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BIOLOGICAL MECHANISMS OF CREATIVITY AND FLOW

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ABSTRACT

What would the world and our lives look like, if creativity had not evolved? Defined as the ability to have ideas and produce artifacts that are at the same time novel and meaningful, *creativity* is arguably one of the faculties that has given the human species adaptive ability beyond any other organism. The goal of this thesis was to elucidate some of the biological mechanisms that enable creative thinking. Four studies, based on three different methodologies are presented.

Study I was performed in order to investigate the putative relationship between creative thinking and dopaminergic function. Scores on divergent thinking tests were correlated with regional D2 receptor densities, as measured by PET. The results showed a negative correlation between divergent thinking and D2 density in the thalamus, controlling for age and general cognitive ability. Decreased D2 receptor densities in the thalamus may be associated with lower thalamic gating thresholds, i.e. an increased thalamocortical information flow, which could facilitate the generative processes that underlie creativity. This is the first study to indicate such a mechanism. This mechanism may also provide a link between creativity and mental illness.

Previous research on the flow experience has shown that flow states facilitate creative thinking. In study II, physiological processes associated with the flow experience were studied. Professional classical pianists were asked to play a musical piece five times and rate state flow after each performance. The arterial pulse pressure, respiration, head movements, and activity from the *corrugator supercilii* and *zygomaticus major* facial muscles were measured for each performance. A significant relation was found between flow and heart period, blood pressure, heart rate variability, activity of the *zygomaticus major* muscle, and respiratory depth. This is the first study to show that subjectively experienced flow is reflected in biological processes. The findings are discussed in relation to a conception of flow as a state of effortless attention.

Previous research suggests that the rostral dorsal premotor regions (PMDr), might be particularly involved in the generation of melodic structures; whereas the pre-supplementary motor area (pre-SMA) may contribute more to the generation of rhythmic sequences. Study III tests this hypothesis. Brain activity during improvisation in professional pianists was measured using fMRI. The results partly confirmed the hypothesis: Melodic improvisation loaded more on the PMDr than did rhythmic improvisation; activity in the pre-SMA was related to rhythmic improvisation, but also to melodic improvisation. The results also indicate that perception, performance, and free generation share neural mechanisms.

Study IV presents an fMRI paradigm aimed at comparing the neural underpinnings of pseudo-random free generation and musical improvisation. Professional classical pianists performed improvisation of melodies, pseudo-random key presses and sight-reading, using either two, six or twelve keys on a piano keyboard. The results showed that musical creativity originates from similar cortical networks as other forms of free generation, and that adding a musical context does not engage additional brain regions. Pseudo-random generation, however, was accompanied by higher activity than improvisation in several fronto-parietal regions, which may be related to the high complexity of this task and the musical expertise of the subjects.

LIST OF PUBLICATIONS INCLUDED IN THE THESIS

I. **de Manzano Ö**., Cervenka S., Karabanov A., Farde L., Ullén F. (2010). Thinking Outside a Less Intact Box: Thalamic Dopamine D2 Receptor Densities Are Negatively Related to Psychometric Creativity in Healthy Individuals. *PLoS ONE 5*(5): e10670.

II. **de Manzano Ö**., Theorell T., Harmat L., Ullén F. (2010). The psychophysiology of flow during piano playing. *Emotion. 10*(3): 301-11.

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IV. **de Manzano Ö**., Ullén F. Neural correlates of musical improvisation and pseudo-random response generation: overlap and differences. (submitted).

LIST OF ADDITIONAL PUBLICATIONS

I. Ullén, F., Forsman L., **Blom Ö**., Karabanov A., Madison G. (2008). Intelligence and variability in a simple timing task share neural substrates in the prefrontal white matter. *J Neurosci 28*(16): 4238-4243.

II. Madison G., Forsman L., **Blom Ö**., Karabanov A., Ullén F. (2009). Correlations between intelligence and components of serial timing variability. *Intelligence 37*(1): 68-75.

III. Karabanov A., **Blom Ö**., Forsman L., Ullén, F. (2009). The dorsal auditory pathway is involved in performance of both visual and auditory rhythms. *NeuroImage 44*(2): 480-488.

IV. Karabanov A., Cervenka S., **de Manzano Ö**., Forssberg H., Farde L., Ullén F. (2010). Dopamine D2 receptor density in the limbic striatum is related to implicit but not explicit movement sequence learning. *Proc Natl Acad Sci U S A 107*(16): 7574-7579.

V. Ullén F., **de Manzano Ö**., Theorell T., Harmat L. (2010). The Physiology of Effortless Attention: Correlates of State Flow and Flow Proneness. In Bruya B. J. (Ed.), *Effortless attention: A new perspective in the cognitive science of attention and action* (pp. 205-217). Cambridge, MA: MIT Press.

VI. Harmat L., Ullén F., **de Manzano Ö**., Olsson E., Elofsson U., von Scheele B., Theorell T. Heart rate variability during piano playing: a case study of three professional solo pianists playing a self-selected and a difficult prima vista piece. *Music and Medicine.* (in press).

CONTENTS

LIST OF ABBREVIATIONS

ACC	Anterior cingulate cortex
Amp	Amplitude
ANOVA	Analysis of variance
B	Concentration of bound radiotracer
BIS	Berliner Intelligenz Struktur Test
Bmax	Receptor density
BOLD	Blood-oxygen-level-dependent
BP	Blood pressure
bpm	Beats per minute
CS	*Corrugator supercilii*
D2BP	Dopamine D2 receptor binding potential
DLPFC	Dorsolateral prefrontal cortex
DMPFC	Dorsomedial prefrontal cortex
DRD2	Dopamine D2 receptor gene
DSM	Diagnostic and Statistical Manual of Mental Disorders
EMG	Electromyography
F	Concentration of free radiotracer
fMRI	Functional magnetic resonance imaging
Fq	Frequency
FWHM	Full-width-at-half-maximum
g	General factor of intelligence
Ga	Auditory processing
Gc	Comprehension – knowledge
Gf	Fluid reasoning
GLM	General linear model
Glr	Long-term memory and retrieval
Gq	Quantitative knowledge
Grw	Reading and writing
Gs	Cognitive processing speed
Gsm	Short-term memory
Gt	Decision and reaction speed
Gv	Visual processing
HF	High-frequency band
HP	Heart period
HRV	Heart rate variability
IFG	Inferior frontal gyrus
IQ	Intelligence quotient
K_D	Apparent affinity
LD	Levenshtein distance
LF	Low-frequency band
MaxP	Maximum blood pressure
MinP	Minimum blood pressure
MR	Magnetic resonance
MRI	Magnetic resonance imaging
N-N	Normalized interbeat interval(s)

NSB	Nonspecifically bound radiotracer
PANSS	Positive and Negative Symptoms Scale
PET	Positron Emission Tomography
PMD	Dorsal premotor region
PMDr	Rostral dorsal premotor region
pre-SMA	Rre-supplementary motor area
Raven	Raven's Standard Progressive Matrices Plus
RD	Respiratory depth
RF	Radiofrequency pulse
RMS	Root-mean-square
ROI	Region-of-interest
RR	Respiratory rate
RSA	Respiratory sinus arrhythmia
SNpc	Substantia nigra nars neticulata
SRTM	Simplified Reference Tissue Model
STG	Superior temporal gyrus
TPH	Tryptophan hydroxilase
Tukey HSD	Tukey Honestly Significant Difference
VTA	Ventral tegmental area
ZM	*Zygomaticus major*

1 INTRODUCTION

The goal of this thesis was to investigate and elucidate some of the biological mechanisms which enable creativity. To that end, four studies based on three different methodologies were conducted, each method providing a different perspective on creative functioning. This broad approach was considered necessary, because creativity is a highly complex phenomenon. As later will be described, creative ability is dependent on a number of variables, including both individual characteristics in terms of cognitive ability and personality, as well as environmental factors which appear to facilitate creative achievement. This thesis is but a small step on the way towards understanding the biological foundations of creativity. Nonetheless, it does represent a strategic initiative to systematically investigate the makings of creative potential. Bit by bit, piece by piece, the puzzle will eventually be solved.

1.1 CREATIVITY

What would our world look like, if creativity had not evolved? The importance of this faculty of our minds can hardly be downplayed. What in our surroundings is not a result of human ingenuity? How would we pursue our lives without the capacity to adapt to our environment in new and original ways? Adaptation is truly the key word. Evolution has through the birth of the creative mind reinvented itself, and thus provided the otherwise embarrassingly exposed primate Homo sapiens with adaptive abilities beyond that of any other organism.

