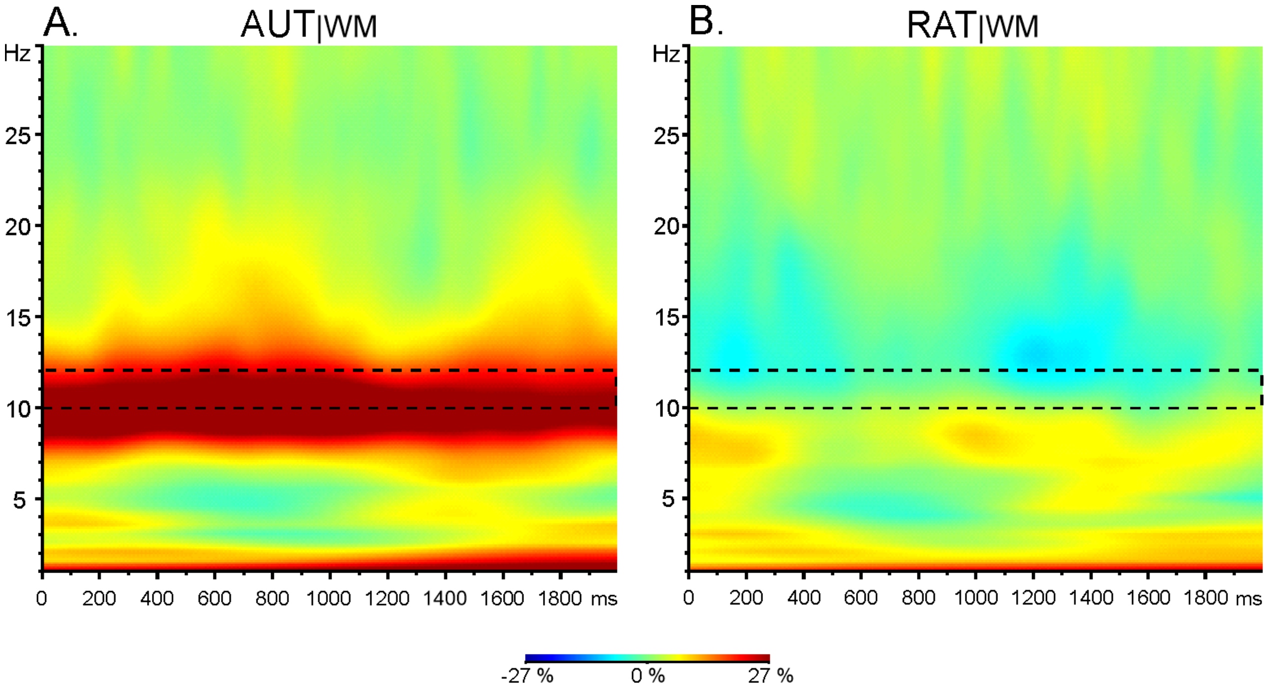


Figure 17. Grand averages of upper alpha (10-12 Hz) oscillatory activity in AUT|WM (A) and RAT|WM (B). Grand averages show activation after subtracting WM-related activity measured by the WM task. Grand averages include all electrodes and all participants to illustrate increase and decrease of upper alpha band.

We also observed a main effect for INTERVAL, *F*(2, 54) = 9.87, $p < .001$, $\eta_p^2 = .26$, where Interval 2 was most synchronized (*M* = 24.32 %, *SE* = 4.71 %, 95% *CI [*14.65, 33.99]) in contrast to Interval 1 (*M* = 15.27 %, *SE* = 4.22 %, 95% *CI [*6.59, 23.94]; *p* = .007) and Interval 3 (*M* = 10.06 %, *SE* = 3.32 %, 95% *CI* [3.24, 16.88]; *p* = .001) in both AUT|WM and RAT|WM (see Figures 18 and 19).

Lastly, we observed an interaction effect between PROCESS and AREA, *F(*6,162) = 9.37, $p < .001$, $\eta_p^2 = .31$. Here we observed that in AUT|WM, prefrontal and frontal areas were more synchronized than prefrontal, frontal and parietal areas in RAT|WM (see Figure 18). Planned contrasts revealed significant differences in areas Fp1/2, F3/4, C3/4, P3/4, and P7/8 (all *p*-values < .02) in contrast to areas F7/8, and T7/8 (all *p*-values > .40).

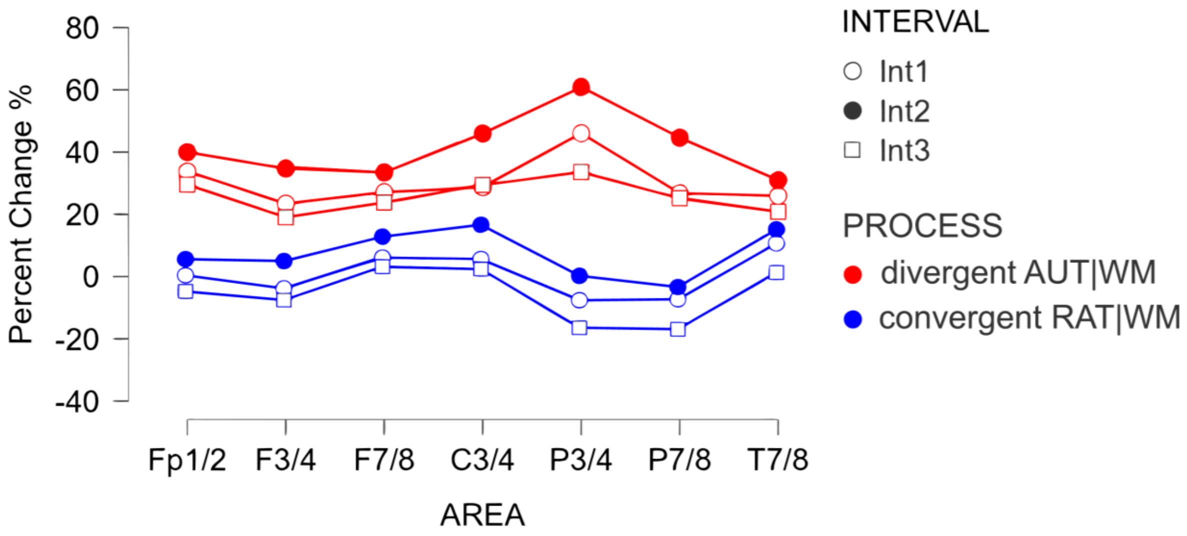


Figure 18. Relative Change in upper alpha (10-12 Hz) oscillatory activity for all electrode pairs during AUT|WM (red) and RAT|WM (blue) relative to the baseline interval. Interval 2 showed highest synchronization in both, AUT|WM and RAT|WM. Furthermore, we observed significantly higher upper alpha synchronization in AUT|WM in contrast to RAT|WM, most pronounced in prefrontal, frontal, and parietal areas. To ease visual comparison between the six conditions, confidence intervals are given in the text.

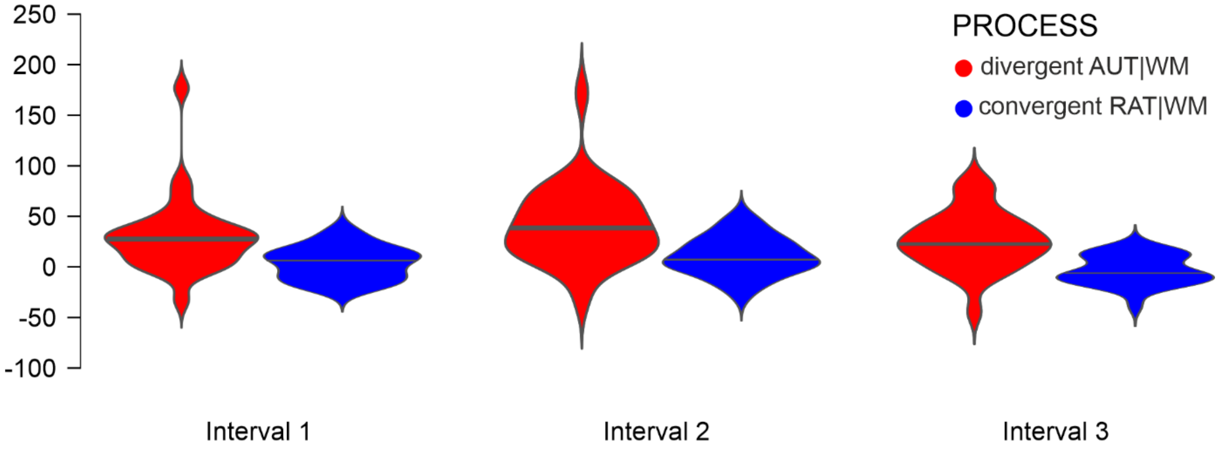


Figure 19. Relative Change in upper alpha (10-12 Hz) oscillatory activity across all electrodes during AUT|WM (red) and RAT|WM (blue), relative to the baseline interval. Interval 2 showed highest synchronization in both, AUT|WM and RAT|WM in contrast to Interval 1 and Interval 3. Black bars indicate the mean, confidence intervals are given in the text.

8.6 Discussion

This study investigated the relationship between divergent and convergent thinking beyond WM for the verbal knowledge domain. Following the analytical approach of our previous study (Eymann et al., 2022), we separated WM-related oscillatory activity from the oscillatory activity measured during divergent thinking (AUT) and convergent thinking (RAT), respectively. After subtraction of WM-related activity, we observed a synchronization in the upper alpha band (10-12 Hz) oscillatory activity during divergent thinking (AUT|WM) in contrast to convergent thinking (RAT|WM), most pronounced at fronto-parietal electrodes. We analyzed both self-paced thinking processes using three consecutive intervals of 2000 ms each. Here, we observed the highest synchronization in the middle of the thinking processes and less synchronization at the beginning and end of the thinking phases for both, AUT|WM and RAT|WM.

The functional role of upper alpha oscillatory activity

Alpha synchronization during creative idea generation (i.e., divergent thinking) is assumed to be one of the most consistent findings regarding the cognitive neuroscience of creativity (Dietrich & Kanso, 2010; Fink & Benedek, 2014). With respect to the functional role of upper alpha oscillatory activity, Benedek and colleagues (2011) suggested that the observation of alpha synchronization during divergent thinking stems from a top-down information processing approach, whereas bottom-up processes (probed by convergent thinking) are accompanied by a decrease in alpha synchronization. At the same time, increased alpha activity during divergent thinking can also be interpreted as a sign of reduced externally and more internally oriented attention (Stevens & Zabelina, 2019) or as a reduced activity level of the brain during the production of original ideas (Fink et al., 2007). Furthermore, the increase in alpha synchronization during divergent thinking has been interpreted as indicating a more efficient transfer of information (Dietrich & Kanso, 2010). In contrast, alpha desynchronization during convergent thinking has been interpreted as the formation of remote associations (Dietrich & Kanso, 2010) or as a correlate of semantic memory consolidation (Klimesch, 1999).

These findings indicate that the pattern of alpha de-/synchronization is not directly attributed to creative cognition per se, but rather to the specific internal processing demands (Benedek et al., 2011). For instance, the RAT, although commonly regarded as a convergent thinking task, also comprises time periods characterized by divergent thinking, as participants need to generate responses for each item which are then evaluated. Hence, the alpha band seems to be distinctly modulated by both, specific task requirements (for example top-down vs. bottom-up processing; Benedek et al., 2011), but potentially also by the knowledge domain of the specific task (e.g., verbal vs. visuo-spatial; Jaušovec & Jaušovec, 2000). In line with our observations, synchronization in the alpha band, specifically during AUT, has also been reported in several other studies (for example, Agnoli et al., 2020; Mazza et al., 2023; Stevens & Zabelina, 2020; Jauk et al., 2012; Fink et al., 2007). In contrast, Razoumnikova (2007) observed desynchronization in upper alpha during RAT performance, in line with the results of this study. In the study of Razoumnikova (2007), this desynchronization-effect was even more pronounced if participants were confronted with highly original verbal associates in contrast to less original ones. Similarly, Rothmaler and colleagues (2017) observed that alpha power decreased when participants were instructed to generate RAT solutions analytically (as compared to insight-driven strategies), which was also emphasized in our instructions.

In line with these prior studies, our results indicate that divergent and convergent thinking are associated with characteristic modulations in the upper alpha band and hence, can be clearly distinguished between these tasks within the same (verbal) knowledge domain. Beyond that, we suggest that upper alpha de-/synchronization may serve as an index to what extend each process is activated during these tasks. Moreover, we demonstrate that upper alpha de/synchronization is process-related (divergent vs. convergent or bottom-up vs. top-down or internal vs. external processing) rather than construct-related (creativity, intelligence or open-, closed problem solving).

Temporal dynamics of upper alpha

In the present study, we observed that during both divergent (AUT|WM) and convergent thinking (RAT|WM), the second interval was most synchronized in contrast to Interval 1 and 3. In a related line of research, Schwab and colleagues (2014) investigated the temporal course of the divergent thinking process in AUT. Similar to our study, they analyzed three consecutive time intervals of task-related EEG upper alpha power changes during idea generation phase. They observed the highest upper alpha synchronization at fronto-parietal regions of the right hemisphere in the beginning and the end of the idea generation phase of the AUT. The middle interval, however, revealed a decrease in upper alpha synchronization, creating an *inverse* U-shaped course of activation. This decrease in upper alpha synchronization towards the middle of the thinking phase was interpreted as a state of reduced memory retrieval, which enables the emergence of more creative, imaginative thinking processes (Schwab et al., 2014). The fact that we observed an increase in upper alpha synchronization (U-shaped time course) could be explained by differences in specific instructions, because we stressed originality while Schwab and colleagues (2014) stressed fluency. Another explanation could be the self-paced speed in our study, which allows for a more natural flow of creative thought. Schwab and colleagues (2014) restricted participant’s idea generation phase to 10 seconds, whereas our study allowed self-paced idea generation during both AUT and RAT. A time restriction might evoke different patterns of activation by stressing the quantity of responses within limited time rather than asking participants to take their own time until reporting one particularly creative solution (efficient vs. effective result).

Alternatively, the increase in upper alpha towards the middle of the (individual) thinking process that we observed could also be attributed to an actual peak in originality. For example, Fink and colleagues (2011) reported that the exposition of participants to cognitive stimulation (in order to increase their originality) resulted in stronger upper alpha synchronization in contrast to no stimulation. Similarly, probing original responses was accompanied by task-related synchronization in upper and lower alpha band (7.5–10.5 Hz and 10.5–12.5 Hz) in a study by Jauk and colleagues (2012). This peak in originality might also be reflected in the upper alpha increase in synchronization in Interval

2 during AUT. On the other hand, as mentioned above, the RAT problems require divergent thinking processes to generate possible solutions for the compound. At the same time, they require the active inhibition of “semantically related associates” (Cortes et al., 2019, p. 92) in order to find the correct solution. Regarding our results, it is arguable that participants generate their highest semantic distance after overcoming more common, semantically closer associates first. This could explain the shift in upper alpha modulation in our data in favor of an enhanced assessment of semantic memory, as alpha has previously been related to semantic information processing (Klimesch et al., 1997; Klimesch, 1999). However, a more refined analysis might be necessary to allow more specific conclusions regarding the time course of upper alpha during divergent and convergent thinking.

Comparison to the visuo-spatial domain

Jaušovec and Jaušovec (2000) reported findings on upper alpha (here: 10.1-12.9 Hz) synchronization being related to the form of problem presentation (i.e., knowledge domain). In this study, upper alpha was systematically more synchronized during verbal as compared to visuo-spatial divergent thinking (Jaušovec & Jaušovec, 2000). Regarding similarities and differences between the verbal and the visuo-spatial knowledge domain, our former study (Eymann et al., 2022), in which we investigated divergent and convergent thinking beyond WM-related activity in the visuo-spatial knowledge domain, is of particular relevance. In the visuo-spatial knowledge domain, we observed a pattern of divergent thinking accompanied by upper alpha synchronization, suggesting that divergent thinking is accompanied by very similar upper alpha oscillatory activity in both knowledge domains. In contrast, during verbal convergent thinking, we observed less desynchronization compared to the visuo-spatial knowledge domain using APM|WM. One potential theoretical consideration to account for this pattern of results is that the RAT requires participants to generate response options before evaluating them, i.e., to alternate between divergent and convergent thinking. By contrast, participants select a single correct answer out of several options presented along with each item in APM. In this regard, the differences in activation that we observe during convergent thinking in the two knowledge domains could potentially be explained either by the specific task requirements and/or by the type of stimuli presented during the tasks. Hence, desynchronization in the upper alpha band may serve as an index for convergent thinking that could be useful in disentangling the complex interplay between knowledge domain and the mode of creative thinking.

Limitations and future directions

The present study focused on the upper alpha band and WM-related activity in the theta band. However, very recent evidence suggests a complex interplay of several EEG frequency bands during divergent and convergent thinking, respectively. For example, Mazza and colleagues (2023) reported alpha synchronization during divergent thinking accompanied by beta and gamma desynchronization, while the opposite pattern was observed during convergent thinking. In their study, alpha desynchronized, whereas beta and gamma activity increased (Mazza et al., 2023). This observation further highlights the importance of identifying the potential functional significance of concurrent modulations in several frequency bands. Based on visual inspection, a substantial increase in delta oscillatory activity is evident in the present study, especially in the WM task. However, in the absence of specific hypotheses, we did not analyze this oscillatory activity in the context of this investigation but aim to further investigate this phenomenon in future studies.

With respect to the role of WM, the influence of WM activity on divergent and convergent thinking might also depend on the knowledge domain. Processing verbal stimuli requires a different WM sub-component (phonological loop) than processing visuo-spatial stimuli (visual-spatial sketch-pad; Baddeley, 1992). This potentially creates different alpha activation patterns not only during thinking, but also when preparing answers (such as finding words, formulate sentences, writing down, semantic processing, etc.). Furthermore, WM is required during convergent thinking, while high WM load might even be beneficial during divergent thinking (see also Cancer et al., 2023). Hence, WM might play a more prominent role during divergent thinking in the verbal knowledge domain (Cancer et al., 2023). This further emphasizes the necessity to also investigate not only WM, but also other cognitive control functions (shifting, inhibition, updating) with our new methodological approach.

Doing so could potentially further unwrap the relationship between divergent and convergent thinking, because WMC has been observed to be less domain-specific in contrast to other aspects of short-term memory (Kane et al., 2004). Future studies are needed to allow for a formal comparison between the knowledge domains to disentangle the precise contribution of WM during creative cognition.

With respect to the assessment of verbal convergent thinking, we observed relatively high error rates during RAT, which we did not anticipate for our sample. Since the German version of the RAT used in the present study was validated using a sample of relatively high verbal intelligence (see Landmann et al., 2014, for details), item difficulty may have been underestimated, which could explain our participant's error rates. As a consequence, a reduced number of segments remained for EEG analysis. It is possible that verbal stimuli are more dependent on factors such as educational level, verbal intelligence, general vocabulary or even gender/sex in contrast to the geometric stimuli used for the visuo-spatial domain that are considered to be culture-fair (CRT, APM). However, this argument would then be expected to affect brain activation and performance during divergent thinking (AUT) to a similar extent, and further illustrate the need to compare cognitive processing within the same knowledge domain. However, in the same knowledge domain, stimuli may overlap between tasks and create salience effects due to stimulus repetition. In the present study we decided to present AUT, RAT and the WM in a fixed order to avoid this potential confound. On the other hand, this solution may have introduced same order effects between tasks, illustrating that future studies need to carefully assess any potential impact of task order.

While our study provides a detailed assessment of the neural correlates underlying creative cognition specifically for the verbal knowledge domain, this came at the expense of related research perspectives. For instance, assessing the impact of potentially moderating variables such as personality attributes or sex/gender on creative cognition or taking into account the originality of ideas would be worthwhile investigating. Finally, it remains open how the temporal dynamics of divergent and convergent thinking that we observed with our new analytical approach relate to real-life like creativity beyond the laboratory environment.

8.7 Conclusion

Using highly similar verbal stimulus material across tasks, we provide evidence for the role of upper alpha oscillatory modulations during divergent and convergent thinking, following the analytical approach used in a prior study in the visuo-spatial knowledge domain (Eymann et al. 2022). After accounting for WM-related activity, we observed a synchronization in the upper alpha band (10-12 Hz) oscillatory activity during divergent in contrast to convergent thinking, most pronounced at fronto-parietal electrodes. The temporal dynamics of the neural oscillations reveal that tasks such as the RAT, although commonly understood as prototypical convergent tasks, still might have divergent thinking aspects. We suggest that the temporal dynamics of upper alpha de-/synchronization may serve as an index to what extend convergent and divergent thinking is activated during creative cognition, respectively.

8.8 Open Issues: The Convergence-Divergence Continuum

Guilford’s (1967) conceptualization of divergent and convergent thinking has been described as a dichotomy (Runco, 2014), or as distinct processes (Cortes et al., 2019). However, the results of Study 2, as well as the observations in prior research (Cancer et al., 2023; Rothmaler et al., 2017; Lee & Therriault, 2013; Nusbaum & Silvia, 2011) suggest that tasks such as RAT and AUT do not provide sensitive tools to measure those processes separately or even distinguish between them (Cortes, 2019), especially on a neuronal level. Also, a non-verbal creativity task such as the CRT, although it provides a structure that allows for different stages encompassing more or less amount of each process, cannot depict the exact temporal dynamics of each process and their interplay (ct. Chapter 7). The only task that was introduced within this thesis that exclusively provokes one process (i.e., convergent thinking) is the APM. Here, there is no room for ambiguity and hence, no need for any type of idea generation (i.e., divergent thinking) as the stimuli as well as response alternatives are immediately accessible for the participant (i.e., visually provided during the task). However, the APM is the only task within the scope of this thesis that is not considered to measure creativity, as it is clearly a task to assess fluid intelligence. Furthermore, the APM assesses exclusively visuo-spatial convergent thinking and allows only limited inferences about convergent thinking within the verbal knowledge domain.

As discussed earlier (ct. Chapter 6.1), several studies using fMRI investigating the underlying brain areas of divergent and convergent thinking provided evidence for overlapping cortical structures that are active during specific tasks, such as RAT and AUT. Because the CRT is a relatively new task, there have been no investigations using fMRI so far. However, these prior fMRI results strengthen the idea that divergent and convergent thinking are not as independent as previously assumed. According to multiple EEG studies (our own included), divergent and convergent thinking nevertheless tend to produce unique patterns regarding synchronization and desynchronization for example in the upper alpha band in different knowledge domains (see Chapter 6.2 for details). As in these neurophysiological studies, divergent and convergent thinking elicited different EEG activity patterns and furthermore, correlated with different other measurements (e.g., Gf, WM; ct. Chapter 5), many researchers viewed this as a clear evidence for a distinction between divergent and convergent thinking, respectively.

However, at this point, it is indisputable that both processes are interwoven within creative cognition (see for example Cortes et al., 2019, Zhu et al., 2019; Cropley, 2006). Yet it remains a challenge to disentangle both processes within these tasks. With Study 1 and Study 2, we provide a possibility of removing shared variance due to WM related activity, but at the same time, there are several more underlying processes overshadowing the ‘pure’ divergent and convergent thinking processes, such as cognitive control or attentional processes, to name but a few (ct. Chapter 7 and Chapter 8). Moreover, standard EEG data analysis generally requires segments with exactly the same length. This makes it necessary to ignore some parts of the data by shortening the observed thinking process and fitting it into the 2000 ms frame, as in our studies (see Methods section in Chapter 7 and Chapter 8 for details), or to deal with different amounts of sampling points when calculating means (for example Benedek et al., 2011). Other researchers have accounted for the same challenges by limiting the response time during divergent thinking (see for example Schwab et al., 2014 for EEG; Japardi et al., 2018 for fMRI). However, this could potentially lead to an abbreviated presentation of the divergent and convergent thinking processes, which in turn might influence researcher’s (dichotomous) view on divergent and convergent thinking.

With the following Opinion Paper, we will provide an insight on several limitations that the neuroscientific investigation of divergent and convergent thinking faces and how it affects and limits our capability to observe the specific temporal dynamics of divergent and convergent thinking during creative cognition. Furthermore, we argue for an establishment of a specific neuro-physiological index that allow this disentanglement of processes.

Chapter 9: STUDY 3

The following chapter describes the third investigation. This Opinion Paper provides an argumentation on how alpha band modulations can be used as a neuro-physiological index to illustrate temporal dynamics of divergent and convergent thinking within creative cognition tasks. It further argues for a view on divergent and convergent thinking that is less dichotomous but more continuous as indicated by our previous studies. This manuscript submitted[3] as part of the cumulative dissertation.

Reconsidering divergent and convergent thinking in creativity – A neurophysiological index for the convergence-divergence continuum

9.1 Abstract

Creative problem-solving has been described as an iterative process of divergent and convergent modes of thinking. With this Opinion Paper, we illustrate how some tasks, commonly used for the neuroscientific investigation of creativity might provide a condensed representation of divergent and convergent thinking, respectively. We have identified the following reasons for this: the challenges to identify specific temporal dynamics of divergent-convergent cycles using standard EEG procedures, the restricted time on task for participants, as well as the specific presentation of stimuli and response alternatives within these tasks (‘*immediate problem space accessibility*’). Thus, specific dynamics of divergent-convergent cycles are difficult to identify using standard EEG procedures. Based on two recent studies, we propose that upper alpha band (10-12 Hz) modulations in particular may serve a) as a neuro-physiological index to disentangle divergent-convergent cycles within these creativity tasks and b) as a data-driven marker for the task demands related to immediate problem space accessibility.

---

[3] Eymann, V., Beck, A. K., Lachmann, T., Jaarsveld, S., & Czernochowski, D. (subm.). Reconsidering divergent and convergent thinking in creativity – A neurophysiological index for the convergence-divergence continuum.

Finally, we argue for a view on divergent and convergent thinking that is less of a dichotomy and more of a continuum.

9.2 Introduction

"Even the most creative [person] must have a modicum of basic knowledge and rigor in his or her thinking; even the most orthodox and rigorous must use some degree of creative intuition to solve the complex formulae that confronts him or her." (Eysenck, 2003, p. 101)

Guilford's differentiation between divergent and convergent thinking implies a dichotomy between those two modes of thinking (Guilford, 1967; Eysenck, 2003; Runco, 2014). For the longest time, this has not been questioned. Moreover, divergent and convergent thinking have been oftentimes even regarded as counterparts where divergent thinking is the ideal form of actual creative problem-solving (or at least the closest approximation; Runco & Acar, 2012), whereas convergent thinking is the non-creative, knowledge-driven, and rational counterpart (Eysenck, 2003; Cropley, 2006; Lee & Therriault, 2013). Even in Guilford's '*structure-of-intellect*' model, it is notable that divergent thinking has the same distance to convergent thinking as it has to the other operations in the model, which include memory, cognition, and evaluation (Guilford, 1967). But can this proposal be correct? Are divergent thinking and convergent thinking distinct processes that are independently used, one for creative and the other for non-creative productions, implying a dichotomous relationship between both?

9.3 Alternating between divergent and convergent thinking

While divergent thinking has widely been recognized as the underlying process of creativity, convergent thinking still is oftentimes exclusively associated with fluid intelligence, reasoning, and logical thinking. However, creativity is defined not only by innovation but also effectiveness (i.e., evaluation and selection of the most appropriate idea; Runco, 2007). From this perspective, the creative process consists of (1) the generation of several ideas, which is achieved by activating numerous mental representations that only share weak associative connections to the given stimulus (i.e., divergent thinking; Mölle et al., 1999*).* Above that, the creative process also consists of (2) a phase of idea evaluation and selection (Getzels & Csikszentmihalyi, 1976; Smilansky, 1984; Smilanski & Halberstadt, 1986; Cropley, 2006; Dietrich & Kanso, 2010; Runco & Jaeger, 2012), which is achieved by applying convergent thinking. In particular, convergent thinking contributes to the creation of inventive end products by critically evaluating loose new ideas generated by divergent thinking. Hence, convergent thinking transforms mere novelty (‘*pseudocreativity*’; Cropley, 2006) into actual creativity.

9.4 Iteration or recursive cycles

The view on creative problem-solving and its underlying sub-processes has moved from a uni-directional path of stages (for example Wallas’ four stage model of preparation, incubation, illumination, and verification; Wallas, 1926; see also Sadler-Smith, 2015 for details) to a conception that views creative problem-solving as a more iterative process of several subsequent divergent-convergent thinking cycles (i.e., generation-evaluation; see Lubart, 2001 for overview). Even Guilford himself proposed that creative ideas are generated through thinking cycles, in which divergent and convergent thinking processes are iteratively used to arrive at the final solution (see for example Guilford, 1967; see also very similar the ‘*Geneplore’* model by Finke et al., 1996). In recent years, researchers have concluded that instead of following a singular, fixed sequence of phases, it is much more plausible that the creative process is loosely recursive, in the sense that it is a more dynamic and a not-predefined reiterating process (see Lubart, 2001 for overview as well as Zhang et al., 2020 for neurocognitive perspective). Furthermore, it has been argued that creative outcomes can be achieved through convergent thinking, when convergent ideas or domain specific knowledge, previously acquired through merely convergent processes, are put in novel combinations that can be labeled as actually creative (see ‘*effortful creativity’*; Cropley, 2006). However, the exact interplay and the temporal dynamics of divergent and convergent thinking in creative cognition remains to be established.

9.5 Divergent and convergent thinking as a continuum

Some researchers proposed that divergent and convergent thinking may be more accurately conceived as continuum rather than as dichotomy (e.g., Lubart, 2001; Eysenck, 2003; Runco, 2014). With the continuum view, it is possible to quantify different proportions of convergent and divergent thinking modes within a particular creative process. In addition, the continuum view allows to characterize the temporal dynamics of divergent and convergent thinking cycles, which may vary between highly creative and less creative individuals, as well as across different creativity tasks. In order to capture quantitative differences on a continuum we need to establish objective markers (for example specific neural modulations) that can be used to infer which process occurs at which time across individuals. Here, we propose that neural activity during the completion of creativity tasks may not only uncover the underlying brain networks mediating creative thinking, but serve precisely this purpose as an index for the proportion of divergent and convergent thinking modes at each point in time.