Defined as the ability to have ideas and produce artifacts that are at the same time novel and meaningful (rather than expected, trivial, random or idiosyncratic) (Sternberg, 1999), creativity has allowed the human species to find ways to overcome just about any obstacle and, ironically enough, forever doomed us to invent new quests to conquer.

Scientific research on creativity as an independent concept appeared only as recent as in the mid-20th century. Up until then, 'creativity' was assumed to be a natural result of intelligence. The initiative to conduct research on creativity *per se*, is generally credited to the psychologist J.P. Guilford, who in his 1950 Presidential Address to the American Psychological Association (Guilford, 1950), pointed out the very important nature of creativity as a research topic and the scarcity of published research related to creativity.

The above mentioned definition of creativity is quite general, and it has proved difficult to reach a more distinct consensual definition of the concept. As a result, different conceptualizations have been used in different research groups.

Some researchers assume that creativity is a trait with a certain distribution – from low to high - in the general population, whereas others define creativity in terms of exceptional real-world creative production, which very few individuals manage to achieve (Sternberg, 1999).

Thus far, research on creativity has focused on identifying cognitive processes, personal characteristics, expertise, life span development factors, or social contexts which are associated with the more creative human phenotype (see e.g. Simonton, 1999). The somewhat overwhelming conclusion from this research is that creativity, and creative genius in particular, is to a various extent dependent on a large number of

factors, stemming from a rare combination of various individual and environmental prerequisites. The following sections will describe these factors further.

1.2 INDIVIDUAL FACTORS IN CREATIVITY

1.2.1 Cognitive abilities

Intelligence usually refers to intellectual precocity and abilities related to abstract reasoning and thinking, problem-solving and capacity to acquire knowledge.

It was shown in the beginning of the last century that people's scores on different cognitive tests, ranging from simple reaction time to abstract reasoning, generally show positive intercorrelations, depending mainly on how much the tests vary in task complexity, information content, and required skills (Jensen, 1993). This finding can be interpreted to mean that all kinds of cognitive ability assessments to some extent measure a common underlying factor. Spearman (1904) called this the general intelligence factor or *g*.

In an attempt to make a comprehensive systematic organization of the research on human cognitive abilities, Carroll made a systematic exploratory factor analysis of over 460 carefully selected human cognitive ability datasets (Carroll, 1993). This factor analysis suggested a model with three layers or strata, in which each layer accounted for the variation in factor loadings at the next lower level. Thus, the three strata are defined as representing narrow, broad, and general cognitive abilities. Carroll's meta-factor analysis gave the first empirically-based taxonomy of human cognitive abilities, presented in a single organized framework. This model has later been merged with another model produced by Cattell and Horn, to form the Cattell-Horn-Carroll (CHC) theory of cognitive abilities (McGrew, 2009).

According to the CHC taxonomy, *g* constitutes a general ability which influences all other cognitive abilities. The broad abilities represented in the second stratum are independent from one another and constitute more modal specific abilities: *Gf* - fluid reasoning, *Gc* - comprehension – knowledge, *Gsm* - short term memory, *Gv* - visual processing, *Ga* - auditory processing, *Glr* - long-term storage and retrieval, *Gs* - cognitive processing speed, *Gt* - decision and reaction speed, *Grw* - reading and writing, *Gq* - quantitative knowledge. These in turn influence different sets of narrow abilities, respectively.

Psychometric tests of general cognitive ability or intelligence are typically designed to measure *g* and can thus be distinguished by how much they load on *g*, i.e. to what extent they correlate with the *g* factor.

In the 1950s-1960s, Barron and colleagues performed a series of studies on intelligence and creativity, with the overall aim to develop and use psychological assessment techniques in the study of effectively functioning persons as opposed to persons with some pathology, with regard to workforce selection (Sternberg & O'Hara, 1999). Creativity scores were generally based on rankings made by experts working within the same field as the particular participant group, or based on a battery of psychometric tests, including divergent thinking tests. Divergent thinking tests typically involve the generation of a multitude of novel and meaningful responses to open-ended questions, and have been widely used to measure individual differences in creative thinking (Plucker & Renzulli, 1999). According to the Cattell-Horn-Carroll framework, divergent thinking should be mostly influenced by the cognitive ability *Glr* – long-term

storage and retrieval (for a more detailed description of divergent thinking, see chapter 4 - Divergent thinking).

In summing up these studies, Barron concluded that there is a low positive correlation between general intelligence and creativity (Sternberg & O'Hara, 1999). However, beyond an intelligence quotient (IQ) of 120, measured intelligence is a negligible factor, and motivational and stylistic variables appear to be the major determiners of creativity. Since these results were presented, it has subsequently been shown that the correlation between creativity and intelligence varies depending on what aspects of each concept are being measured, how they are measured, and in what field they are measured (Sternberg & O'Hara, 1999). The role of intelligence is e.g. different in art and science. Hence, a certain amount of intelligence appears to be necessary for creative thinking, speculatively because a certain level of quality of function of the neural system is required, and to allow for the acquisition of necessary knowledge.

As would be expected, high intelligence appears to be particularly important in the context of creative genius. Catherine Cox (1926) was able to provide intelligence estimates for three-hundred-one eminent individuals who lived between 1450-1850, by going through biographical records and assessing mental age in relation to chronological age. She found that the IQ of a typical genius was 3-4 standard deviations above the mean in the general population. The group average IQ was 155 for childhood and 165 for young adulthood. Nevertheless, as Eysenck points out in his review of the literature on the topic, high IQ is neither sufficient for genius, nor a sufficient predictor of creativity (Eysenck, 1995).

1.2.2 Personality

Another factor important to creativity, apart from intelligence, is personality. According to a meta-analysis by Feist (1998) based on 83 studies in the arts and sciences, the most prominent features of the creative personality are: high openness to experience, low conscientiousness and high extraversion, as well as high self-confidence, self-acceptance, hostility, impulsivity and psychoticism, which is in line with previous more qualitative reviews (e.g. Eysenck, 1995) These traits, which usually remain stable across the life span (Soldz & Vaillant, 1999), distinguished scientists and artists from controls, as well as more creative scientists from their less creative colleagues. Feist also showed that it is the confidence/dominance facet of extraversion that is related to creativity and *not* sociability, which solves the otherwise apparent contradiction that that creative individuals also score high on psychoticism, which is associated with being antisocial, aggressive, egocentric, impulsive, unempathic and tough-minded (Eysenck, 1995). These results can be viewed in relation to the work of Depue and Collins (1999), who plotted loadings of personality traits derived from eleven studies on a two dimensional model with the orthogonal axes constraint and extraversion. Three clusters of traits were observed: an extraversion cluster at the high end of the extraversion dimension; conscientiousness and psychoticism-aggression clusters at the high and low ends of the constraint dimension, respectively; and an impulsivity-sensation seeking cluster at an angle between high extraversion and low constraint. Interestingly, the traits in this last cluster, which Depue and Collins claimed to be associated with strong positive affect and arising as a joint function of the interaction of

extraversion and constraint, are rather identical to those listed above that generally show positive correlations with measures of creativity.

1.2.3 Genes

Thus far, the genetic prerequisites for creativity remain largely unexplored. Nonetheless, three candidate genes have been linked to creative ability. Reuter and colleagues were able to show that the TPH gene and the DRD2 gene were associated with divergent thinking (Reuter, Roth, Holve, & Hennig, 2006). TPH is the rate-limiting biosynthetic enzyme in the pathway for the neurotransmitter serotonin. It regulates serotonin levels by converting tryptophan into 5-hydroxytryptophan, which is the direct precursor of serotonin. A bulk of studies display the importance of serotonin in cognitive functioning (e.g. Evers, et al., 2005), but it is still unclear through what mechanism the TPH gene might affect creative thinking. DRD2 regulates dopamine D2 receptor density (Ritchie & Noble, 2003) and therefore modulates the effect of the neurotransmitter dopamine. Dopamine might play a particular role in creative thinking and study I presented in this thesis was aimed at investigating the relationship between dopamine D2 receptor density and divergent thinking. A more detailed description of the dopamine system and its relation to creativity is given in chapter 7 – Dopamine and creativity.

Neuregulin 1 is one of the most widely investigated candidate genes for psychosis. It has been shown to affect a number of processes, including neuronal development, synaptic plasticity, glutamatergic neurotransmission, and glial functioning (Harrison & Law, 2006). Keri (2009) was able to show that the T/T genotype, which has previously been shown to be related to psychosis risk and altered brain structure and function, was associated with higher creative achievement and divergent thinking in healthy individuals. Again, the exact mechanism is still not known, but Keri speculated that the T/T genotype might be linked to decreased cognitive inhibition, which could potentially facilitate free associative thinking. This finding might also serve as one piece of the puzzle linking mental illness and creativity.

2 ENVIRONMENTAL INFLUENCES ON CREATIVITY

While the studies in this thesis focus on individual factors in creativity, other factors including environmental variables and personal experience are also highly important to creative achievement, by influencing individual factors, such as motivation, personality and creative thinking, and by constituting a setting in which creative ideas may spur. Simonton (1999) has made an account of such factors, which is based on quantitative studies of historical biographical data on creative individuals. These 'historiometric' inquiries have e.g. identified the following variables: Birth order – the ordinal position to success depends on the domain of creativity (eminent scientists are e.g. more likely to be firstborns than creative writers); childhood trauma – parental loss or other difficult events may contribute to the development of creative potential; family background – there is a tendency for creative individuals to come from somewhat marginalized home environments; education – the most notable creators have emerged from something less than mainstream educational environments; role models and mentors – being exposed to a number of quite diverse mentors appears to have positive benefits; cultural factors – a promoting disciplinary or aesthetic milieu; societal factors – e.g. social structure, population growth etc.; political factors – war exerts a negative influence on creative output.

3 NEURAL CORRELATES OF CREATIVE THINKING

3.1 BROWNIAN MOTION IN THE NEUROSCIENCE OF CREATIVITY

Studies on the neural correlates of creative thinking have mainly focused on experimental paradigms involving insight, divergent thinking or artistic creativity (Dietrich & Kanso, 2010).

Insight is the experience of suddenly realizing the solution to a problem or of grasping a familiar situation in a new and more productive way. Insight or "illumination" has been described as one essential stage of creative thinking, when a promising idea abruptly, and often unexpectedly, becomes consciously available. Various experimental paradigms have been developed in order to capture brain activity at this sudden 'Aha'-moment. Tasks generally involve realizing solutions to different problems (e.g. Jung-Beeman, et al., 2004).

Divergent thinking, which involves the generation of ideas in response to open-ended problems (see chapter 4 – Divergent thinking), has been tested using e.g. fantasy story generation (Martindale, Hines, Mitchell, & Covello, 1984), inventing alternative uses for common objects (Fink, Grabner, et al., 2009) or other elaborate problem solving tasks, as e.g. coming up with solutions for how to measure the length of hundreds of poisonous snakes in the zoo (Razoumnikova, 2000).

Artistic creativity has been explored in several domains. It can be argued that the ecological validity of such tasks with respect to creative thinking is greater than that of other experimental tasks, as they – despite being carried out in a laboratory setting – resemble closer to real-life creative endeavors. Examples of tasks include; mentally performing creative dance (Fink, Graif, & Neubauer, 2009), singing melodies (Brown, Martinez, & Parsons, 2006) and piano improvisation (Bengtsson, Csikszentmihályi, & Ullen, 2007).

The neural basis of insight, divergent thinking and artistic creativity have been investigated using various methods, including electroencephalography, near-infrared-spectroscopy, single positron emission computed tomography, positron emission tomography and magnetic resonance imaging (both structural and functional MRI). Typically, studies have focused on individual differences, dividing participants into highly-creative/low-creative or expert/novice groups. Using such a setup, findings from each sub-group can be contrasted and interpretations can be made on what distinguishes highly-creative individuals from low-creative individuals with regard to structural and functional anatomical differences in the brain. Results are generally used, either to characterize the creative individual (by assuming that creative brains have unique properties which less creative brains lack), or to identify regions, networks and processes which might be particularly important to creative thinking.

Dietrich and Kanso (2010) have produced a comprehensive review of neurophysiological and neuroimaging studies of creativity thus far. Based on the examination of a total of 72 experiments, reported in 63 articles, the authors conclude "that not a single currently circulating notion on the possible neural mechanisms underlying creative thinking survives close scrutiny". In another review, published in the same year as Dietrich, Arden and colleagues (Arden, Chavez, Grazioplene, & Jung, 2010) report findings from 45 brain imaging studies and arrives at a similar conclusion. They observe that nearly as many different tests have been used as there are studies. Moreover, most tests appear to have unknown test-retest reliability and external

validity. This obviously makes it very difficult to interpret different findings across studies with any confidence.

Thus, from a superficial glance at the literature, studies on the neural foundation of creativity have produced largely inconsistent and diverging results. No single brain area or process appears to be either necessary or sufficient for creativity. There are certainly interesting leads to follow up, but given the complex nature of the issue at hand, the study of creativity demands a strategic and systematic approach.

3.2 A CALL FOR REDUCTIONISM AND SYSTEMATIC RESEARCH

Creativity is at the pinnacle of human cognition and therefore one should expect this phenomenon to be complex and influenced by a number of variables. As described in the introduction (chapter 1), there are genetic factors, individual abilities, personal traits and environmental conditions which have all been linked to creativity. Creative thinking, involves both free association and rational thought, conscious and subconscious processes, and as will be dealt with in some detail later in this thesis, even aberrant thought processes may play some importance. Hence, the idea of finding one gene, one brain region, or even one configuration of neural (or other) properties which explains creative potential is plain ridiculous. Nor can we expect all creative individuals to be creative for all the same reasons.

Presented with such a complex matter, a reductionist approach seems the only option. By reducing creativity to simpler or more fundamental component parts, and trying to understand the biological basis of each of them, it might be possible, in the end, to give an account of how these parts (in various configurations) might interact to produce creativity *per se*.

There are many ways in which to pursue this undertaking. One example would be to investigate the neural substrates which underlie the abilities, personality traits and mediating factors of environmental variables which have previously been associated with real-life creativity. A second approach would be to explore real-life creativity directly within different task domains, and identify neural correlates which support creative thinking within each of these domains. A third line of attack could be to use a bottom up approach, in which different anatomical regions and functional networks are systematically investigated with reference to how they (potentially) influence creative thinking and/or are linked to real-life creativity.

With reference to the studies presented within the frame of this thesis, studies I and II are in line with the first approach. Study I builds on converging evidence indicating that several factors (both genetic, cognitive and environmental) which have previously been associated with creativity can be linked (directly, indirectly or speculatively) to dopaminergic function. Thus, one of these factors, *divergent thinking*, which is thought illustrate one facet of creative thought, is investigated with regard to dopamine D2 receptor density in the brain. In study II, *flow*, which is described as being conducive to creative thinking but hitherto only studied as a subjective psychological mental state, is matched to psychophysiological variables (such as respiration), in a first attempt to put the concept into a more common psychological and biological framework. Studies III and IV expose the functional anatomy of *musical creativity* in the form of free piano improvisation and thus conform to the second approach.

The subsequent sections will give a fuller description of musical creativity, divergent thinking and flow and review the existing literature on these topics in brief. In

addition, an introduction will be given to research indicating that the dopamine system of the brain may play a particular role in creative thought processes.

4 DIVERGENT THINKING

Guilford, which was a prominent researcher in the field of psychometric creativity research, claimed that creative people could be characterized by the ability to produce a large number of ideas per unit of time, having novel ideas, and having a flexibility of mind (Guilford, 1950). Inspired by this, several psychometric tests have been developed to measure individual differences in divergent thinking in the general population. These tests typically involve generating a multitude of novel and meaningful responses to open-ended questions, as opposed to the convergent problem-solving abilities measured by traditional intelligence tests where each problem has a single answer. For instance, in the classical Guilford's alternate uses test (Christensen, Guilford, Merrifield, & Wilson, 1960), participants are instructed to propose different uses for everyday objects, such as a brick, within a limited time. Several different measures can be obtained, depending on the particular type of test: Fluency – the number of correct responses, originality – the occurrence of a participant's response in relation to the rest of the sample, flexibility – the number of semantic categories produced, switching – the number of shifts between semantic categories, elaboration – how extensive each response is (if the task involves producing more than single words).

Scores on (certain) divergent thinking tests show positive correlations with involvement in real-life creative activities, self-rated creativity, as well as objective measures of creative achievement (Furnham & Bachtiar, 2008), even when controlling for IQ (Carson, Peterson, & Higgins, 2003). They are also correlated with several personality traits, such as openness to experience, common to individuals with documented creative capacity (Carson, et al., 2003), including schizotypal traits (Burch, Pavelis, Hemsley, & Corr, 2006a; Burch, Hemsley, Pavelis, & Corr, 2006b). In the standard three-stratum model of human cognitive abilities, the Cattell- Horn-Carroll-framework (McGrew, 2009), the main ability captured by divergent thinking tests corresponds to the second-order factor ''long-term storage and retrieval'' (*Glr*), which captures individual differences in fluent retrieval of information through association. This factor, thus, predicts creative achievement over and above fluid reasoning (*Gf*) and crystallized ability (*Gc*), i.e. beyond traditional measures of ''intelligence'' and ''knowledge''.