9.6 Divergent and convergent thinking tasks

Over the last decades, many tasks have been developed to measure divergent and convergent thinking, some of them labeled as creativity tasks (e.g., Alternate Uses Task/AUT; Guilford et al., 1978; Compound Remote Associates task/RAT; Mednick, 1962; Torrance Test of Creative Thinking/TTCT; Torrance, 1974), as tasks of creative reasoning (i.e., Creative Reasoning Task/CRT; Jaarsveld et al., 2010, 2015), as tasks that exclusively measure fluid intelligence (Raven’s Advanced Progressive Matrices test/APM; Raven, Raven, & Court, 1998), or as tasks referring to related cognitive processes that require convergent thinking (for example mental arithmetic, or solving anagrams).

Generally speaking, when directly comparing these tasks to investigate divergent and convergent modes of thinking, researchers run into several problems. These tasks do not only assess different thinking processes (divergent and convergent), they further differ in two important aspects: First, they do not operate within the same problem space (i.e., open and closed; see for example

Mumford, 1991; Jaarsveld et al., 2010; Benedek et al., 2011; Runco, 2014; Jaarsveld & Lachmann, 2017); second, these tasks assess divergent and convergent thinking using different types of stimuli (e.g., verbal, visuo-spatial) and hence, do not share the same knowledge domain (Jaarsveld & Lachmann, 2017). Both, the respective knowledge domain and problem space, however, are important to consider as these tasks characteristics may be confounded with the obtained results in individual studies and hence preclude direct comparisons (Jauk et al., 2012; Jaarsveld & Lachmann, 2017). Thus, when comparing divergent and convergent modes of thinking, it is necessary to ensure that these tasks assess divergent and convergent thinking within the same knowledge domain and provide highly similar stimulus material.

Another limitation is that creativity tasks, even when labeled 'divergent thinking tasks' do not exclusively assess divergent thinking (see Cortes et al., 2019 for overview). As elaborated above, creative problem-solving involves divergent and convergent thinking cycles that not only re-occur during one creative thinking phase (for example when solving one AUT item), but could possibly differ in their *temporal* and *qualitative* dynamics across and even within individuals. Hence, on a behavioral level, it is nearly impossible to disentangle these cycles and to quantify them accordingly using well-established tasks focusing only on the end-product of creative thinking. On the other hand, tasks that assess convergent thinking are also very dissimilar in terms of stimuli and even more problematic, in terms of how the problem space and the response alternatives are provided as part of the task (in the following referred to as the '*immediate problem space accessibility*'). In other words, a convergent thinking task like the APM does not only provide the problem, but also presents the one and only correct response option among several incorrect lures. However, the RAT, which also assesses convergent thinking mode, solely presents the problem while the (only) correct response needs to be generated by individuals. To put it in Eysenck's words: "(…) the answer is implied in the question, but is unknown to the solver; he or she is required to discover something new – new to him or her (…)" (Eysenck, 2003, p. 101). Hence, these relatively subtle differences in immediate problem space accessibility necessitate divergent thinking processes in some, but not all convergent thinking tasks.

Lastly, differences in immediate problem space accessibility could also potentially modulate the thinking process by creating specific internal processing demands (see Benedek et al., 2011).

In sum, the categorization as divergent and convergent thinking task can be seen as oversimplification of prototypical creative thinking modes, which is possibly necessary for a systematization to research on divergent and convergent thinking. This, however, comes at the expense of limited information about the specific dynamics of both processes during creative thinking. Furthermore, it does not allow to characterize the creative process as specific proportions of divergent and convergent thinking. Hence, an objective marker for divergent vs. convergent thinking modes is also needed to dissociate variations within established creativity tasks.

9.7 Alpha band modulations during divergent and convergent thinking

Neurophysiological measurements such as Electroencephalography (EEG) provide the required time-sensitive resolution to observe these underlying cognitive processes in detail. Creativity studies using EEG have reported specific modulations in the upper alpha band during divergent and convergent thinking (see Dietrich & Kanso, 2010; Fink & Benedek, 2014 for systematic overviews). Moreover, upper alpha *synchronization* during divergent thinking has been labeled as one of the most consistent finding within the field of cognitive neuroscience of creativity (Fink & Benedek, 2014) and has been repeatedly observed in various studies (for example Fink et al., 2007; Jauk et al., 2012; Agnoli et al., 2020; Stevens & Zabelina, 2020; Mazza et al., 2023;). On the other hand, during convergent thinking *desynchronization* was observed in upper alpha band (Jaušovec & Jaušovec, 2012; Eymann et al., 2022) during APM as well as upper and lower alpha band during mental arithmetic (Razumnikova, 2000) and RAT (Razumnikova, 2007; see also Doppelmayr et al., 2005 as well as Jauk et al., 2012 for different types of convergent thinking tasks). However, other researchers observed that the same frequency band did not fully desynchronize nor even synchronized during RAT (e.g., Benedek et al., 2011; Jauk et al., 2012; Rothmaler et al., 2017; Eymann et al., 2024). Hence, in regards to convergent thinking, upper alpha evidence seems to be more inconclusive. Lastly, the direct comparison of alpha band modulations during divergent and convergent thinking has been impeded by the dissimilarities of these tasks in terms of stimulus material (Jauk et al., 2012), internal processing demands (Benedek et al., 2011), problem-space, and knowledge domain (Jaarsveld et al., 2010; Jauk et al., 2012).

Despite this ambiguity, we argue that especially alpha band modulations hold a potential to represent a neuro-physiological marker to dissociate between creative and non-creative processes within these tasks. Using the temporal resolution of EEG and observing the time-course of a potential neurophysiological marker, such as alpha band, might give us the possibility to disentangle divergent-convergent thinking cycles in more detail.

9.8 An attempt to establish upper alpha as a neurophysiological marker

Two previous studies provide an example of how upper alpha (10-12 Hz) can be used as a neurophysiological marker to investigate the temporal dynamics and qualitative differences between divergent and convergent thinking modes within well-established tasks (Eymann et al., 2022; Eymann et al., 2024). Both studies (assessing independent, yet highly similar samples) provide insight on the specific interplay of divergent and convergent thinking within and across the different knowledge domains. Beyond that, they allow theoretical considerations about the usefulness of alpha band oscillatory activity serving as an index for both modes of processing. Divergent and convergent thinking were assessed using CRT (Jaarsveld et al., 2015) and APM (Raven et al., 1998) within the visuo-spatial knowledge domain, and using AUT (Guilford et al., 1978) and RAT (Mednick, 1962) in the verbal knowledge domain. Within each study, highly similar stimulus material from the same knowledge domain was used, to ensure that differences between convergent and divergent thinking modes cannot be attributed to stimulus characteristics. Hence, a direct comparison between divergent and convergent thinking within each knowledge domain was possible. By providing the following theoretical consideration, we intend to add an additional perspective to the existing debate on divergent and convergent thinking during creative problem-solving and to provide insight on how upper alpha activity changes in accordance to task requirements and underlying thinking processes. In these studies, divergent thinking was characterized by upper alpha synchronization regardless of the knowledge domain, demonstrating the well-researched effect of upper alpha synchronization during these tasks (AUT and CRT[4]) irrespective of stimulus material. In contrast, during convergent thinking, merely a slight desynchronization was observed in the verbal task (RAT) compared to the visuo-spatial task (APM). Based on upper alpha de-/synchronization as a neuronal index to quantify the proportion of divergent and convergent thinking in each task, a more precise classification of divergent and convergent thinking tasks becomes possible (see Figure 20).

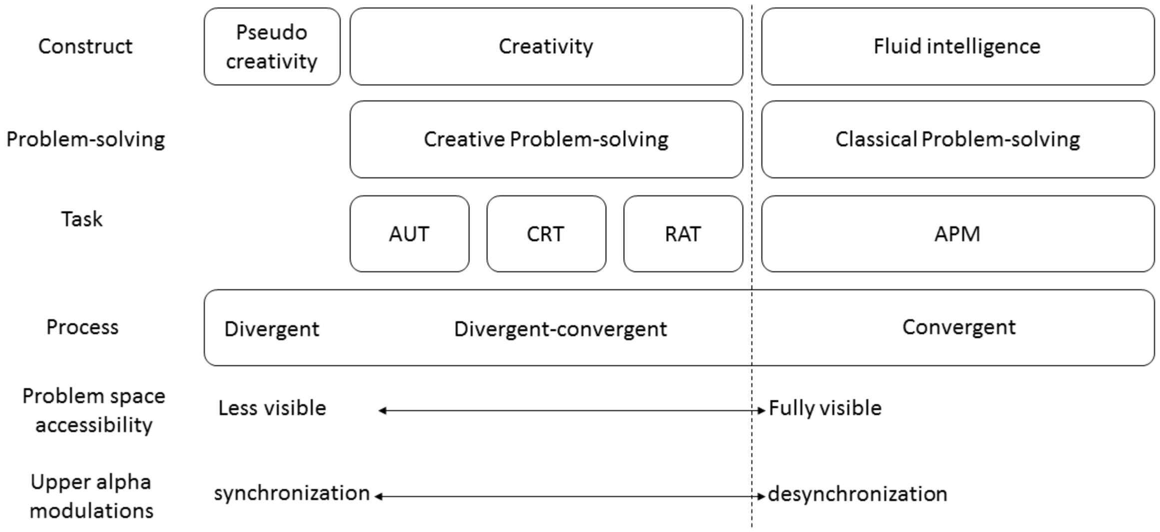


Figure 20. Schematic representation of divergent and convergent thinking as continuum indexed by upper alpha modulations. While tasks such as AUT, CRT, and RAT can be localized at the continuum, encompassing different amounts of divergent and convergent thinking cycles; the APM can clearly be localized at the convergent part of the continuum. Similarly, AUT shows the strongest upper alpha synchronization, followed by CRT and RAT. APM was accompanied by strong upper alpha desynchronization.

AUT and CRT require the highest amount of divergent thinking, as both clearly present an open-problem space which encourages and requires divergent thinking processes in order to generate possible solutions. We therefore argue that AUT and CRT are tasks that elicit a predominantly divergent mode of thinking. In terms of divergent-convergent thinking cycles, this could mean that there are either more of these cycles or they occur with a pronunciation on divergent thinking in these tasks (for example, the divergent part requires more time as compared to the convergent part). In general, it

---

[4] Please note that in the following CRT represents the results of CRTdiv (i.e., the divergent thinking part of CRT); for details see Eymann et al., 2022.

remains a challenge to disentangle both thinking modes even when using time-sensitive instruments such as EEG due to idiosyncratic differences in timing for each item and/ or individual participant. This fact makes it likely that especially in typical divergent thinking tasks such as AUT, the role of convergent thinking might not be detected and hence remain underestimated. However, from a theoretical perspective it is undeniable that convergent thinking has a major impact on generated creative ideas through divergent thinking, by evaluating their applicability in the larger focus of the solution/end product aimed for.

Notably, during RAT only minimal desynchronization was observed. Considering its specific structure and problem space accessibility, it is possible that verbal convergent thinking is different from visuo-spatial convergent thinking and hence, is accompanied by different upper alpha band modulations. This in turn would indicate that upper alpha oscillatory activity during convergent thinking is modulated by and sensitive to domain specific requirements (i.e. different types of stimuli or the induced thinking process). In the following, we present two additional interpretations for this observation: (1) The underlying thinking processes as well as (2) the immediate problem space accessibility, which will be discussed in turn below.

Although often conceptualized as convergent thinking task, RAT resembles divergent thinking tasks in the requirement to generate multiple response options: During RAT, participants first generate any possible compound (via divergent thinking) which they then evaluate in a second step (via convergent thinking). If the solution generated in this way does not meet the criteria of the correct compound, the process starts again. Creating alternate uses (as in AUT) as well as the generation of remote associations (as in RAT) both require the generation of novel ideas as well as the suppression of initial and mostly general/conventional or closely associated responses. From this perspective, what defines these tasks as either divergent or convergent is not the thinking process, but the number of solutions that solve the problem (AUT: numerous, potentially infinite, RAT: one). Hence, they operate in open or closed problem-spaces, although the applied cognitive strategies share certain similarities. This in turn could make the RAT less similar to APM - despite both being convergent thinking tasks - but more similar to the AUT.

More generally, existing studies on convergent thinking provide inconclusive results for convergent as opposed to divergent thinking. We argue that this stems from greater variability regarding the problem space accessibility in convergent tasks, while divergent tasks exhibit more consistency. In RAT, the problem-space is only partially accessible because the missing compound is not directly presented from the beginning, but has to be generated by the participant. Hence, this requires divergent thinking (i.e., generating possible solutions) within a pre-defined and considerably narrow frame of three words and then evaluating them in terms of their fit (i.e., convergent thinking). In contrast to RAT, characterized by a substantial upper alpha desynchronization, during APM no divergent thinking processes are required at all, as all possible solutions are presented directly and thus the problem space is completely transparent from the very beginning. Hence, for solving the APM, there is no need for participants to generate a range of possible solutions (i.e., divergent thinking): Participants can converge to the single correct solution out of the given possible answer choices (i.e., convergent thinking). In this regard, the differences that we observe during convergent thinking in both knowledge domains would largely be explained by the task requirements (of generating vs. not generating answers) and not (solely) by the type of stimuli presented.

When assessing divergent and convergent modes of thinking using well-established tasks like the ones mentioned above, several limitations need to be considered. For example, the AUT requires participants to not only produce original but also numerous ideas (i.e., fluency). However, by stressing fluency in AUT, we lose track of divergent and convergent thinking cycles by introducing numerous creative thinking phases for each solution generated. The reason for that is that participants will start to think about the next possible use for each item after creating the current solution. In doing so, the temporal resolution of divergent and convergent thinking during creative problem-solving becomes even more disguised. As a potential solution, two recent studies focused on originality only by not asking participants for many responses (Eymann et al., 2022; Eymann et al., 2024). Another limitation arises from the time-restriction that is generally applied in all of these tasks. However, restricting time on task diminishes ecological validity by cutting the natural flow of the thinking process. Hence, if we analyze data obtained during experimenter-controlled time periods, we will compare different stages within or between creative thinking processes across individuals. This in turn impedes the attempt to show the actual temporal course and activation pattern of these processes in EEG. Only a few studies allowed self-paced thinking processes in all tasks, aiming to provide an uninterrupted, more real life-like course of the thinking modes. At the same time, in line with prior studies, for standard EEG analyses during the self-paced thinking process specific time windows need to be segmented (Eymann et al., 2022; Eymann et al., 2024; see also; Jaarsveld et al., 2015; Jia & Zeng, 2021; Shemyakina et al., 2023). Although this allows to assess temporal dynamics at key periods of time, it does not provide a continuous observation of divergent-convergent cycles during the entire (self-paced) thinking process. Furthermore, due to individual differences in processing speed (which are observed when trials are self-paced), different phases of these divergent-convergent cycles across participants are compared.

9.9 Neurophysiological index for the convergence-divergence continuum

Based on the studies reviewed above, we propose a less clear distinction between divergent and convergent thinking modes than previously assumed, implying a continuity rather than a dichotomy between both processes. This can especially be observed in the case of RAT, which requires certain amounts of divergent thinking although assumed to be a convergent task. Upper alpha could potentially serve as a neurophysiological marker to indicate which mode of thinking (i.e. divergent and convergent; see Figure 1) is elicited predominantly during a particular task. Previously, only a few researchers have argued for a more continuous view on both processes. Within the scope of scientific creativity, Eysenck (2003) argued that convergent and divergent tests require basically the same processes (multiple associations of ideas), "(...) the two only differ in that in the one case only one of these is required and accepted, whereas in the other all are accepted". This implicates that "the cognitive processes may not be entirely dissimilar" (Eysenck, 2003, p.110) and solely differ in their end-product (one vs. many; Eysenck, 2003). Lubart (2001) argued in a similar way, proposing that different subprocesses might be used more frequently or for a longer time during divergent vs. convergent thinking. In our opinion, the studies reviewed above support and extend this view: Using upper alpha as a neurophysiological index allows to quantify different proportions of divergent and convergent thinking modes within established tasks of creativity when taking into account a detailed theoretical perspective regarding the necessary underlying processes of creative problem-solving. Divergent thinking (as indexed by upper alpha synchronization) is clearly elicited by tasks such as AUT and CRT. While convergent thinking (as indexed by upper alpha desynchronization) is still required to evaluate the ideas generated during divergent thinking mode, there should be a predominance of divergent thinking processes.

Upper alpha modulations reflect the extend of divergent and convergent thinking modes elicited by RAT and APM, respectively. RAT requires divergent thinking, as the problem-space is not initially assessable for the participant. In contrast, APM elicits the purest form of convergent thinking possible (accompanied by upper alpha desynchronization) as predefined response alternatives are presented along with each item. Similar to individual differences which usually fall along continua (Runco, 2014), pure divergent and convergent thinking modes may reflect two ends of a continuum, and depending on the task requirements, one or the other mode might be predominant (i.e., triggered more/longer) during creative problem-solving.

9.10 Conclusion

By conceptualizing the well-researched role of upper alpha de-/synchronization as a neurophysiological marker, we might be able to assess to what extend each process is activated during several phases of solving divergent and convergent thinking tasks, respectively. Furthermore, this indicates the necessity to understand upper alpha de-/synchronization as process-related (divergent vs. convergent) rather than simply construct-related (creativity, intelligence or open-, closed- problem solving), as it might give us the opportunity to disentangle those processes within these constructs.

However, we argue that as of now the advantage of precise time resolution that EEG provides has not been fully capitalized, which might explain at least some inconsistencies in prior research.

With this work, we emphasize the need to (1) provide participants a more real-life like experience when solving divergent and convergent thinking tasks, which in turn will (2) provide researchers with more reliable data on what is actually happening in the brain. Lastly, (3) we as researchers need to become creative on how to better capitalize on the full range of benefits that EEG holds for the neuroscientific research on creativity.

Chapter 10: GENERAL DISCUSSION

In the following chapter, I will summarize Study 1 and Study 2, as well as the resulting theoretical considerations described in Study 3 and their implications for future research. For the sake of brevity, not all results are described again in great detail (please refer to Chapter 7 - 9 for a comprehensive description and discussion of the specific results and theoretical considerations). In this chapter, the most important insights of these investigations are discussed, as well as an outlook on which implications can be derived for future studies.

10.1 Divergent and Convergent Thinking across Knowledge Domains

With Study 1 and Study 2, we introduced a new methodological approach to investigate divergent and convergent thinking within different knowledge domains by accounting for WM-related activity. Using self-paced trials in all tasks, our approach further accounts for individual differences of processing speed during idea generation phases and allows to observe the creative thinking processes more realistically (see Chapter 7 and Chapter 8 for details).

Across both knowledge domains, we observed divergent thinking being accompanied by upper alpha synchronization, whereas upper alpha desynchronization was more pronounced during convergent thinking in the visuo-spatial domain (measured with APM) in contrast to convergent thinking in the verbal domain (measured by RAT). At the same time, during the convergent part of the CRT (CRT$_{\text{con}}$), upper alpha desynchronized, although less pronounced as in APM$_{|\text{WM}}$. This effect can be interpreted as a major similarity between convergent thinking in CRT and in APM, potentially as a result of similar problem space accessibility (ct. Chapter 9). During this stage of the CRT, participants have already generated all geometrical components and hence, at this point use mostly convergent operations (ct. Chapter 4 and Chapter 7). Furthermore, these similarities can be attributed to the shared visuo-spatial knowledge domain. As a result, the accessibility of the response required to solve the respective item (as in APM and CRT$_{\text{con}}$) might also influence upper alpha oscillatory activity and hence produce a different pattern during RAT, in which participants have to keep them in an active state in their memory (ct. Chapter 9).

At the same time, we observed different temporal dynamics of upper alpha across knowledge domains. In Study 1, CRT$_{\text{div|WM}}$ showed the strongest upper alpha synchronization towards the middle (Int 2) in contrast to the beginning and end of the thinking process (Int 1 and Int 3; cf. Chapter 7). Likewise, in Study 2, both AUT|WM and RAT|WM showed the strongest upper alpha synchronization towards the middle (Int 2) in contrast to the beginning and end of the thinking phase (Int 1 and Int 3; cf. Chapter 8). These observations suggest that creativity-driven processes (present in tasks that involve idea generation phases) show similarities in their temporal dynamics across different knowledge domains. Hence, divergent modes of thinking might share underlying neural mechanisms despite different stimulus material. Furthermore, as WM-related activity was accounted for during all of these processes, we can conclude that their similarities exist beyond their shared underlying task demands in regard to WM.

10.2 The Role of Working Memory

Although EEG is limited in its potential to localize the neural origins of an effect, our data indicate that divergent and convergent thinking share certain characteristics beyond WM within as well as across knowledge domains. Both studies revealed that upper alpha modulations during the different divergent and convergent thinking tasks were most pronounced at (bilateral) fronto-parietal areas in Study 1 and Study 2 (see Chapter 7 and Chapter 8 for details). This indicates that across knowledge domains, these processes are regulated mainly at frontal and parietal areas within both hemispheres, which have been associated with complex problem solving and executive functions, such as cognitive control (Niendam et al., 2012) as well as WM (Harding et al., 2015; Wallis et al., 2015; Rutishauser et al., 2010; Sauseng et al., 2005). This emphasizes the necessity to investigate divergent and convergent thinking beyond WM, but also in regards to other cognitive processes. While in our studies, WM-related activity was removed from the data, we did not control for related cognitive processes at the same time. This limitation needs to be considered in future studies to further identify the underlying commonalities and differences between both processes. Furthermore, a more precise investigation of both divergent and convergent thinking could also transfer to a more detailed representation of fluid intelligence and creativity, which helps us to capture both constructs more precisely.

However, it is important to note that the impact of WM seems to differ in certain aspects within as well as across knowledge domains. On one hand, we can assume that different WM-subcomponents are involved during divergent and convergent thinking in different knowledge domains (i.e., visuo-spatial sketchpad vs. phonological loop; ct. Chapter 5) and to potentially varying degrees. In this regard, it is arguable that WM, WMC and related cognitive control functions might play a more prominent role during AUT due to our particular experimental design as compared to other studies. As we did not ask participants to explicitly verbalize all of their ideas but only their most original answer (see Chapter 8 for details), we might have introduced a higher WM load by the requirement to keep several ideas activated in WM at the same time. This increases cognitive load, which was in turn observed to enhance divergent thinking (Lin & Lien, 2013) due to a limited cognitive control capacity (Cancer et al., 2023). Additionally, our results are in line with De Dreu and colleagues (2012), who observed that WMC helped creative performance in terms of fluency and originality of ideas. The authors' interpretation was that WMC enables focus on task, similar to how WM contributes to diverse higher order cognitive processes. Hence, WM might enhance divergent thinking by regulating attentional control (De Dreu et al., 2012). Furthermore, we can assume that both verbal tasks used in Study 2 in general required more WM-related activity, as participants had to keep their generated ideas (AUT) or compounds (RAT) in an activated state to compare and evaluate them. In a related line of research, Benedek and colleagues (2011) observed that upper alpha synchronization was related to top-down processing (the stimulus disappeared after 500 ms, provoking high internal processing demands) in contrast to bottom-up processing, when the stimulus was presented throughout the entire trial (provoking low internal processing demands). Hence, these differences in task structure and procedure may become apparent in the neural signature.

On the other hand, during the visuo-spatial tasks we assessed in Study 1, participants were able to draw their ideas (CRT) or directly see the possible solutions (APM), which unburdens their WM and WMC. Hence, our verbal tasks might have evoked more or stronger neural correlates of WM, WMC and related cognitive control processes due to the differences in internal processing demands in response to the task structure and stimulus presentation (see Chapter 9 for details on problem space accessibility).

Corresponding to this argument, we observed slight differences in theta activity as well as neighboring frequencies across both WM tasks that we employed in our studies (see Chapter 7 and Chapter 8 for details). This again highlights the necessity to include more frequency bands and investigate related cognitive processes in more detail, in particular across knowledge domains.

10.3 Investigating Divergent and Convergent Thinking with Creative Cognition Tasks

The details of the dynamic regulation between divergent and convergent thinking might still differ across different creative cognition tasks (i.e., tasks that require both divergent and convergent thinking). This idea is supported as in AUT, a serial order effect has been observed in prior studies (i.e., generated responses become more original over time; ct. Chapter 3.1). The AUT requires the generation of ideas on how to use an object in an original way. Hence, the idea generation process (i.e., divergent thinking) occurs within different concepts that are more or less semantically related, starting with the closest semantic relatedness. For example, when generating potential uses for a shoe, the first association could be ‘put it on my foot’ (shoe and foot can be considered as semantically closely related concepts) and later in the process, a more creative association could be ‘using it for eating soup’ (shoe and food/eating can be considered as semantically distant concepts). Hence, during AUT the semantic space is gradually explored and extended from close to distant relationships.

Here, I assume that in RAT a similar process happens in which participants over time become less tied to strong, but incorrect associations to the compound words. As already discussed (ct. Chapter 4), words used in RAT items are generally not semantically linked (Cortes et al., 2019), neither the three presented words to one another, nor the compound. In fact, RAT problems require the active inhibition of semantically associated concepts in order to solve the task. As already discussed (ct. Chapter 4), semantic networks of highly creative individuals show differences with respect to structure and quality (e.g., higher connectivity, lower modularity, shorter distances between concepts) in the verbal, but not the visuo-spatial knowledge domain (He et al., 2020). These differences in regards to the consolidation of semantic networks, as well as certain characteristics regarding the structures and timings of these tasks could result in observed differences that are not so much due to the un-relatedness of divergent and convergent thinking, but more so due to specifics of the measurement instruments. Although our research attempts to account for confounding factors regarding the structure, timing and task presentation, the semantic distance of words and concepts presented in tasks such as AUT and RAT is still an unsolved issue.

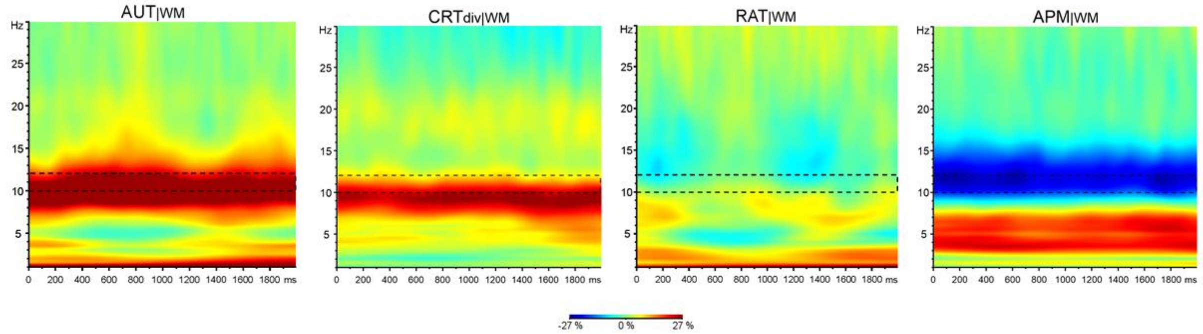
Regarding the task for the visuo-spatial knowledge domain (CRT), divergent and convergent thinking are both assessed within the same task by two designated sub-scores (see Chapter 4 and Chapter 7 for details). Furthermore, tasks encompassing geometric components such as CRT and APM do not require semantic knowledge consolidation. As mentioned above, the CRT sub-score *Relations* is considered a convergent production sub-score, whereas the CRT sub-score *Components and Specifications* is considered a divergent production sub-score (Jaarsveld et al., 2012, 2010). As already discussed in Chapter 4, correlation of the convergent CRT sub-score with performance in the RPM and the SPM (Raven et al., 1989a, 1989b) was observed in children (Jaarsveld et al., 2010, 2012). At the same time, the divergent sub-score correlated with the performance in the TTCT – Drawing Production (Jaarsveld et al., 2012, 2013). The authors hence conclude that classical and creative reasoning strategies are different (even potentially "independent faculties"; Jaarsveld et al., 2010, p. 306) as creative problem solving does not entirely depend on classical problem solving (Jaarsveld et al., 2010, 2017). However, these psychometric characteristics of the CRT do not imply that divergent and convergent thinking are two completely independent mental processes but rather that creative problem-solving encompasses both, divergent and convergent thinking processes.

10.4 Upper Alpha as Neurophysiological Index and Problem Space Access

In the studies presented in this dissertation, we employed tasks that exclusively assess convergent thinking (i.e., APM), but also tasks that elicit both, divergent and convergent thinking to various extents and in different temporal dynamics (AUT, RAT, CRT). However, disentangling both processes within creative problem-solving requires a marker that is both time-sensitive and objective. In Study 3, we propose that upper alpha might hold the potential to index the temporal dynamics of divergent-convergent cycles during creative cognition tasks (see Chapter 9 for details). Furthermore, the neuronal pattern of upper alpha modulations (i.e., de-/synchronization) which we observed in Study 1 and Study 2 indicates that divergent and convergent thinking might be more accurately represented as a continuum rather than as dichotomy (ct. Chapter 9). Both claims become especially obvious, if I present the obtained upper alpha results in a range from the task that requires the most (i.e., AUT) to the task that requires no divergent thinking (APM; see Figure 21).

Figure 21

Divergent and convergent thinking tasks ordered by the amount of divergent or convergent thinking assumed to be elicited by each task



Note. Grand averages for every task after subtracting oscillatory activity measured the respective WM-task. Grand averages include all electrodes, all intervals and all participants.