It is important to note that divergent thinking does not equal creativity in real life. Rather, it is an ability that facilitates creative thinking, presumably in conjunction with other factors, such as personality traits. Also, divergent thinking tests load on a range of other cognitive abilities, e.g. intelligence. Therefore, it is vital that tests are developed in such a way as to load predominantly on that factor which is related to real-life creativity. Much of the critique formulated by Dietrich and Arden (see chapter 3) comes from the observation that many of the divergent thinking tests which have been used to study the neural correlates of divergent thinking have not been properly validated. By using an appropriate test which loads maximally on 'divergent thinking', and controlling for potential nuisance variables, the chance of finding the neural underpinnings of this ability is increased.

5 FLOW AND CREATIVITY

Studying the creative process in painters in the 1960s, Mihály Csikszentmihályi was struck by the fact that when work on a painting was going well, the artist persisted single-mindedly, disregarding hunger, fatigue, and discomfort. Yet, interest was rapidly lost in the artistic creation once it had been completed (Csikszentmihályi, 1990). Flow research and theory had their origin in a desire to understand this phenomenon of intrinsically motivated, or autotelic activities, which are rewarding in and of themselves (auto = self, telos = goal) apart from their end-product or any extrinsic rewards, such as money.

Since then, the nature and conditions of enjoyment has been explored in several domains, by qualitative research and interviews of chess players, rock climbers, dancers and others who emphasize enjoyment as the main reason for pursuing an activity (Csikszentmihályi & Csikszentmihályi, 1992). Based on these investigations a picture was formed of the general characteristics of 'optimal experience' and its conditions. These conditions may be summarized in the following nine elements: (i) challenge-skill balance – task difficulty must be equal to person's ability, or feelings of anxiety/boredom will emerge; (ii) action-awareness merging – actions feel automatic and little or no attentional resources are required for executing action sequences; (iii) clear goals; (iv) unambiguous feedback; (v) high concentration; (vi) sense of control; (vii) loss of self-consciousness – self-reflective thoughts and fear of social evaluation are absent; (viii) transformation of time – time may seem to move faster or slower than usual; and (ix) autotelic experience – an induced state of positive affect, which can make a task intrinsically rewarding, i.e. performing the task becomes a goal in itself. When these elements are present, a person may enter an absorbed state of effortless attention, termed *flow*; being fully immersed in a feeling of energized focus, full involvement, and success in the process of the activity. The flow experience appears to be universal and similar across lines of culture, class, gender and age as well as across different kinds of activity (Csikszentmihályi, 1990).

Findings from a wide range of domains, including chess playing, writing, sports, and visual arts, show a positive correlation between flow state measures and objective measures of quality of performance (Csikszentmihályi & Csikszentmihályi, 1992). In addition, flow has been suggested to function as a reward signal to promote practice (Csikszentmihályi, 1997). According to theory, flow encourages a person to persist at and return to an activity because of the experiential rewards it promises, and thereby fosters the growth of skills over time. Other studies have also found positive correlations between flow and quality of life (Csikszentmihályi, 1990).

Flow may also play a particular role in creative thinking, as alluded to in the beginning of this section. Numerous accounts have been obtained from distinguished individuals in the arts and sciences, on how flow has enabled and intensified their creative process (Csikszentmihályi, 1997). Again, effortless attention appears to be the key concept. Intuitively, one might presume that the more challenging a mental activity, the more effort will be exerted. However, when in flow, greater challenge results in less subjective effort and resulting self-regulatory fatigue. Flow is a state of complete attentional focus, but at the same time cognition appears to be driven by free-association and implicit processes rather than by explicit rational reasoning or self-

referential thought. This state of unforced concentration may spur novel and relevant ideas. As Csikszentmihályi explains:

"For original ideas to come about, you have to let them percolate under the level of consciousness, in a place where we have no way to make them obey our own desires or our own direction. So they find their way; random combinations that are driven by forces we don't know about [yet]. It's through this recombination that something new may come up—not when we try to push them directly."

Hence, flow experiences may promote creativity in at least two ways: Firstly, by promoting the hard work which is required to gain necessary knowledge and to pursue an idea. Secondly, the flow state itself may facilitate creative thinking.

5.1 MEASURING FLOW

When operationalizing flow, the nine elements described in the previous section are generally transformed into dimensions that load equally on a composite flow score (Jackson & Eklund, 2004). It is thus important to note that flow is usually not regarded as an all-or-nothing peak experience; rather, degree of flow is a continuous variable that can be used to characterize the experiential quality of any everyday activity (Csikszentmihályi & Csikszentmihályi, 1992).

State flow can be measured using questionnaires that are administered directly after task performance (Jackson & Eklund, 2004). Another popular method in flow research is the Experience Sampling Method: Participants are fitted with pagers to randomly sample everyday experience. Every time the pager beeps, the participant has to fill out a questionnaire in order to probe flow at that particular moment (Csikszentmihályi & Csikszentmihályi, 1992).

Flow proneness, as a trait, refers to the tendency of a person to experience flow states (Ullén, de Manzano, Theorell, & Harmat, 2010). It can be measured by questionnaires by which participants indicate how frequently they have experiences with the various characteristics of the flow state.

6 MUSICAL CREATIVITIY

As described in the introduction (chapter 1), all creative behaviors share two common features: They involve generating or producing something which is at the same time both original and meaningful. Musical improvisation, which involves spontaneous and continuous extemporization of novel and contextually meaningful musical content, has been used as a model of creative behavior in neuroimaging studies (Bengtsson, et al., 2007). Thus far, the literature amounts to only four studies (excluding the two studies presented in this thesis), which have directly contrasted creative musical improvisation to music production.

The first of these studies was performed by Bengtsson and colleagues (Bengtsson, et al., 2007). During this experiment, eleven professional classical concert pianists were asked to perform improvisations based on visually displayed melodies on a twelve-key/one octave piano keyboard. The participants were also instructed to memorize each performance for subsequent reproduction. The results were based on a conjunction between the contrast improvisation-reproduction and a free improvisation condition (thus discarding the effect of memorization). The brain regions found predominantly active during the generation of musical structures in this study were the right dorsolateral prefrontal cortex (DLPFC), the bilateral rostral dorsal premotor regions (PMDr), the left posterior superior temporal gyrus (STG), the right fusiform gyrus and the bilateral middle occipital gyrus. In addition, activity in the pre-supplementary motor area (pre-SMA) was correlated with a measure of complexity of the improvisations. The authors claimed the DLPFC activation as the key finding, based on this region being previously associated with free choice, attention to selection of action, and monitoring in working memory (Desmond, Gabrieli, & Glover, 1998; Lau, Rogers, Ramnani, & Passingham, 2004; Nathaniel-James & Frith, 2002). It was also suggested, given earlier work on movement sequence production (Bengtsson, Ehrsson, Forssberg, & Ullén, 2004; Schubotz & von Cramon, 2001), that during improvisation, activity in the pre-SMA and PMD may correspond to the shaping of rhythmic and melodic structures, respectively.

Since Bengtsson et al., there have been two other studies, which have also investigated brain regions predominantly active during piano improvisation. In Limb and Brown (2008), improvisation was compared to execution of over-learned musical sequences at two levels of complexity. The participants – six professional jazz pianists – were asked to play either a C major scale, improvise in C major, play a Jazz composition from memory to auditory musical accompaniment, or improvise to this accompaniment. The instrument was a thirty-five-key piano keyboard. Contrasting improvisation to the over-learned sequences, a decreased activation of dorsolateral prefrontal and lateral orbital regions, the limbic and paralimbic regions, the basal ganglia, insula and the temporoparietal junction, was observed. A comparably greater activation was found in the frontal polar portion of the medial prefrontal cortex along with spread activations in the temporal, occipital and parietal cortices, the cingulate gyrus and cerebellum. The results unfortunately have to be viewed as indicative rather than conclusive, based on the small sample size and the fixed effects analysis which was used. Nonetheless, the findings are interesting in that they differ from the earlier Bengtsson study. In fact, they are completely opposite with regard to DLFPC involvement. The apparent discrepancy could possibly be accounted for by a difference

in expertise/improvisational skills between the two experimental groups. Improvisation is a much more central feature of jazz than classical music, and jazz pianists are arguably more accustomed with performing spontaneous improvisations than classical pianists. Furthermore, it could be argued the two experimental paradigms differ in complexity. Free improvisation on a well-learned scale or chord structure, as in Limb and Braun, is conceivably a less intricate task than ornamentation of a melody presented a prima vista. In line with this reasoning, it can be observed that classical pianists activate a network including the pre-SMA and DLPFC, typically associated with explicit processing of novel motor sequences, while jazz pianists rely on regions for implicit routine and automated behavior, showing a more caudal distribution of activity in the SMA and PMD, in conjunction with activity in limbic regions and the basal ganglia (Doyon & Benali, 2005). It should also be noted that the control conditions in Limb and Braun were based on over-learned sequences, which were simple for the participants to perform. This could explain why much of the deactivations found, resembles a "default network" of resting state activity, which is typically reduced during active conditions (Buckner, Andrews-Hanna, & Schacter, 2008).