Here we can see that if we use upper alpha as an index for divergent and convergent thinking modes, AUT elicits the strongest synchronization effect as the task mainly requires divergent thinking processes (due to semantic search but also the originality instruction in Study 2). Next, the CRT$_{div}$ requires mainly divergent thinking processes as well, however, it can be assumed that also convergent thinking processes occur at this stage, as participants have to decide which geometric components they want to use for the respective matrix. They further have to organize the first row (Row 1) of the matrix using their generated components, which can be assumed to also require convergent thinking. Here, Figure 21 indicates that upper alpha in CRT$_{div}$ is slightly less synchronized in contrast to AUT. Next, the RAT shows only small deviations from the baseline, neither a strong synchronization, nor a strong desynchronization is visible in the data. In the context of indexing divergent and convergent modes of thinking, this could mean that during RAT the proportion that both thinking modes hold is rather balanced. The reason for that could be that participants are confronted with parts of the problem space (i.e., three words, which prevents them from having to generate possible solutions). However, the task requires participants to generate the missing compound by overcoming semantically close associations (i.e., divergent thinking). This close interdependence of processes could be the cause for the observed pattern of activation. Lastly, APM elicits strong upper alpha desynchronization as it requires exclusively convergent thinking to solve the task (as the problem and the correct solution are directly presented).

Our results show the necessity to evaluate divergent and convergent thinking tasks in more detail in accordance to their proposed in contrast to their actual modes of thinking. Here, a neurophysiological marker such as upper alpha might provide insight which thinking mode (i.e., divergent or convergent thinking) are actually evoked by which task and even more precisely, at which stage/time period within each task. Besides providing evidence that divergent and convergent thinking might be more accurately represented on a continuum, this opens up the possibility of disentangling divergent-convergent thinking cycles underlying each of these creative cognition tasks (ct. Chapter 9).

10.5 Future Directions

There are several issues future studies will need to examine. For instance, we exclusively investigated a specific demographic group (i.e., German university students) in our studies. However, there have been arguments for a complex underlying relation of divergent and convergent thinking which could potentially be influenced by factors such as personality traits, but also social and cultural background of participants (De Vries & Lubart, 2019). Considering that a large number of studies in the field of psychology and associated disciplines are conducted in western, educated, industrialized, rich, and democratic (WEIRD; Henrich, et al., 2010) cultures, which have been found to be a poorly suited candidate for inferences about the human population in general, future studies should employ our approach to different cultures, age groups, and educational backgrounds. This could lead to a more representative depiction of divergent and convergent thinking processes in general.

Furthermore, as already discussed (ct. Chapter 8), there is recent evidence suggesting that divergent and convergent thinking might be accompanied not only by alpha modulations, but also specific neuronal patterns in other EEG frequency bands, such as beta and gamma (Mazza et al., 2023) or theta (Wokke et al., 2018; Bayrami et al., 2011) implying a more complex neurophysiological signature of creative cognition. For example, Bayrami and colleagues (2011) did not observe any significant differences when analyzing the coherence of theta band during divergent and convergent thinking. Hence, the authors concluded that both processes have highly similar neuronal underpinnings, similar to our considerations in regards to upper alpha (ct. Chapter 9). While in absence of a specific hypothesis, we did not analyze oscillatory activity of other frequency bands in Study 1 and Study 2, we urge future investigations to examine these results comparable to our methodological approach.

Moreover, future studies should reconsider the WM tasks that we used and extend this approach to other cognitive domains, such as WMC, cognitive control processes, and executive functions. Daneman and Carpenter (1980) for example argued that a word span test (similar to what we employed in Study 2) used to assess WM might have limited explanatory power, as these tasks requires “relatively simple processes of rehearsal and access of common lexical items” (Daneman & Carpenter, 1980; p. 451). The authors suggested that the use of tasks with heavier processing demands might be required to achieve a better balance between processing and storage. This in turn can potentially prevent poor processing performance from being confused with a low storage capacity of participants (Daneman & Carpenter, 1980).

Lastly, I want to emphasize that RAT especially seems to hold some interesting insights. It has been argued that RAT performance might rely not so much on Gf but rather more on Gc (e.g., background vocabulary, Razumnikova 2007). Hence, this might impede the possibility to directly compare RAT and APM, besides their obvious differences in knowledge domain and problem space accessibility. In regards to the latter, it might be necessary to vary RAT items in regard to their problem space accessibility in future studies. By exposing participants to different modes of problem space accessibility, for instance by presenting response alternatives directly with each item as opposed to participants generating possible compounds (as in the original RAT), a more precise differentiation of upper alpha modulations specifically in regards to differences in problem space accessibility might be possible.

Chapter 11: CONCLUSION

The studies conducted within the scope of this thesis contribute to a more refined understanding on neuronal underpinnings and temporal dynamics of divergent and convergent thinking within as well as across different knowledge domains. Furthermore, our results emphasize the necessity to investigate both processes apart from their shared communalities due to WM, WMC, and related cognitive processes. In addition, we were able to draw overarching conclusions from both empirical studies (i.e., Study 1 and Study 2) into theoretical considerations, resulting in the Opinion Paper (i.e., Study 3). Here, we were able to propose the idea of a neuronal index to identify divergent-convergent dynamics more precisely and independent of stimulus material. Lastly, our results introduced an additional perspective on the previously proposed convergence-divergence continuum as well as the impact of problem space accessibility in creative cognition tasks. Thus, we added new perspectives and insights to further understand divergent and convergent thinking within and beyond their relationship with creativity and fluid intelligence, respectively.

REFERENCES

Abraham, A. (2018). *The neuroscience of creativity*. Cambridge University Press.

Abraham, A. (2023). Why the Standard Definition of Creativity Fails to Capture the Creative Act. *Qeios*. doi:10.32388/LS88G9.

Abraham, A., Pieritz, K., Thybusch, K., Rutter, B., Kröger, S., Schweckendiek, J., Stark, R., Windmann, S., & Hermann, C. (2012). Creativity and the brain: uncovering the neural signature of conceptual expansion. *Neuropsychologia*, *50*(8), 1906-1917.

Abraham, A., Rutter, B., Bantin, T., & Hermann, C. (2018). Creative conceptual expansion: A combined fMRI replication and extension study to examine individual differences in creativity. *Neuropsychologia*, *118*, 29-39.

Abraham, A., Thybusch, K., Pieritz, K., & Hermann, C. (2014). Gender differences in creative thinking: behavioral and fMRI findings. *Brain imaging and behavior*, *8*(1), 39-51.

Agnoli, S., Zanon, M., Mastria, S., Avenanti, A., & Corazza, G. E. (2020). Predicting response originality through brain activity: An analysis of changes in EEG alpha power during the generation of alternative ideas. *NeuroImage*, *207*, 116385.

Alexander, P. A. (1992). Domain knowledge: Evolving themes and emerging concerns. *Educational psychologist*, *27*(1), 33-51.

Alexander, P. A., & Judy, J. E. (1988). The interaction of domain-specific and strategic knowledge in academic performance. *Review of Educational research*, *58*(4), 375-404.

Arthur Jr, W., & Day, D. V. (1994). Development of a short form for the Raven Advanced Progressive Matrices Test. Educational and Psychological measurement, 54(2), 394-403.

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In I. K. W. Spence, & J. T. Spence (Eds.), *The psychology of learning and motivation: II*. Academic Press.

Azouvi, P., Couillet, J., Leclercq, M., Martin, Y., Asloun, S., & Rousseaux, M. (2004). Divided attention and mental effort after severe traumatic brain injury. *Neuropsychologia*, *42*(9), 1260-1268.

Azouvi, P., Jokic, C., Der Linden, M. V., Marlier, N., & Bussel, B. (1996). Working memory and supervisory control after severe closed-head injury. A study of dual task performance and random generation. *Journal of Clinical and Experimental Neuropsychology*, *18*(3), 317-337.

Baddeley, A. (1992). Working memory. *Science*, *255*(5044), 556-559.

Baddeley, A. (2000). The episodic buffer: a new component of working memory? *Trends in cognitive sciences*, *4*(11), 417-423.

Baddeley, A. (2010). Working memory. *Current biology*, *20*(4), R136-R140.

Baddeley, A. D. & Hitch, G. J. (1974). Working memory. In G. H. Bower (Ed.), *The Psychology of Learning and Motivation: Advances in Research and Theory*, VIII (pp. 47–89). New York, NJ: Academic Press.

Baddeley, A. D., & Hitch, G. J. (2007). Working memory: Past, present… and future. In N. Osaka, R.H. Logie, & M. D' Esposito (Eds.), *The cognitive neuroscience of working memory*, 1-20.

Barron, F., & Harrington, D. M. (1981). Creativity, intelligence, and personality. *Annual review of psychology*, *32*(1), 439-476.

Basadur, M. (1995). Optimal ideation-evaluation ratios. *Creativity research journal*, *8*(1), 63-75.

Bayrami, M., Nazari, M. A., & Andalib Kooraeim, M. (2011). EEG patterns coherence in theta band during convergent and divergent thinking. *Advances in Cognitive Science*, *13*(2), 1.

Beaty, R. E., Benedek, M., Silvia, P. J., & Schacter, D. L. (2016). Creative cognition and brain network dynamics. *Trends in cognitive sciences*, *20*(2), 87-95.

Beaty, R. E., Cortes, R. A., Zeitlen, D. C., Weinberger, A. B., & Green, A. E. (2021). Functional realignment of frontoparietal subnetworks during divergent creative thinking. *Cerebral cortex*, *31*(10), 4464-4476.

Beaty, R. E., Nusbaum, E. C., & Silvia, P. J. (2014). Does insight problem solving predict real-world creativity? *Psychology of Aesthetics, Creativity, and the Arts*, *8*(3), 287.

Becker, M. (1995). Nineteenth-century foundations of creativity research. *Creativity Research Journal*, *8*(3), 219-229.

Benedek, M., Bergner, S., Könen, T., Fink, A., & Neubauer, A. C. (2011). EEG alpha synchronization is related to top-down processing in convergent and divergent thinking. *Neuropsychologia*, *49*(12), 3505-3511.

Benedek, M., Jauk, E., Sommer, M., Arendasy, M., & Neubauer, A. C. (2014). Intelligence, creativity, and cognitive control: The common and differential involvement of executive functions in intelligence and creativity. *Intelligence*, *46*, 73-83.

Berti, S. (2010). Arbeitsgedächtnis: Vergangenheit, Gegenwart und Zukunft eines theoretischen Konstruktes. *Psychologische Rundschau*, 61 (1), 3–9.

Boccia, M., Piccardi, L., Palermo, L., Nori, R., & Palmiero, M. (2015). Where do bright ideas occur in our brain? Meta-analytic evidence from neuroimaging studies of domain-specific creativity. *Frontiers in psychology*, *6*, 1195.

Bramwell, B. S. (1948). Galton's “hereditary genius”: And the three following generations since 1869. *The Eugenics Review*, *39*(4), 146.

Braunlich, K., Gomez-Lavin, J., & Seger, C. A. (2015). Frontoparietal networks involved in categorization and item working memory. *NeuroImage*, *107*, 146-162.

Brody, N. (2004). History of Theories and Measurements of Intelligence. In R.J. Sternberg (Ed.), *Handbook of Intelligence* (2nd ed., pp. 16-33). Academic Press.

Bullough, V., Bullough, B., & MAURO, M. (1981). History and creativity: Research problems and some possible solutions. *The Journal of Creative Behavior*, *15*(2), 102-116.

Camarda, A., Salvia, E., Vidal, J., Weil, B., Poirel, N., Houde, O., Borst, G.; & Cassotti, M. (2018). Neural basis of functional fixedness during creative idea generation: an EEG study. *Neuropsychologia*, *118*, 4-12.

Campbell, D. T. (1960). Blind variation and selective retentions in creative thought as in other knowledge processes. *Psychological review*, *67*(6), 380.

Cancer, A., Iannello, P., Salvi, C., & Antonietti, A. (2023). Executive functioning and divergent thinking predict creative problem-solving in young adults and elderlies. *Psychological Research*, *87*(2), 388-396.

Carpenter, P. A., Just, M. A., & Shell, P. (1990). What one intelligence test measures: a theoretical account of the processing in the Raven Progressive Matrices Test. *Psychological review, 97*(3), 404.

Carroll, J. B. (1968). Reviews: Guilford, JP The Nature of Human Intelligence. New York: McGraw-Hill, 1967. *American Educational Research Journal*, *5*(2), 249-256.

Carroll, J. B. (1993). *Human Cognitive Abilities: A survey of factoranalytic studies*. Cambridge: Cambridge University Press.

Cattell, J. M. (1890). Mental tests and measurements. *Mind*, 15, 373-381.

Cattell, R. B. (1963). Theory of fluid and crystallized intelligence: A critical experiment. *Journal of educational psychology*, *54*(1), 1-22.

Cattell, R. B. and Butcher, H. J. (1968). *The prediction of achievement and creativity*. New York: Bobbs-Merrill.

Chen, Q., Beaty, R. E., Cui, Z., Sun, J., He, H., Zhuang, K., ... & Qiu, J. (2019). Brain hemispheric involvement in visuospatial and verbal divergent thinking. *Neuroimage*, *202*, 116065.

Chen, Z., De Beuckelaer, A., Wang, X., & Liu, J. (2017). Distinct neural substrates of visuospatial and verbal-analytic reasoning as assessed by Raven's Advanced Progressive Matrices. *Scientific reports*, *7*(1), 16230.

Cho, S. H., Nijenhuis, J. T., Van Vianen, A. E., Kim, H. B., & Lee, K. H. (2010). The relationship between diverse components of intelligence and creativity. *The Journal of Creative Behavior, 44*(2), 125-137.

Christoff, K., Prabhakaran, V., Dorfman, J., Zhao, Z., Kroger, J. K., Holyoak, K. J., & Gabrieli, J. D. (2001). Rostrolateral prefrontal cortex involvement in relational integration during reasoning. *Neuroimage, 14*(5), 1136-1149.

Chrysikou, E. G., Motyka, K., Nigro, C., Yang, S. I., & Thompson-Schill, S. L. (2016). Functional fixedness in creative thinking tasks depends on stimulus modality. *Psychology of aesthetics, creativity, and the arts, 10*(4), 425.

Chuderski, A., Taraday, M., Nęcka, E., & Smoleń, T. (2012). Storage capacity explains fluid intelligence but executive control does not. *Intelligence, 40*(3), 278-295.

Cocchini, G., Logie, R. H., Sala, S. D., MacPherson, S. E., & Baddeley, A. D. (2002). Concurrent performance of two memory tasks: Evidence for domain-specific working memory systems. *Memory & Cognition, 30*(7), 1086-1095.

Cogdell-Brooke, L. S., Sowden, P. T., Violante, I. R., & Thompson, H. E. (2020). A meta-analysis of functional magnetic resonance imaging studies of divergent thinking using activation likelihood estimation. *Human Brain Mapping*, *41*(17), 5057-5077.

Cohen, M. X. (2014). *Analyzing neural time series data: theory and practice*. MIT press.

Cortes, R. A., Weinberger, A. B., Daker, R. J., & Green, A. E. (2019). Re-examining prominent measures of divergent and convergent creativity. *Current Opinion in Behavioral Sciences*, *27*, 90-93.

Cowan, N., & Morey, C. C. (2007). How can dual-task working memory retention limits be investigated? *Psychological science, 18*(8), 686-688.

Cropley, A. (2006). In praise of convergent thinking. *Creativity research journal*, *18*(3), 391-404.