The last of these studies was conducted by Berkowitz and Ansari (2008). Their sample consisted of thirteen classically trained undergraduate pianists. The experimental conditions, which were carried out on a piano-like response device with five keys, shifted between improvisation and performance of pre-learned five-note sequences. A two-by-two factorial design was used to examine the generation of melodic and rhythmic content both separately and together. The main effect of melodic improvisation showed activations in the anterior cingulate cortex, ventral and dorsal premotor cortices, supramarginal gyrus and cerebellum. Deactivations were found in the superior and medial frontal gyri, posterior cingulate cortex and angular gyrus. The main effect of rhythmic improvisation illustrated greater activity in regions of the anterior cingulate cortex and inferior frontal gyrus as well as the dorsal premotor, sensorimotor and parietal cortices. The results show similarities to Limb & Braun in that the default network is deactivated during improvisation. More interesting however, is that this makes the third study which illustrates the importance of dorsal premotor regions in musical improvisation. There are however some issues with this last study which needs to be addressed. First, the results are based on only two thirds of the data, because one third of the data had to be removed (and one participant was completely excluded) due to excessive participant movements during scanning. Second, the control condition also included an element of free choice or improvisation, as the participants were free to choose which sequence of pre-learned patterns they wanted to play. Third, the metronome only sounded during the conditions were rhythm was constrained, and not during rhythm improvisation. This means that the main effect of rhythmic improvisation was to some extent confounded by the difference in auditory stimulation. Fourth, based on the behavioral data, melodic freedom was shown to have a significant effect on both melody and rhythm. Thus, it is not clear from this study whether melodic and rhythmic improvisation load differently on different anatomical regions. Study III, presented in this thesis, is an attempt to resolve this matter more definitely.

In conclusion, even though there are methodological differences to be regarded between these studies, the differences in results speak against improvisation being dependent on a completely fixed set of regions, but rather favor a view of domain

specific regions being able to generate novel and appropriate content during creative performance, depending on the task and skill-challenge balance.

7 DOPAMINE AND CREATIVITY

Both direct and indirect evidence show that the dopamine system may play a particular role in creative thinking. This chapter will firstly give an introduction to the dopamine system and secondly, give a brief review of the bulk of studies which associate the functional properties of dopaminergic pathways with creativity.

7.1.1 The dopamine system

Dopamine is a catecholamine neurotransmitter which is synthesized in the brain from the amino acid tyrosine. It is produced in the substantia nigra pars compacta (SNpc), ventral tegmental area (VTA) and the hypothalamus. The dopaminergic projections from these regions can be divided into four major pathways (for a review see Guillin, Abi-Dargham, & Laruelle, 2007):

The nigrostriatal system projects from the SNpc to the dorsal striatum and has classically been implied in cognitive integration, habituation, sensorimotor coordination, and initiation of movement. The mesolimbic system projects from the ventral tegmental area to limbic structures such as the ventral striatum, the hippocampus, and the amygdala. The mesocortical system projects from the VTA to cortical regions, mostly orbitofrontal, medial prefrontal, and cingulate cortices, but also to the dorsolateral prefrontal cortex, temporal, and parietal cortex. The mesolimbic and mesocortical systems are involved in regulation of motivation, attention, and reward. The tuberoinfundibular system, which projects from the hypothalamus to the median eminence, regulates the secretion of prolactin from the anterior pituitary gland.

Dopamine is not inhibitory or excitatory, but its action will depend on the state of the neurons at the time of the stimulation and the receptor type which is active (Yang, Seamans, & Gorelova, 1999). There are five types of dopamine receptors that are regionally distributed across the brain. They can be classified on the basis of their sequence homologies into two categories: A D1-like family (including D1 and D5 receptors), and a D2-like family (D2, D3, and D4 receptors) (Guillin, et al., 2007).

Dopamine modulates higher order cognition primarily by regulating neuron firing thresholds and information gating in corticostriatal–thalamocortical loops (Alexander, DeLong, & Strick, 1986). These loops are divided into limbic, associative and motor loops based on their cortical projections, although they are not completely segregated but form open circuits and serve integrative processes.

Considering that the nature of creative thought is to generate a multitude of ideas and form novel and original semantic associations between previously unrelated concepts (Plucker & Renzulli, 1999), the modulation of information gating and integrative processes and consequently dopaminergic function within these loops, should be of great interest.

There is strongest evidence for an involvement of the D2 receptors in creativity, which will be described further in subsequent sections. This receptor is expressed primarily in the striatum, though moderate levels are found also in the thalamus and hippocampus (Hurd, Suzuki, & Sedvall, 2001). The thalamus displays the highest density of D2 receptors among extra-striatal brain regions (Kessler, et al., 1993). The density of D2 in cortical regions is extremely low.

7.1.2 Creative personality traits and dopamine

There is substantial evidence for that the personality traits which are linked to creativity are modulated by dopaminergic activity and in particular the activity of dopamine D2

receptors: Novelty seeking is negatively correlated with D2 binding potential (D2BP) values in the right insular cortex (Kaasinen, Aalto, Nagren, & Rinne, 2004; Suhara, et al., 2002), and has also been associated with polymorphisms of the dopamine D2 receptor gene 'DRD2' (Berman, Ozkaragoz, Young, & Noble, 2002).

Extraversion is related to dopaminergic activity in hypothalamus and VTA (Depue & Collins, 1999) and agentic extraversion modulates the effect of dopamine D2-receptor agonists (Wacker & Stemmler, 2006). Self-confidence is negatively correlated with pharmacologically increased D2 receptor occupancy in the striatum (de Haan, Lavalaye, Booij, & Linszen, 2005). Aggression and impulsivity are associated with elevated levels of dopaminergic function and related to activity of D2 receptors in the striatum (de Almeida, Ferrari, Parmigiani, & Miczek, 2005). Also, animal studies show that social dominance increases D2 receptor distribution volume in the striatum, (Morgan, et al., 2002) and that activity of D2 receptors in the striatum is related to dominance in aggressive behavior (Dennis, Muir, & Cheng, 2006). Lastly, psychoticism, detachment and irritability are negatively related to D2BP in the striatum (Gray, Pickering, & Gray, 1994; Farde, Gustavsson, & Jonsson, 1997) and detachment is related to polymorphisms of the dopamine D2 receptor gene (Jönsson, et al., 2003).

7.1.3 Mental illness, dopamine and creativity

Extending on the link between psychoticism and creativity, enhanced creativity has also been found in individuals displaying psychosis-like schizotypal personality traits and a genetic liability for bipolar and schizophrenia spectrum disorders (see Creativity Research Journal 2001, vol 13, issue 1, for a number of papers on the subject). Creativity is generally low in patients but more often than by chance elevated in close relatives or in subjects at genetic risk and/or in subjects displaying mild positive and asocial schizotypal symptoms (Folley & Park, 2005; Richards, Kinney, Lunde, Benet, & Merzel, 1988). Supposedly, the neural networks which are relevant to creativity overlap to some degree with those responsible for the display of such symptoms, and certain disorder-related alterations in these networks may affect personality and performance, in some cases even in such a way as to enhance creative output. Interestingly, positive symptoms are not necessarily related to problems in executive function, at least not to the same extent as negative symptoms (Dibben, Rice, Laws, & McKenna, 2009).

These findings present a valuable lead to follow up, because a considerable amount of neuroscientific research has been devoted to disclose the underpinnings of these traits and disorders, which could provide important insights and testable hypothesis about the biological makings of creativity. Here, a brief overlook will be given on some of the studies that associate creativity to these abnormal neuropsychological states:

In a study by Burch and colleagues (2006a), visual artists, compared to non-artists, were found to score higher on the unusual experiences, cognitive disorganization and impulsive nonconformity, in addition to displaying increased psychometric creativity (divergent thinking) and more creative personality (higher openness and lower agreeableness). In a later study by Batey and Furnham (2008) it was found that even within a sample of healthy college undergraduate students, unusual experiences and impulsive nonconformity was significantly related to self-rated creativity, creative personality, and an inventory of creative behaviors. Among writers, as well as their first-degree relatives, there is a substantially higher rate of mental illness,

predominantly affective disorder with a tendency toward the bipolar subtype, compared to controls. (Andreasen, et al., 1987). This liability in writers was later confirmed by Post (1994, 1996), who in addition showed that the prevalence of potentially handicapping DSM-related traits were more prevalent among two-hundred-ninety famous men in science, thought, politics, and art than in the general population, though to a varying extent in different creative professions (e.g. 40% of the scientists and 70% of the writers displayed symptoms). Post also noted that the prevalence of actual psychosis among these outstanding individuals was *less* than in the general population. Creative accomplishment has accordingly been shown to be significantly higher among manic-depressives, cyclothymes, and normal relatives than among controls, and suggestively higher among normal index relatives than among manic-depressives (cyclothymes fell close to normal relatives) (Richards, et al., 1988). Karlsson (1970) also found that psychologically healthier biological relatives of persons with schizophrenia had unusually creative jobs and hobbies. In a more recent study, adoptees of schizophrenics with either schizotypal or schizoid personality disorder or multiple schizotypal signs were rated to have significantly higher real-life creativity than other participants (Kinney, et al., 2001). Lastly, with reference to the introduction (section 1.2.3 – Genes), Keri (2009) was able to show that the gene neuregulin 1, which has been implicated in psychosis, was associated with creative achievement and divergent thinking in healthy individuals.

A large body of research shows that positive symptoms are related to the dopamine system and the activation of D2 receptors: All antipsychotic drugs provide at least some degree of D2 receptor blockade and the blockade of D2 receptors is most effective against positive symptoms (Weinberger & Laruelle, 2001). Striatum is the structure which has received most attention in relation to this finding, as it displays the highest D2 receptor density. However, it has also been shown that thalamus, which has moderate levels of D2 receptors, is important in neuroleptic response (Buchsbaum, et al., 2006). Receptor imaging studies have also given interesting results: A meta-analysis found a small but significant elevation of striatal D2 receptors in untreated patients with schizophrenia, however without clinical correlates (Weinberger & Laruelle, 2001). D2 receptor levels in the caudate was found to be increased in healthy monozygotic twins compared to dizygotic twins of patients with schizophrenia, which implies that the upregulation is related to a genetic risk for schizophrenia (Hirvonen, et al., 2005). It should be noted however, that the sample size was very low (six and five individuals in respective group). An increase in D2BP was also found in off-medication and never medicated schizophrenics, in the substantia nigra bilaterally, which projects dopamine to the striatum (Kessler, et al., 2009). A more reliable finding is that drug-naïve schizophrenia patients demonstrate reduced dopamine D2 receptor binding in the thalamus (Buchsbaum, et al., 2006; Kessler, et al., 2009; Talvik, et al., 2006; Yasuno, et al., 2004). Some studies have also found D2BP levels to be decreased in the temporal cortex (Buchsbaum, et al., 2006; Tuppurainen, et al., 2003), anterior cingulate cortex (Buchsbaum, et al., 2006; Suhara, et al., 2002) and amygdala (Buchsbaum, et al., 2006).

In terms of relating these findings to clinical symptoms; D2BP in the temporal cortex showed a positive correlation with positive symptoms (Kessler, et al., 2009) and a negative correlation with general and negative symptoms (Tuppurainen, et al., 2003). Ventral striatal D2BP was correlated with positive symptoms (Kessler, et al., 2009) and Disorientation to D2BP in bilateral caudate (Talvik, et al., 2006). D2BP in subregions

of the thalamus was found to be negatively related to total symptoms, general symptoms, positive symptoms, hostility and suspiciousness (Buchsbaum, et al., 2006; Yasuno, et al., 2004) and Grandiosity (Talvik, et al., 2006). A significant negative correlation was observed between D2BP in the anterior cingulate cortex (Suhara, et al., 2002) and a significant positive correlation was found between frontal D2BP values and positive schizophrenic symptoms among male but not female subjects (Glenthoj, et al., 2006).

Additionally, patients with schizophrenia showed higher dopamine synthesis in the left caudate nucleus compared to controls; dopamine synthesis rates in the thalamus exhibited a significant positive correlation with the Positive and Negative Symptom Scale (PANSS) total scores, and a significant positive correlation was observed between the PANSS positive subscale scores and dopamine synthesis rates in the right temporal cortex (Nozaki, et al., 2009).

7.1.4 Environmental factors, dopamine and creativity

In terms of life span development and social context, Simonton (1999) has shown that factors such as birth order, adverse life events (e.g. loss of parent) and challenging social context (e.g. poverty or immigrant status) seem to have had an influence on the life and cognition of eminent creators. Factors such as these, may also affect the function of the dopamine system:

Trauma, or discriminatory experiences, may progressively increase the behavioral and biological response to subsequent exposures (van Winkel, Stefanis, & Myin-Germeys, 2008). The risk for psychosis (particularly in individuals at high risk for schizophrenia) increases with the number of adverse live events. This sensitization is suggested to involve dysregulation of the hypothalamus-pituitary-adrenal axis, contributing to dopamine sensitization in mesolimbic areas and increased stress-induced striatal dopamine release. Furthermore, it has been suggested that such an "endogenous" sensitization process can manifest itself in great attention to details, intense feeling of curiosity, repetitive searching and sorting behavior, i.e. openness to experience (Glenthoj & Hemmingsen, 1997; Laruelle, 2000). An interaction have also been described between adverse life events and synaptic dopamine levels, such that individuals with lower levels of dopamine catabolism are more likely than others to display a disposition toward violence and other antisocial behavior when maltreated (de Almeida, et al., 2005).

7.1.5 Cognitive processes, creativity and dopamine

7.1.5.1 Divergent thinking, creativity and dopamine

Divergent thinking is influenced by dopaminergic function. In a study by Reuter (Reuter, et al., 2006) a correlation was found between divergent thinking (the Inventiveness battery of the Berliner Intelligenz Struktur Test) and polymorphisms of the dopamine D2 receptor gene 'DRD2 TAQ IA'. Higher creativity scores were observed in carriers of the A1 allele. This polymorphism is unrelated to general intelligence (Ball, et al., 1998; Moises, et al., 2001), which suggests that it is more specifically related to *Glr* (see chapter 4 – Divergent thinking). This finding is in line with functional imaging research showing the D2 system to be involved in attentional set shifting and response flexibility, which are important components of divergent

thinking (Durstewitz & Seamans, 2008). Furthermore, the finding indicates that divergent thinking is related to regional differences in D2 densities, since the DRD2 TAQ IA polymorphism has been shown to modulate D2BP in both striatal (Ritchie & Noble, 2003) and extrastriatal regions (M. M. Hirvonen, et al., 2009).

As can be concluded from the theoretical background presented in this chapter on dopamine and creativity, there is great support for that several traits, abilities and experiences which have been described as central to the creative phenotype are associated with the dopamine system and D2 receptors in particular.

8 AIMS

Study I was performed in order to investigate the putative relationship between creative thinking and dopaminergic function. Such an association would directly indicate neural mechanisms important to creative thinking, and furthermore give some explanation to the observed links between mental illness and creative achievement.

In study II, physiological processes associated with the flow experience were studied. This would be the first study to show that the subjective experience of flow is reflected in biological processes. Since flow has been associated with both optimal performance and creative achievement, such a finding would motivate further studies of biological mechanisms which may link flow and creativity.

Study III, sought to identify the functional brain regions which are predominantly involved in creative behavior, using piano improvisation as model behavior. The study was specifically aimed at investigating functional networks related to the internal generation of melodic and rhythmic structures, respectively.

In study IV was similarly to study III dedicated to examine the neural correlates of musical creativity, though with a different approach. In this study musical improvisation was compared to pseudo-random generation of key presses. Pseudo-random tasks have previously been used to study willed action, but these experimental tasks to some extent lack ecological validity as the behavior differs notably from that in everyday life. Therefore study IV was considered important, firstly, in order to validate previous findings based on pseudo-random task paradigms and secondly, compare creative performance with another generative task, to illustrate how musical context may affect neural processing.

9 METHODS

9.1 PARTICIPANTS

The participants in study I had previously served as control subjects in a clinical study on dopaminergic hypoactivity in the restless leg syndrome (Cervenka, et al., 2006) and had thus already been scanned with positron emission tomography (PET) for D2BP. This enabled us to use the same group of subjects to examine the relationship between creativity and D2BP, without performing further PET measurements. Fourteen participants with at least nine years of basic education were included (6 male, $M = 56 \pm 8$ years). One participant was excluded from analysis because of an extremely low Raven score, which gave a total of thirteen participants.