Cropley, A. J., & Maslany, G. W. (1969). Reliability and factorial validity of the Wallach-Kogan creativity tests. *British Journal of psychology*, *60*(3), 395-398.

Csikszentmihalyi, M. (1988). The dangers of originality: Creativity and the artistic process. In M. M. Gedo (Ed.), *Psychoanalytic perspectives on art* (pp.213-224). Hillsdale, NJ: Analytic Press.

Dake, D. M. (1991). The visual definition of visual creativity. *Journal of Visual Literacy*, *11*(1), 100-104.

Daneman, M. (1991). Working memory as a predictor of verbal fluency. *Journal of Psycholinguistic Research,* 20(6), 445–464.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of verbal learning and verbal behavior*, *19*(4), 450-466.

Danko, S. G., Shemyakina, N. V., Nagornova, Z. V., & Starchenko, M. G. (2009). Comparison of the effects of the subjective complexity and verbal creativity on EEG spectral power parameters. *Human Physiology*, *35*(3), 381-383.

Davidson, J. E., & Downing, C. L. (2000). Contemporary models of intelligence. In R. J. Sternberg (Ed.), *Handbook of intelligence*, Cambridge University Press, 34-49.

De Dreu, C. K., Nijstad, B. A., Baas, M., Wolsink, I., & Roskes, M. (2012). Working memory benefits creative insight, musical improvisation, and original ideation through maintained task-focused attention. *Personality and Social Psychology Bulletin*, *38*(5), 656-669.

De Vries, H. B., & Lubart, T. I. (2019). Scientific creativity: divergent and convergent thinking and the impact of culture. *The Journal of Creative Behavior*, *53*(2), 145-155.

De Vries, I. E., Slagter, H. A., & Olivers, C. N. (2020). Oscillatory control over representational states in working memory. *Trends in cognitive sciences*, *24*(2), 150-162.

Diakidoy, I. A. N., & Spanoudis, G. (2002). Domain specificity in creativity testing: A comparison of performance on a general divergent-thinking test and a parallel, content-specific test. *The Journal of Creative Behavior*, *36*(1), 41-61.

Dietrich, A., & Kanso, R. (2010). A review of EEG, ERP, and neuroimaging studies of creativity and insight. *Psychological bulletin*, *136*(5), 822.

Dietrich, A., & Srinivasan, N. (2007). The optimal age to start a revolution. *The Journal of Creative Behavior*, *41*(1), 54-74.

Domnick, F., Zimmer, H. D., Becker, N., & Spinath, F. M. (2017). Is the Correlation between Storage Capacity and Matrix Reasoning Driven by the Storage of Partial Solutions? A Pilot Study of an Experimental Approach. *Journal of Intelligence*, *5*(2), 21.

Donoghue, T., Haller, M., Peterson, E. J., Varma, P., Sebastian, P., Gao, R., ... & Voytek, B. (2020). Parameterizing neural power spectra into periodic and aperiodic components. *Nature neuroscience*, *23*(12), 1655-1665.

Egner, T., & Siqi-Liu, A. (2024). Insights into control over cognitive flexibility from studies of task-switching. *Current Opinion in Behavioral Sciences*, *55*, 101342.

Ellamil, M., Dobson, C., Beeman, M., & Christoff, K. (2012). Evaluative and generative modes of thought during the creative process. *Neuroimage*, *59*(2), 1783-1794.

Emch, M., von Bastian, C. C., & Koch, K. (2019). Neural correlates of verbal working memory: an fMRI meta-analysis. Front. Hum. Neurosci. 13, 180.

Engle, R. W. (2001). What is working memory capacity? In H. L. Roediger III, J. S. Nairne, I. Neath, & A. M. Surprenant (Eds.), *The nature of remembering: Essays in honor of Robert G. Crowder* (pp. 297–314). American Psychological Association.

Ericsson, K. A. (1999). Creative expertise as superior reproducible performance: Innovative and flexible aspects of expert performance. *Psychological Inquiry*, *10*(4), 329-333.

Ericsson, K. A., & Lehmann, A. C. (1996). Expert and exceptional performance: Evidence of maximal adaptation to task constraints. *Annual review of psychology*, *47*(1), 273-305.

Eymann, V., Beck, A. K., Jaarsveld, S., Lachmann, T., & Czernochowski, D. (2022). Alpha oscillatory evidence for shared underlying mechanisms of creativity and fluid intelligence above and beyond working memory-related activity. *Intelligence*, *91*, 101630.

Eymann, V., Lachmann, T., Beck, A. K., & Czernochowski, D. (2024). EEG oscillatory evidence for the temporal dynamics of divergent and convergent thinking in the verbal knowledge domain. *Intelligence*, *104*, 101828.

Eysenck, H. J. (2003). Creativity, personality and the convergent-divergent continuum. In M. A. Runco (Ed.), *Critical creative processes* (pp. 95–114). Hampton Press.

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior research methods*, *39*(2), 175-191.

Ferdinand, N. K., & Czernochowski, D. (2018). Motivational Influences on Performance Monitoring and Cognitive Control Across the Adult Lifespan. *Front Psychol*, *9*, 1-18. doi:10.3389/fpsyg.2018.01018

Fink, A., & Benedek, M. (2014). EEG alpha power and creative ideation. *Neuroscience & Biobehavioral Reviews*, *44*, 111-123.

Fink, A., Benedek, M., Grabner, R. H., Staudt, B., & Neubauer, A. C. (2007). Creativity meets neuroscience: Experimental tasks for the neuroscientific study of creative thinking. *Methods*, *42*(1), 68-76.

Fink, A., Grabner, R.H., Benedek, M., Reishofer, G., Hauswirth, V., Fally, M., Neuper,C., Ebner, F., Neubauer, A.C. (2009b). The creative brain: Investigation of brain activity during creative problem solving by means of EEG and fMRI. HumanBrain Mapping 30, 734–748.

Fink, A., Grabner, R. H., Neuper, C., & Neubauer, A. C. (2005). EEG alpha band dissociation with increasing task demands. *Cognitive brain research*, *24*(2), 252-259.

Fink, A., Graif, B., Neubauer, A.C. (2009a). Brain correlates underlying creative thinking: EEG alpha activity in professional vs. novice dancers. NeuroImage 46,854–862.

Fink, A., & Neubauer, A. C. (2006). EEG alpha oscillations during the performance of verbal creativity tasks: Differential effects of sex and verbal intelligence. *International Journal of Psychophysiology*, *62*(1), 46-53.

Fink, A., & Neubauer, A. C. (2008). Eysenck meets Martindale: The relationship between extraversion and originality from the neuroscientific perspective. *Personality and Individual Differences*, *44*(1), 299-310.

Fink, A., Schwab, D., & Papousek, I. (2011). Sensitivity of EEG upper alpha activity to cognitive and affective creativity interventions. *International Journal of Psychophysiology*, *82*(3), 233-239.

Fink, G. R., Marshall, J. C., Halligan, P. W., Frith, C. D., Frackowiak, R. S., & Dolan, R. J. (1997). Hemispheric specialization for global and local processing: the effect of stimulus category. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, *264*(1381), 487-494.

Finke, R. A., Ward, T. B., & Smith, S. M. (1996). *Creative cognition: Theory, research, and applications*. MIT press.

Fougnie, D., Zughni, S., Godwin, D., & Marois, R. (2015). Working memory storage is intrinsically domain specific. *Journal of Experimental Psychology: General*, *144*(1), 30.

Freunberger, R., Werkle-Bergner, M., Griesmayr, B., Lindenberger, U., & Klimesch, W. (2011). Brain oscillatory correlates of working memory constraints. *Brain research*, *1375*, 93-102.

Frith, E., Elbich, D. B., Christensen, A. P., Rosenberg, M. D., Chen, Q., Kane, M. J., Silvia, P.J., Seli, P., & Beaty, R. E. (2021a). Intelligence and creativity share a common cognitive and neural basis. *Journal of Experimental Psychology: General*, *150*(4), 609.

Frith, E., Kane, M. J., Welhaf, M. S., Christensen, A. P., Silvia, P. J., & Beaty, R. E. (2021b). Keeping creativity under control: contributions of attention control and fluid intelligence to divergent thinking. *Creativity Research Journal*, *33*(2), 138-157.

Fukuda, K., Vogel, E., Mayr, U., & Awh, E. (2010). Quantity, not quality: The relationship between fluid intelligence and working memory capacity. *Psychonomic bulletin & review*, *17*(5), 673-679.

Galton, F. (1870). *Hereditary genius.* NYC: Appleton.

Gao, Y., Wu, X., Yan, Y., Li, M., Qin, F., Ma, M., ... & Qiu, J. (2023). The unity and diversity of verbal and visuospatial creativity: Dynamic changes in hemispheric lateralisation. *Human Brain Mapping*, *44*(17), 6031-6042.

Geisser, S., & Greenhouse, S. W. (1958). An extension of box's results on the use of the F distribution in multivariate analysis. The Annals of Mathematical Statistics, 29(3), 885-891.

Gerver, C. R., Griffin, J. W., Dennis, N. A., & Beaty, R. E. (2023). Memory and creativity: A meta-analytic examination of the relationship between memory systems and creative cognition. *Psychonomic Bulletin & Review*, 1-39.

Getzels, J.W., & Csikszentmihalyi, M. (1976). *The creative vision: A longitudinal study of problem finding in art.* New York: Wiley.

Getzels, J. A. and Jackson, P. W. (1962). *Creativity and intelligence*. New York: Wiley.

Ghiselin, B. (1952). The creative process. Los Angeles: University of California

Gilhooly, K. J., Fioratou, E., Anthony, S. H., & Wynn, V. (2007). Divergent thinking: Strategies and executive involvement in generating novel uses for familiar objects. *British Journal of Psychology*, *98*(4), 611-625.

Gonen-Yaacovi, G., De Souza, L. C., Levy, R., Urbanski, M., Josse, G., & Volle, E. (2013). Rostral and caudal prefrontal contribution to creativity: a meta-analysis of functional imaging data. *Frontiers in human neuroscience*, *7*, 465.

Gottfredson, L. S. (1997): Why g Matters: The Complexity of Everyday Life. In: Intelligence, 24 (1), 79–132.

Grabner, R. H., Fink, A., Stipacek, A., Neuper, C., & Neubauer, A. C. (2004). Intelligence and working memory systems: evidence of neural efficiency in alpha band ERD. *Cognitive Brain Research, 20*(2), 212-225.

Guilford, J. E (1950). Creativity. *American Psychologist*, 5, 444-454.

Guilford, J. P. (1956). The structure of intellect model. Psychological Bulletin, 53, 267–293. doi:10.1037/h0040755

Guilford, J. P. (1967). The nature of human intelligence. New York: McGraw-Hill.

Guilford, J. P. (1968). *Intelligence, creativity, and their educational implications*. New York: Robert R. Knapp.

Guilford, J. P. (1974). Rotational problems in factor analysis. *Psychological Bulletin, 81,* 498–501.

Guilford, J. P. (1975). Creativity: A quarter century of progress. In I.A. Taylor & J.W. Getzels (Eds.), *Perspectives in creativity* (pp. 37–59). Chicago: Aldine.

Guilford, J. P. (1983). Transformation abilities of functions. *Journal of Creative Behavior, 17,* 75–83.

Guilford, J. P., Christensen, P. R., Merrifield, P. R. and Wilson, R. C. (1978). *Alternate Uses: Manual of Instructions and Interpretation*, Orange, CA: Sheridan Psychological Services.

Harding, I. H., Yücel, M., Harrison, B. J., Pantelis, C., & Breakspear, M. (2015). Effective connectivity within the frontoparietal control network differentiates cognitive control and working memory. *Neuroimage*, *106*, 144-153.

He, L., Kenett, Y. N., Zhuang, K., Liu, C., Zeng, R., Yan, T., ... & Qiu, J. (2020). The relation between semantic memory structure, associative abilities, and verbal and figural creativity. *Thinking & Reasoning*, *27*(2), 268-293.

Heeger, D. J., & Ress, D. (2002). What does fMRI tell us about neuronal activity?. *Nature reviews neuroscience*, *3*(2), 142-151.

Henrich, J., Heine, S. J., & Norenzayan, A. (2010). The weirdest people in the world? *Behavioral and Brain Sciences, 33*(2–3), 61–83.

Herrmann, C. S., Senkowski, D., & Röttger, S. (2004). Phase-locking and amplitude modulations of EEG alpha: Two measures reflect different cognitive processes in a working memory task. *Experimental psychology, 51*(4), 311-318.

Horn, J. L. (1968). Organization of abilities and the development of intelligence. *Psychological review*, *75*(3), 242.

Horn, J. L., & Cattell, R. B. (1966). Refinement and test of the theory of fluid and crystallized general intelligences. *Journal of educational psychology*, *57*(5), 253.

Horn, J. L., & Cattell, R. B. (1967). Age differences in fluid and crystallized intelligence. *Acta psychologica*, *26*, 107-129.

Howkins, J. (2002). *The creative economy: How people make money from ideas*. Penguin UK.

Isaksen, S. G., Puccio, G. J., & Gryskiewicz, S. S. (1993). Profiling creativity: Nature and implications of a new research program. In S.S. *Gryskiewicz, Discovering Creativity: Proceedings of the 1992 International Creativity & Innovation Networking Conference.* Center for Creative Leadership. (pp. 163-166).

Jaarsveld, S., Fink, A., Rinner, M., Schwab, D., Benedek, M., & Lachmann, T. (2015). Intelligence in creative processes: An EEG study. *Intelligence, 49*, 171-178.

Jaarsveld, S., & Lachmann, T. (2017). Intelligence and creativity in problem solving: the importance of test features in cognition research. *Frontiers in psychology, 8*, 134.

Jaarsveld, S., Lachmann, T., Hamel, R., & Leeuwen, C. V. (2010). Solving and creating raven progressive matrices: reasoning in well-and ill-defined problem spaces. *Creativity Research Journal*, *22*(3), 304-319.

Jaarsveld, S., Lachmann, T., & van Leeuwen, C. (2012). Creative reasoning across developmental levels: Convergence and divergence in problem creation. *Intelligence*, *40*(2), 172-188.

Jaarsveld, S., Lachmann, T., and van Leeuwen, C. (2013). "The impact of problem space on reasoning: Solving versus creating matrices," in *Proceedings of the 35th Annual Conference of the Cognitive Science Society*, eds M. Knauff, M. Pauen, N. Sebanz, and I. Wachsmuth (Austin, TX: Cognitive Science Society),2632–2638.

Jaarsveld, S., & van Leeuwen, C. (2005). Sketches from a design process: Creative cognition inferred from intermediate products. *Cognitive Science*, *29*(1), 79-101.

Japardi, K., Bookheimer, S., Knudsen, K., Ghahremani, D. G., & Bilder, R. M. (2018). Functional magnetic resonance imaging of divergent and convergent thinking in Big-C creativity. *Neuropsychologia*, *118*, 59-67.

Jasper, H. H. (1958). The ten-twenty electrode system of the International Federation. Electroencephalography Clinical Neurophysiology, 10, 370–375

Jauk, E., Benedek, M., Dunst, B., & Neubauer, A. C. (2013). The relationship between intelligence and creativity: New support for the threshold hypothesis by means of empirical breakpoint detection. *Intelligence*, *41*(4), 212-221.