In study II, a group of experts was chosen to perform the experimental task, since expertise will, at least theoretically, increase the probability for achieving flow: Twenty-one professionally active classical pianists, including three students from the Royal Academy of Music in Stockholm, were recruited from the Stockholm region, (18 male; $M = 41 \pm 11$ years old) and volunteered to participate in the study. This can be regarded as a representative sample of the target population.

During the design of Study III and IV, it was argued that it would be important for the participants to be proficient enough with a piano keyboard to be able to perform well under the experimental constraints induced by lying in the MR scanner. It has also been shown that amateur and professional musicians differ in functional and structural brain anatomy (e.g. Gaser & Schlaug, 2003). Furthermore, expertise enables creativity (Sternberg, 1999). Hence, a relatively homogenous sample in terms of musical professionalism was recruited. Since the data for study III and IV were collected during the same scanning sessions, the participant group for these two studies was essentially identical. In study III, eighteen right-handed classical concert pianists (17 male, $M = 39 \pm 12$ years) participated. In study IV, two of these participants had to be excluded: One, because of a technical failure with the MR-scanner; another, based on the analysis of behavioral data. Hence, sixteen participants (15 male, $M = 40 \pm 12$ years) were included in study IV.

9.2 MR COMPATIBLE PIANO KEYBOARD AND MUSIC FEEDBACK

A custom made MR-compatible fiber optic piano keyboard (LUMItouch, Inc.) of one octave (twelve keys with authentic dimensions, ranging from F to E) was used to collect behavioral data in studies III and IV. The keyboard was connected to an optical-electrical converter outside the scanner room. The converter was in turn connected to a MIDI-keyboard (Midistart-2; miditech), generating a signal that was subsequently stored on a laptop using a standard recording and sequencer software (Cubase SE 3; Steinberg). The same software was also used together with a sound sampler (Kontakt 2/Steinway D convolution instrument; Native instruments) and an external sound card (TerraTec Producer Phase 26 USB; TerraTec) to provide auditory feedback to the participants.

9.3 VISUAL STIMULI

In study III visual templates were presented for the four active conditions. The templates differed with regard to if rhythm and melody were notated or left unspecified, according to the employed two-by-two factorial design (see Figure 1). For Notes both rhythm and melody were specified. For Melody the rhythm was specified using standard pitch-less percussion notation; the melody was thus left unspecified. For Rhythm the melody was specified using filled note heads; the rhythm was unspecified. For Free neither rhythm nor melody were specified; crosses were used to indicate the approximate number of notes to be played. For the three conditions constrained by external stimuli (Notes, Melody and Rhythm), there were eight notes in each bar. For the Rest condition empty staffs were shown. Since all active conditions were presented twice during each of the four sessions, a total of thirty-three unique templates (including one template for the Rest condition) were used. Throughout the preparatory period before each condition, the musical score was surrounded by a red rectangular frame. The removal of this frame signaled to the participant to either start playing or remain at rest, depending on the experimental task.

In study IV a total of nineteen visual templates were used: Twelve for the Notes condition (two, six and twelve keys for each of the four sessions), three for the Improvise condition (two, six and twelve keys), three for the Random condition (two, six and twelve keys), and one for the Rest condition. As in study III, the musical score was surrounded by a red rectangular frame throughout the preparatory period before each condition.

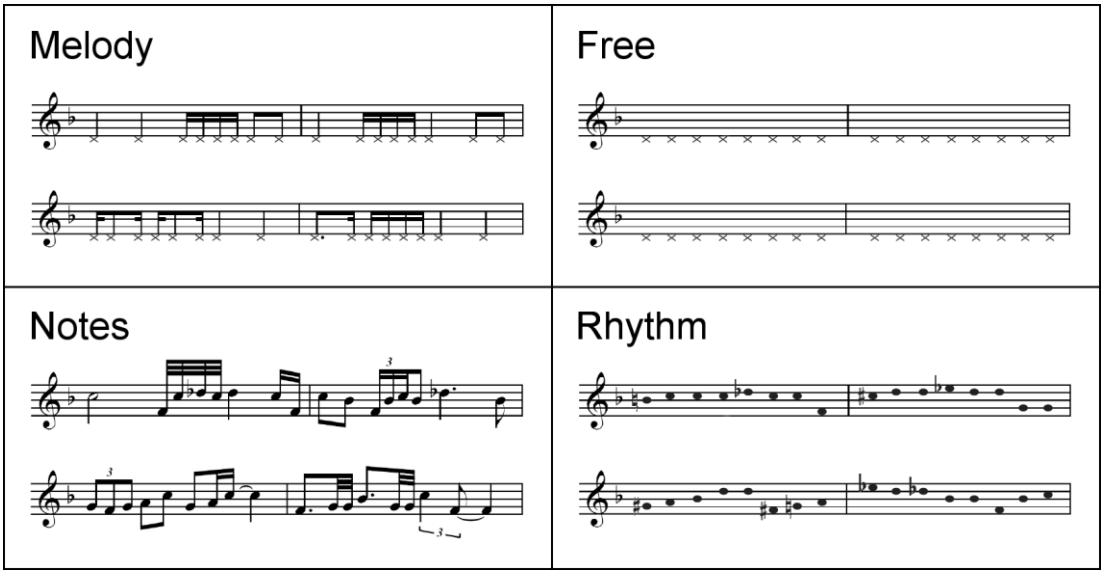

Figure 1. Experimental design and conditions. Four active conditions were used which were arranged into a 2 × 2 factorial design according to the factors Melody and Rhythm: Notes – both melody and rhythm specified; Melody – melody unspecified, rhythm specified; Rhythm – melody specified, rhythm unspecified; Free – both melody and rhythm unspecified.

9.4 AUDITORY STIMULI

During the preparatory period in study III, four beats of a metronome (clapping sound), corresponding to one bar of music (quadruple time, 60 bpm), were played before all conditions, to pace subsequent performance.

Similar auditory stimuli were given during the preparatory period in study IV. Three beats of a metronome, corresponding to one bar of music in triple time (80 bpm), were played before all conditions.

9.5 PSYCHOLOGICAL TESTING

9.5.1 Creativity

In study I, creativity was measured through the use of a divergent thinking test. Three timed subtests from the 'inventiveness' test battery of the 'Berliner Intelligenz Struktur Test' (BIS) (Jäger, Süß, & Beauducel, 1997) were administered. The inventiveness tests measure the components figural, verbal, and numeric creativity and challenges the flexible production of ideas, the power of imagination, and the skill to consider many possible ways and solutions for solving a problem.

The tests were chosen based on their having the highest factor loadings on the total inventiveness-score. In the figural test, a simple line drawing should be completed in various ways in order to create pictures of as many possible real objects as possible. In the verbal test, the participant was instructed to produce as many alternate uses for a given object as possible. In the numeric test the participant had to generate as many logical number sequences as possible, while trying to vary the rule of construction. Raw scores from each subtest were transformed into Z scores (Jäger, Süß, & Beauducel, 1997), which were subsequently summed and used as a composite measure of divergent thinking.

9.5.2 Intelligence

In study I, intelligence was assessed using the Raven's Standard Progressive Matrices Plus (Raven) (Raven, Styles, & Raven, 1998), a widely used test that mainly reflects psychometric general intelligence (*g*) (Gustafsson, 1984). Raven was designed to measure a person's ability to form perceptual relations and to reason by analogy independent of language and formal schooling, and may be used with persons ranging in age from six years to adult (Raven, Styles, & Raven, 1998). The Raven consists of 60 items arranged in five sets (A, B, C, D, & E) of twelve items each. Each item contains a figure with a missing piece. Below the figure are either six (sets A & B) or eight (sets C through E) alternative pieces to complete the figure, only one of which is correct. Each set involves a different principle or "theme" for obtaining the missing piece, and within a set the items are roughly arranged in increasing order of difficulty. There are no time limits and simple oral instructions corresponding to the above description. The raw score is typically converted to a percentile rank by using appropriate norms.

9.5.3 Flow

In study II, the participants' level of flow was estimated using a subset of the Flow State Scale, which has been shown to be a reliable and valid measure of the flow construct (Jackson & Eklund, 2004). Items in this self-report questionnaire are formulated as propositions about the trial experience, with which the respondent will agree or disagree, answering on a Likert-scale. Nine items were selected from the original questionnaire to probe each dimension of flow (see chapter 5 – Flow and creativity). Those items were chosen that according to the test manual (Jackson &

Eklund, 2004) load most on each flow dimension respectively. Answers were given on a nine-step scale, from strongly disagree (1) to strongly agree (9).

9.6 POSITRON EMISSION TOMOGRAPHY

PET is a technique used in clinical medicine and biomedical research for functional imaging and imaging of neuroreceptors (Balázs & Sjöholm, 2007).