Jauk, E., Benedek, M., & Neubauer, A. C. (2012). Tackling creativity at its roots: Evidence for different patterns of EEG alpha activity related to convergent and divergent modes of task processing. *International Journal of Psychophysiology*, *84*(2), 219-225.

Jaušovec, N. (1997). Differences in EEG activity during the solution of closed and open problems. *Creativity Research Journal*, *10*(4), 317-324.

Jaušovec, N., & Jaušovec, K. (2000). EEG activity during the performance of complex mental problems. *International Journal of Psychophysiology*, *36*(1), 73-88.

Jaušovec, N., & Jaušovec, K. (2012). Working memory training: improving intelligence–changing brain activity. *Brain and cognition*, *79*(2), 96-106.

Jia, W., von Wegner, F., Zhao, M., & Zeng, Y. (2021). Network oscillations imply the highest cognitive workload and lowest cognitive control during idea generation in open-ended creation tasks

Jia, W., & Zeng, Y. (2021). EEG signals respond differently to idea generation, idea evolution and evaluation in a loosely controlled creativity experiment. *Scientific Reports*, *11*(1), 1-20.

Jones, K., Runco, M. A., Dorman, C., & Freeland, D. C. (1997). Influential factors in artist's lives and themes in their artwork. *Creativity Research Journal*, *10*(2-3), 221-228.

Jonides, J., Reuter-Lorenz, P. A., Smith, E. E., Awh, E., Barnes, L. L., Drain, M., ... & Schumacher, E. H. (1996). Verbal and spatial working memory in humans. *Psychology of learning and motivation*, *35*, 43-88.

Jung, R. E., & Haier, R. J. (2007). The Parieto-Frontal Integration Theory (P-FIT) of intelligence: converging neuroimaging evidence. *Behavioral and brain sciences*, *30*(2), 135-154.

Jung, T. P., Humphries, C., Lee, T. W., Makeig, S., McKeown, M. J., Iragui, V., & Sejnowski, T. J. (1998). Extended ICA removes artifacts from electroencephalographic recordings. Advances in neural information processing systems, 10, 894-900.

Kampylis, P. G., & Valtanen, J. (2010). Redefining creativity—analyzing definitions, collocations, and consequences. *The Journal of Creative Behavior*, *44*(3), 191-214.

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: a latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of experimental psychology: General*, *133*(2), 189.

Kaufman, J. C., & Baer, J. (2004). Sure, I'm creative—but not in mathematics!: Self-reported creativity in diverse domains. *Empirical studies of the Arts*, *22*(2), 143-155.

Kaufman, J. C., & Beghetto, R. A. (2009). Beyond big and little: The four c model of creativity. *Review of general psychology*, *13*(1), 1-12.

Kaufman, J. C., & Beghetto, R. A. (2013). Do people recognize the four Cs? Examining layperson conceptions of creativity. *Psychology of Aesthetics, Creativity, and the Arts*, *7*(3), 229.

Kaufman, J. C., Cole, J. C., & Baer, J. (2009). The construct of creativity: Structural model for self-reported creativity ratings. *The Journal of Creative Behavior*, *43*(2), 119-134.

Kim, K. H. (2006). Can we trust creativity tests? A review of the Torrance Tests of Creative Thinking (TTCT). *Creativity research journal*, *18*(1), 3-14.

Kinney, D. K., & Richards, R. L. (2019). Artistic creativity and affective disorders: Are they connected? In Martindale, C., Locher, P., Petrov, V., & Berleant, A. (Eds.), *Evolutionary and neurocognitive approaches to aesthetics, creativity and the arts,* Routledge, New York, 225-237.

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain research reviews*, *29*(2-3), 169-195.

Kozbelt, A., Beghetto, R.A., & Runco, M.A. (2010). Creativity research. In Kaufman, J.C. & Sternberg, R.J. (Eds.), *The Cambridge handbook of creativity*. Cambridge University Press.

Kraus, B., Cadle, C., & Simon-Dack, S. (2019). EEG alpha activity is moderated by the serial order effect during divergent thinking. *Biological psychology*, *145*, 84-95.

Landmann, N., Kuhn, M., Piosczyk, H., Feige, B., Riemann, D., & Nissen, C. (2014). Entwicklung von 130 deutschsprachigen compound remote associate (CRA)-worträtseln zur Untersuchung kreativer Prozesse im deutschen Sprachraum. *Psychologische Rundschau*, 65(4), 200-211.

Lee, C. S., Huggins, A. C., & Therriault, D. J. (2014). A measure of creativity or intelligence? Examining internal and external structure validity evidence of the Remote Associates Test. *Psychology of Aesthetics, Creativity, and the Arts*, *8*(4), 446.

Lee, C. S., & Therriault, D. J. (2013). The cognitive underpinnings of creative thought: A latent variable analysis exploring the roles of intelligence and working memory in three creative thinking processes. *Intelligence*, *41*(5), 306-320.

Lee, H. K. (2022). Rethinking creativity: creative industries, AI and everyday creativity. *Media, Culture & Society*, *44*(3), 601-612.

Lee, M. H., Smyser, C. D., & Shimony, J. S. (2013). Resting-state fMRI: a review of methods and clinical applications. *American Journal of neuroradiology, 34*(10), 1866-1872.

Li, S., Ren, X., Schweizer, K., Brinthaupt, T. M., & Wang, T. (2021). Executive functions as predictors of critical thinking: Behavioral and neural evidence. *Learning and Instruction, 71*, 101376.

Li, X., O'Sullivan, M. J., & Mattingley, J. B. (2022). Delay activity during visual working memory: A meta-analysis of 30 fMRI experiments. *Neuroimage, 255*, 119204.

Lin, W. L., & Lien, Y. W. (2013). The different role of working memory in open-ended versus closed-ended creative problem solving: a dual-process theory account. *Creativity Research Journal, 25*(1), 85-96.

Lubart, T. I. (2001). Models of the creative process: Past, present and future. *Creativity research journal*, *13*(3-4), 295-308.

Ludwig, A. M. (1995). *The price of greatness: Resolving the creativity and madness controversy*. Guilford Press.

Lunke, K., & Meier, B. (2016). Disentangling the impact of artistic creativity on creative thinking, working memory, attention, and intelligence: Evidence for domain-specific relationships with a new self-report questionnaire. *Frontiers in psychology*, *7*, 1089.

Marko, M., Michalko, D., & Riečanský, I. (2019). Remote associates test: An empirical proof of concept. *Behavior Research Methods*, *51*, 2700-2711.

Martindale, C., & Hasenfus, N. (1978). EEG differences as a function of creativity, stage of the creative process, and effort to be original. *Biological psychology*, *6*(3), 157-167.

Martindale, C., Hines, D., Mitchell, L., & Covello, E. (1984). EEG alpha asymmetry and creativity. *Personality and Individual Differences, 5*(1), 77-86.

Mastria, S., Agnoli, S., Zanon, M., Acar, S., Runco, M. A., & Corazza, G. E. (2021). Clustering and switching in divergent thinking: Neurophysiological correlates underlying flexibility during idea generation. *Neuropsychologia*, *158*, 107890.

Mazza, A., Dal Monte, O., Schintu, S., Colombo, S., Michielli, N., Sarasso, P., ... & Ricci, R. (2023). Beyond alpha-band: The neural correlate of creative thinking. *Neuropsychologia*, *179*, 108446.

McGrew, K. S., Flanagan, D. P., Keith, T. Z., & Vanderwood, M. (1997). Beyond g: The impact of Gf-Gc specific cognitive abilities research on the future use and interpretation of intelligence tests in the schools. *School Psychology Review*, *26*(2), 189-210.

Mednick, S. (1962). The associative basis of the creative process. *Psychological review*, *69*(3), 220-232.

Mejia, C., D'Ippolito, B., & Kajikawa, Y. (2021). Major and recent trends in creativity research: An overview of the field with the aid of computational methods. *Creativity and Innovation Management, 30*(3), 475-497.

Miyake, A., & Shah, P. (1999). *Models of working memory* (pp. 442-481). Cambridge: Cambridge University Press.

Mölle, M., Marshall, L., Wolf, B., Fehm, H. L., & Born, J. (1999). EEG complexity and performance measures of creative thinking. *Psychophysiology*, *36*(1), 95-104.

Monsell, S. (2003). Task switching. *Trends in cognitive sciences*, *7*(3), 134-140.

Mumford, M. D., Mobley, M. I., Reiter‐Palmon, R., Uhlman, C. E., & Doares, L. M. (1991). Process analytic models of creative capacities. *Creativity research journal*, *4*(2), 91-122.

Murray, P. (Ed.). (1996). *Plato on Poetry: Ion; Republic 376e-398b9; Republic 595-608b10*. Cambridge University Press.

Musslick, S., Jang, S. J., Shvartsman, M., Shenhav, A., & Cohen, J. D. (2018). Constraints associated with cognitive control and the stability-flexibility dilemma. In: *Proceedings of the 40th Annual Meeting of the Cognitive Science Society,* Madison, WI. 2018: 806-811.

Neubauer, A. C., & Fink, A. (2003). Fluid intelligence and neural efficiency: effects of task complexity and sex. *Personality and Individual Differences*, *35*(4), 811-827.

Niendam, T. A., Laird, A. R., Ray, K. L., Dean, Y. M., Glahn, D. C., & Carter, C. S. (2012). Meta-analytic evidence for a superordinate cognitive control network subserving diverse executive functions. *Cognitive, Affective, & Behavioral Neuroscience*, *12*(2), 241-268.

Nijstad, B. A., De Dreu, C. K., Rietzschel, E. F., & Baas, M. (2010). The dual pathway to creativity model: Creative ideation as a function of flexibility and persistence. *European review of social psychology*, *21*(1), 34-77.

Niu, W., & Sternberg, R. J. (2006). The philosophical roots of Western and Eastern conceptions of creativity. *Journal of Theoretical and Philosophical Psychology*, *26*(1-2), 18.

Palmiero, M., Nakatani, C., Raver, D., Belardinelli, M. O., & van Leeuwen, C. (2010). Abilities within and across visual and verbal domains: How specific is their influence on creativity? *Creativity Research Journal*, *22*(4), 369-377.

Paulus, M. P., Hozack, N., Zauscher, B., McDowell, J. E., Frank, L., Brown, G. G., & Braff, D. L. (2001). Prefrontal, parietal, and temporal cortex networks underlie decision-making in the presence of uncertainty. *Neuroimage*, *13*(1), 91-100.

Perchtold-Stefan, C. M., Rominger, C., Papousek, I., & Fink, A. (2023). Functional EEG alpha activation patterns during malevolent creativity. *Neuroscience*, *522*, 98-108.

Perfetti, B., Saggino, A., Ferretti, A., Caulo, M., Romani, G. L., & Onofrj, M. (2009). Differential patterns of cortical activation as a function of fluid reasoning complexity. *Human brain mapping*, *30*(2), 497-510.

Pfurtscheller, G., Stancak Jr, A., & Neuper, C. (1996). Event-related synchronization (ERS) in the alpha band—an electrophysiological correlate of cortical idling: a review. *International journal of psychophysiology*, *24*(1-2), 39-46.

Plucker, J.A., & Makel, M.C. (2010). Assessment of creativity. In Kaufman, J.C. & Sternberg, R.J. (Eds.), *The Cambridge handbook of creativity*. Cambridge University Press, 48-73.

Posner, M. I., & Rothbart, M. K. (2017). Integrating brain, cognition and culture. *Journal of Cultural Cognitive Science*, *1*(1), 3-15.

Prabhakaran, V., Smith, J. A., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. (1997). Neural substrates of fluid reasoning: an fMRI study of neocortical activation during performance of the Raven's Progressive Matrices Test. *Cognitive psychology*, *33*(1), 43-63.

Raven, J., Raven, J. C., & Court, J. H. (1998a). *Raven manual section 4: Advanced Progressive Matrices*. Oxford: Oxford Psychologists Press.

Raven, J., Raven, J. C., & Court, J. H. (1998b). Raven manual: Section 1, general overview. Oxford, England: Oxford Psychologists Press.

Razoumnikova, O. M. (2000). Functional organization of different brain areas during convergent and divergent thinking: an EEG investigation. *Cognitive brain research*, *10*(1-2), 11-18.

Razoumnikova, O. M. (2007). Creativity related cortex activity in the remote associates task. *Brain Research Bulletin*, *73,* 96–102.

Ren, J., Huang, F., Zhou, Y., Zhuang, L., Xu, J., Gao, C., ... & Luo, J. (2020). The function of the hippocampus and middle temporal gyrus in forming new associations and concepts during the processing of novelty and usefulness features in creative designs. *Neuroimage*, *214,* 116751.

Reynolds, F. (2004). Conversations about creativity and chronic illness II: Textile artists coping with long-term health problems reflect on the creative process. *Creativity Research Journal*, *16*(1), 79-89.

Rhodes, M. (1961). An analysis of creativity. *The Phi delta kappan*, *42*(7), 305-310.

Riddle, J., Scimeca, J. M., Cellier, D., Dhanani, S., & D'Esposito, M. (2020). Causal evidence for a role of theta and alpha oscillations in the control of working memory. *Current Biology*, *30*(9), 1748-1754.

Rodriguez-Boerwinkle, R. M., Welhaf, M. S., Smeekens, B. A., Booth, R. A., Kwapil, T. R., Silvia, P. J., & Kane, M. J. (2024). Variation in divergent thinking, executive-control abilities, and mind-wandering measured in and out of the laboratory. *Creativity Research Journal*, 1-35.

Rogers, B. P., Morgan, V. L., Newton, A. T., & Gore, J. C. (2007). Assessing functional connectivity in the human brain by fMRI. *Magnetic resonance imaging*, *25*(10), 1347-1357.

Rominger, C., Papousek, I., Perchtold, C. M., Weber, B., Weiss, E. M., & Fink, A. (2018). The creative brain in the figural domain: Distinct patterns of EEG alpha power during idea generation and idea elaboration. *Neuropsychologia*, *118*, 13-19.

Rothenberg, A., & Hausman, C. R. (Eds.). (1976). *The creativity question*. Duke University Press.

Rothmaler, K., Nigbur, R., & Ivanova, G. (2017). New insights into insight: Neurophysiological correlates of the difference between the intrinsic "aha" and the extrinsic "oh yes" moment. *Neuropsychologia*, *95*, 204-214.

Rottschy, C., Langner, R., Dogan, I., Reetz, K., Laird, A. R., Schulz, J. B., ... & Eickhoff, S. B. (2012). Modelling neural correlates of working memory: a coordinate-based meta-analysis. *Neuroimage*, *60*(1), 830-846.

Runco, M. A. (2007). Creativity: Theories and themes: Research, development, and practice. San Diego, CA: Academic Press.

Runco, M. A. (2008). Commentary: Divergent thinking is not synonymous with creativity. Psychology of Aesthetics, Creativity, and the Arts, 2, 93-96.

Runco, M. A. (2010). Divergent thinking, creativity, and ideation. In J.C. Kaufman & R.J. Sternberg (Eds.), *The Cambridge handbook of creativity*. Cambridge University Press, 413-446.

Runco, M. A. (2012). Creative and imaginative thinking. In V. S. Ramachandran (Ed.). *Encyclopedia of human behavior.* Academic Press., 602–605.

Runco, M. A. (2014). *Creativity: Theories and themes: Research, development, and practice* (2nd ed.). Elsevier Academic Press.

Runco, M. A. (2015). Tension, adaptability, and creativity. In S.W. Russ (Ed.), *Affect, creative experience, and psychological adjustment* (pp. 165-194). Routledge.

Runco, M. A. (2017). Comments on where the creativity research has been and where is it going. *The Journal of Creative Behavior*, *51*(4), 308–313.

Runco, M. A., & Acar, S. (2010). Do tests of divergent thinking have an experiential bias?. *Psychology of Aesthetics, Creativity, and the Arts*, *4*(3), 144.

Runco, M. A., & Acar, S. (2012). Divergent thinking as an indicator of creative potential. *Creativity research journal*, *24*(1), 66-75.

Runco, M. A., & Albert, R. S. (1986). The threshold theory regarding creativity and intelligence: An empirical test with gifted and nongifted children. *Creative Child and Adult Quarterly*, *11*(4), 212-218.

Runco, M.A. & Albert, R.S. (2010). Creativity research. In J.C. Kaufman & R.J. Sternberg (Eds.), *The Cambridge handbook of creativity*. Cambridge University Press, 3-19.

Runco, M. A., & Chand, I. (1995). Cognition and creativity. *Educational psychology review*, *7*, 243-267.

Runco, M. A., & Jaeger, G. J. (2012). The standard definition of creativity. *Creativity research journal*, *24*(1), 92-96.

Rutishauser, U., Ross, I. B., Mamelak, A. N., & Schuman, E. M. (2010). Human memory strength is predicted by theta-frequency phase-locking of single neurons. *Nature*, *464*(7290), 903-907.

Sadler-Smith, E. (2015). Wallas' four-stage model of the creative process: More than meets the eye?. *Creativity Research Journal*, *27*(4), 342-352.

Said-Metwaly, S., Van den Noortgate, W., & Kyndt, E. (2017). Approaches to measuring creativity: A systematic literature review. *Creativity. Theories–Research-Applications*, *4*(2), 238-275.

Sauseng, P., Freunberger, R., Feldheim, J. F., & Hummel, F. C. (2011). Right prefrontal TMS disrupts interregional anticipatory EEG alpha activity during shifting of visuospatial attention. *Frontiers in psychology*, *2*, 241.

Sauseng, P., Klimesch, W., Schabus, M., & Doppelmayr, M. (2005). Fronto-parietal EEG coherence in theta and upper alpha reflect central executive functions of working memory. *International journal of Psychophysiology*, *57*(2), 97-103.

Schack, B., Klimesch, W., & Sauseng, P. (2005). Phase synchronization between theta and upper alpha oscillations in a working memory task. *International Journal of Psychophysiology*, *57*(2), 105-114.

Schonfeld, I. S. (1986). The Genevan and Cattell-Horn conceptions of intelligence compared: Early implementation of numerical solution aids. *Developmental Psychology, 22*(2), 204.

Schwab, D., Benedek, M., Papousek, I., Weiss, E. M., & Fink, A. (2014). The time-course of EEG alpha power changes in creative ideation. *Frontiers in human neuroscience*, *8*, 310.

Shemyakina, N., Velicoborets, G. S., & Nagornova, Z. V. (2023). Machine-learning applications for differentiation across states/stages of creative thinking based on time-series and time-frequency features of electroencephalography signals and event-related potentials. *Genes & Cells*.

Shiffrin, R. M. (1993). Short-term memory: A brief commentary. *Memory & Cognition*, *21*, 193-197.

Siegler, R. S. (1992). The other Alfred Binet. *Developmental psychology*, *28*(2), 179.

Silvia, P. J. (2008). Creativity and intelligence revisited: A latent variable analysis of Wallach and Kogan. *Creativity Research Journal*, *20*(1), 34-39.

Silvia, P. J., & Kaufman, J. C. (2010). Creativity and mental illness. In J.C. Kaufman & R.J. Sternberg (Eds.), *The Cambridge handbook of creativity*. Cambridge University Press. Pages 381-394.

Silvia, P. J., Martin, C., & Nusbaum, E. C. (2009). A snapshot of creativity: Evaluating a quick and simple method for assessing divergent thinking. *Thinking skills and Creativity*, *4*(2), 79-85.

Sisk, D. A. (2021). JP Guilford: a pioneer of modern creativity research. *Celebrating Giants and Trailblazers: AZ of Who's Who in Creativity Research and Related Fields*, 171-185.

Sligh, A. C., Conners, F. A., & Roskos-Ewoldsen, B. (2005). Relation of creativity to fluid and crystallized intelligence. *The Journal of Creative Behavior*, *39*(2), 123-136.

Smeekens, B. A., & Kane, M. J. (2016). Working memory capacity, mind wandering, and creative cognition: An individual-differences investigation into the benefits of controlled versus spontaneous thought. *Psychology of Aesthetics, Creativity, and the Arts*, *10*(4), 389.

Smilansky, J. (1984). Problem solving and the quality of invention: An empirical investigation. *Journal of Educational Psychology, 76*(3), 377–386.

Smilanski, J., & Halberstadt, N. (1986). Inventors versus problem solvers: An empirical investigation. *Journal of Creative Behavior, 20,* 183–201.

Smith, E. E., & Jonides, J. (1997). Working memory: A view from neuroimaging. *Cognitive psychology, 33*(1), 5-42.

Sowden, P., Pringle, A., & Gabora, L. (2015). The shifting sands of creative thinking: Connections to dual process theory. *Thinking & Reasoning, 21*(1), 40-60.

Spearman, C. (1904). General intelligence, objectively determined and measured. *American Journal of Psychology,15,* 201-293.

Spearman, C. (1961). *The abilities of man*. London: Macmillan.

Srinivasan, N. (2007). Cognitive neuroscience of creativity: EEG based approaches. *Methods*, *42*(1), 109-116.

Srivastava, P., Jaarsveld, S., & Sangani, K. (2023). Verbal-analytical rather than visuo-spatial Raven’s puzzle solving favors Raven’s-like puzzle generation. *Front. Psychol* 14,1205056.

Stern, E., & Neubauer, A. (2016). Intelligenz: Kein Mythos, sondern Realität. *Psychologische Rundschau, 67*(1), 15-27.

Sternberg, R. J. (1988). A three-facet model of creativity. In R. J. Sternberg (Ed.), *The nature of creativity: Contemporary psychological perspectives*. Cambridge University Press, 125–147.

Sternberg, R. J. (1999). A propulsion model of types of creative contributions. *Review of general psychology, 3*(2), 83-100.

Sternberg, R. J., Kaufman, J. C., & Pretz, J. E. (2001). The propulsion model of creative contributions applied to the arts and letters. *The Journal of Creative Behavior*, *35*(2), 75-101.

Sternberg, R. J., & Grigorenko, E. L. (2001). Guilford's structure of intellect model and model of creativity: Contributions and limitations. *Creativity Research Journal*, *13*(3-4), 309-316.

Sternberg, R. J., & Lubart, T. I. (1996). Investing in creativity. *American psychologist*, *51*(7), 677.

Sternberg, R. J., & O'Hara, L. A. (2000). Intelligence and creativity. In R. J. Sternberg (Ed.), Handbook of intelligence (p. 611–630). Cambridge University Press.

Sternberg, R. J., Todhunter, R. J., Litvak, A., & Sternberg, K. (2020). The relation of scientific creativity and evaluation of scientific impact to scientific reasoning and general intelligence. *Journal of Intelligence*, *8*(2), 17.

Stevens Jr, C. E., & Zabelina, D. L. (2019). Creativity comes in waves: an EEG-focused exploration of the creative brain. *Current Opinion in Behavioral Sciences*, *27*, 154-162.

Stevens Jr, C. E., & Zabelina, D. L. (2020). Classifying creativity: Applying machine learning techniques to divergent thinking EEG data. *NeuroImage*, *219*, 116990.

Stipacek, A., Grabner, R. H., Neuper, C., Fink, A., & Neubauer, A. C. (2003). Sensitivity of human EEG alpha band desynchronization to different working memory components and increasing levels of memory load. *Neuroscience letters*, *353*(3), 193-196.

Sun, J., Liu, Z., Rolls, E. T., Chen, Q., Yao, Y., Yang, W., ... & Qiu, J. (2019). Verbal creativity correlates with the temporal variability of brain networks during the resting state. *Cerebral Cortex*, *29*(3), 1047-1058.

Sunavsky, A., & Poppenk, J. (2020). Neuroimaging predictors of creativity in healthy adults. *Neuroimage*, *206*, 116292.

Sviderskaya, N. E. (2011). The EEG spatial pattern and psychophysiological characteristics of divergent and convergent thinking in humans. *Human Physiology*, *37*, 31-38.

Takeuchi, H., Taki, Y., Hashizume, H., Sassa, Y., Nagase, T., Nouchi, R., & Kawashima, R. (2011). Failing to deactivate: the association between brain activity during a working memory task and creativity. *Neuroimage*, *55*(2), 681-687.

Thurstone, L. L. (1935). *Vectors of mind: Multiple-factor analysis of the isolation of primary traits.* Chicago: University of Chicago Press.

Torrance, E. P. (1974). *Torrance Test of Creative Thinking.* Lexington, MA: Personal Press.

Torrance, E. P. (1979). Unique needs of the creative child and adult. In A. H. Passow (Ed.). *The Gifted and the Talented: Their Education and Development*, 78th Yearbook of the National Society for the Study of Education, Part I. Chicago, III.: University of Chicago Press, 352-371.

Unsworth, N., & Spillers, G. J. (2010). Working memory capacity: Attention control, secondary memory, or both? A direct test of the dual-component model. *Journal of Memory and Language*, *62*(4), 392-406.

Urban, K.K., and Jellen, H. G. (1995). *Test of Creative Thinking – Drawing Production*. Frankfurt: Swets Test Services.

Vallat-Azouvi, C., Weber, T., Legrand, L., & Azouvi, P. (2007). Working memory after severe traumatic brain injury. *Journal of the International Neuropsychological Society*, *13*(5), 770-780.

Vandervert, L. R., Schimpf, P. H., & Liu, H. (2007). How working memory and the cerebellum collaborate to produce creativity and innovation. *Creativity Research Journal*, *19*(1), 1-18.

Vincent, J. L., Kahn, I., Snyder, A. Z., Raichle, M. E., & Buckner, R. L. (2008). Evidence for a frontoparietal control system revealed by intrinsic functional connectivity. *Journal of neurophysiology*, *100*(6), 3328-3342.

Wallas, G. (1926). *The art of thought*. London, UK: Jonathan Cape.

Wallis, G., Stokes, M., Cousijn, H., Woolrich, M., & Nobre, A. C. (2015). Frontoparietal and cingulo-opercular networks play dissociable roles in control of working memory. *Journal of Cognitive Neuroscience*, *27*(10), 2019-2034.

Wang, M., Hao, N., Ku, Y., Grabner, R. H., & Fink, A. (2017). Neural correlates of serial order effect in verbal divergent thinking. *Neuropsychologia*, *99*, 92-100.

Wang, X., Hommel, B., Colzato, L., He, D., Ding, K., Liu, C., ... & Chen, Q. (2023). The contribution of divergent and convergent thinking to visual creativity. *Thinking Skills and Creativity*, *49*, 101372.

Weiner, R. P. (2000). Creativity and beyond: Cultures. *Values and Change, State University of New York Press, New York, NY.*

Welter, M. M., Jaarsveld, S., & Lachmann, T. (2017). Problem space matters: The development of creativity and intelligence in primary school children. *Creativity Research Journal*, *29*(2), 125-132.

Welter, M. M., Jaarsveld, S., van Leeuwen, C., & Lachmann, T. (2016). Intelligence and creativity: over the threshold together? *Creativity Research Journal*, *28*(2), 212-218.

Wertheimer, M. (1945/1968). Productive thinking (Enlarged edition). London: Travistock.

Wilhelm, O., Hildebrandt, A., & Oberauer, K. (2013). What is working memory capacity, and how can we measure it?.*Frontiers in psychology, 4,* 433.

Wixted, J. T. (2023). Atkinson and Shiffrin's (1968) influential model overshadowed their contemporary theory of human memory. *Journal of Memory and Language*, 104471.

Wokke, M. E., Padding, L., & Ridderinkhof, K. R. (2018). Creative minds are out of control: mid frontal theta and creative thinking. *bioRxiv*, 370494.

Wu, C. L., Huang, S. Y., Chen, P. Z., & Chen, H. C. (2020). A systematic review of creativity-related studies applying the remote associates test from 2000 to 2019. *Frontiers in psychology*, *11*, 573432.

Zhang, Q., Chen, X., & Qiu, J. (2017). Common and distinct brain networks underlying verbal and visual creativity. *Human Brain Mapping*, *38*(4), 2094-2111.

Zhang, W., Sjoerds, Z., & Hommel, B. (2020). Metacontrol of human creativity: The neurocognitive mechanisms of convergent and divergent thinking. *NeuroImage*, *210*, 116572.

Zhu, W., Chen, Q., Xia, L., Beaty, R. E., Yang, W., Tian, F., ... & Qiu, J. (2017). Common and distinct brain networks underlying verbal and visual creativity. *Human Brain Mapping*, *38*(4), 2094-2111.

Zhu, W., Shang, S., Jiang, W., Pei, M., & Su, Y. (2019). Convergent thinking moderates the relationship between divergent thinking and scientific creativity. *Creativity Research Journal*, *31*(3), 320-328.

DECLARATION

Hiermit versichere ich,

– dass ich die vorgelegte Arbeit selbst angefertigt und alle benutzten Hilfsmittel in der Arbeit angegeben habe,

– dass ich diese Dissertation nicht schon als Prüfungsarbeit für eine staatliche oder andere wissenschaftliche Prüfung eingereicht, und

– dass weder die gleiche noch eine andere Abhandlung der Dissertation bei einer anderen Universität oder einem anderen Fachbereich der Rheinland-Pfälzischen Technischen Universität Kaiserslautern-Landau veröffentlicht wurde.

Kaiserslautern, den 22.04.2024

Vera Eymann

CURRICULUM VITAE

Persönliche Angaben

Name: Vera Eymann

Anschrift: Erwin-Schrödinger-Straße; Building 57-429, 67653 Kaiserslautern

Email: vera.eymann@rptu.de

Beruflicher Werdegang

12/2019 – 06/2024	Promotion (Dr. rer. nat) Rheinland-Pfälzische Technische Universität Kaiserslautern Landau
10/2017 – 11/2019	Studium Cognitive Science (M.Sc.) Technische Universität Kaiserslautern
09/2013 – 07/2017	Studium Psychologie (B.Sc.) Universität Mannheim
10/2007 – 01/2012	Studium Soziale Arbeit (Dipl. FH) Evangelische Fachhochschule Ludwigshafen am Rhein