Tracer molecules designed to probe specific physiological processes are labeled with radioactive isotopes and introduced to the body. The radioactive nuclei emit positrons that annihilate when they encounter electrons in the tissue. An annihilation event results in two gamma photons being emitted in almost exactly 180 degrees. The gamma photons are detected in coincidence in a detector ring (or several detector rings) so that two detected gamma photons represent a straight line along which the event took place. An assembly of such lines is then reconstructed to finally produce a series of three-dimensional images representing the regional distribution of the radioactive molecules over time. This information is used to generate curves of radioactivity over time for any given brain region. Different radioligands are manufactured to target different functional processes or anatomical features, e.g. different neurotransmitter receptors.

A radioligand targeted to a certain neuroreceptor distributes to the brain by passively crossing the blood-brain barrier. Each radioligand for a given receptor system has its own kinetic behavior which depends on the input function itself (i.e. how the tracer arrives to the brain), the degree of non-specific binding and on the affinity of the radioligand for the given target binding site. Data from time-activity curves are entered in a model to derive model parameters that describe the distribution of the tracer in the brain. The model defines the kinetics of the tracer and the exchange between different compartments.

One such model is the simplified reference tissue model (SRTM) (Lammertsma & Hume, 1996). In this model, the radioligand in the brain can be free (F), specifically bound to a receptor (B) and nonspecifically bound to other binding sites in the brain tissue (NSB). These different fractions of the tracer are in equilibrium between each-other. With PET these tracer fractions cannot be separated, thus it is rather the whole activity (F+B+NSB) plus a fraction of the blood volume which is measured. In the SRTM, the free tracer concentration and the concentration of non-specific bound radioligand are assumed to equilibrate rapidly and the two compartments can therefore be treated as one. By then comparing measurements in a receptor-rich region to that of a region devoid of receptors (reference region), it is possible to subtract out the NSB and retrieve an estimate of the specifically bound ligand in the form of binding potential.

Binding potential is equal to the ratio B_{max}/K_D which represents the ratio of receptor density and apparent affinity (Mintun, Raichle, Kilbourn, Wooten, & Welch, 1984). The affinity is termed ‘apparent’ when measurements are not corrected for non-specific binding. SRTM builds on the assumption that the distribution volume is the same for the tissue of interest and the reference tissue (Lammertsma & Hume, 1996).

9.6.1.1 Acquisition of PET data

In study I, PET measurements were performed on an ECAT Exact HR system (CTI Siemens, Knoxville, TN) using the radioligands [^{11}C]raclopride and [^{11}C]FLB 457, to investigate dopamine D2BP in striatal and extrastriatal regions respectively. The radioligands were given intravenously as a rapid bolus. Radioactivity in the brain was measured during 51 min for [^{11}C]raclopride and 87 min for [^{11}C] FLB 457.

9.7 PSYCHOPHYSIOLOGICAL MEASUREMENTS

9.7.1 Electromyography

Muscle tone of the *corrugator supercilii* (CS) and *zygomaticus major* (ZM) muscles was recorded using electromyography (EMG) and Ag/AgCl surface electrodes (AMBU® Blue Sensor) attached to muscle sites on the left side of the face. The participant's skin was prepared with a low-alcohol detergent to minimize impedance. The raw EMG signal was amplified (ML135 Dual Bio Amp, ADInstruments) and filtered, using a notchfilter of 50 Hz and bandpass filter removing frequencies below 20 Hz and above 400 Hz.

9.7.2 Respiration

Thoracic respiration was measured using a piezo-electric respiratory belt transducer with an output range of 20–400 mV and a sensitivity of 4.5 ± 1 mV/mm (MLT1133, ADInstruments). The belt was attached around the chest below the nipple line (or below the breast for women).

9.7.3 Arterial pulse pressure

Heart period (HP) and blood pressure (BP) measurements were based on arterial pulse pressure acquired with an IR plethysmograph (MLT1020EC, ADInstruments) attached to the right ear. In addition to HP and BP, we explored the possibility of acquiring HRV related measures using the plethysmograph. HRV was primarily calculated to potentially strengthen the ability to interpret HP and BP. In order to minimize artifacts and confounding respiratory influence on cardiac measures, the plethysmographic waveform was band-pass filtered. Since the data would not be pooled across participants in the later statistical analysis, bandpass filters could be created and optimized for each individual separately: (i) A preliminary filter (0.5–3.5 Hz) was first applied, then (ii) the minimum and maximum heart period for the individual across trials were obtained, based on which (iii) a new bandpass filter could be created. Steps two and three were iterated until a stable solution was reached, meaning that an optimized filter had been found based on the minimum and maximum heart period across trials for that participant.

9.7.4 Head movements

Head movements were recorded for two reasons: to allow for crosschecking in regard to potential movement artifacts in other physiological measures and to explore a potential association between head movement pattern and flow. Head movements were registered using a 3-axis accelerometer with a range of ± 19.6 m/s^2 and a sensitivity of 30.6 $mV/(m/s^2)$ (ACA302, Star Micronics America, Inc.) fitted to a headband.

9.8 MAGNETIC RESONANCE IMAGING

Human brain imaging with magnetic resonance imaging (MRI) is a fairly recent development which started to gain momentum in the 1990s (Buxton, 2002). The main advantages to MRI (and functional MRI, fMRI) as a technique to image the brain include, (i) the signal does not require injections of radioactive isotopes, (ii) the total

scan time required can be very short, and (ii) the resolution of the images is relatively good (for MRI typically 1 x 1 x 1 mm).

Electrons, protons, neutrons-and in many cases the atomic nuclei-behave as though spinning about their axes, a property called spin angular momentum, which has both magnitude and direction. Such a spinning particle generates a magnetic field and associated "magnetic moment"-acting like a tiny bar magnet with north and south poles. When placed in a strong external magnetic field the "magnetic moment" of a nucleus tends to align with (parallel to) or against (antiparallel to) the external field.

This is exactly what happens in an MR-scanner which induces a strong magnetic field, typically in the range of 1.5-7 Tesla. Within the human body, hydrogen atoms contained in water align with the surrounding external field.

By additionally applying a radio frequency pulse (RF) which matches the resonance frequency of the spinning nuclei, the nuclei absorb energy from the radio signal and are excited to a higher energy state. The magnetic moments “flip” from the external field. This is called magnetic resonance. The nuclei then emit this energy as a radio signal and again realign with the external field. The speed of this “relaxation” is affected by surrounding tissue. Thus, by applying different RF gradients and using an elaborate radio transceiver (integrated in a radio frequency coil surrounding the body or body part of interest), it is possible to measure and locate the energy emission at different time constants, and recreate images illustrating the progression of signal decay at given moments during the relaxation. Depending on the time points chosen and the direction in which the signal is measured, tissues will appear with different signal intensity and it is possible to get different contrast images (usually in grey scale) outlining the structural anatomy of the scanned region. This is called magnetic resonance imaging. In T1 weighted images (T1 refers to the time it takes the nuclei to return to their alignment with the external field; longitudinal magnetization) tissues or fluid with high water content appears as dark grey/black (short T1 relaxation time) and fat appears as white. In T2 weighted images (T2 refers to how long the resonating nuclei remain coherent or precess (rotate) "in phase" following a RF pulse; transverse magnetization) water instead appears as white. The resolution of MR images is usually described in terms of voxel-size, i.e. the size of the volumetric picture elements, e.g. 1 x 1 x1 mm.

9.8.1 Functional magnetic resonance imaging

Functional MRI is based on the increase in blood flow to the local vasculature that accompanies neural activity in the brain. This results in a corresponding local reduction in deoxygenated blood because the increase in blood flow occurs without an increase of similar magnitude in oxygen extraction (Buxton, 2002).

The magnetic susceptibility of fully oxygenated arterial blood differs from that of fully deoxygenated venous blood. Deoxygenated hemoglobin, when placed in a magnetic field, will increase the strength of the field in its vicinity, while oxygenated hemoglobin will not. Neural activity can consequently be measured indirectly in an MR-scanner by obtaining the blood-oxygen-level-dependent (BOLD) signal. By subtracting images acquired during one experimental condition, e.g. rest, from those obtained during another, e.g. playing the piano, it is possible to create a contrast image which illustrates regions in which there was a relative increase in neural activity, e.g. playing the piano compared to rest. Hence, fMRI enables an investigation of the functional properties of various regions.

9.8.1.1 Acquisition of fMRI data

Functional MRI data for Study III and IV were acquired using a 1.5 Tesla MRI system (Signa Excite, GE Medical Systems) with a standard eight-channel head coil. At the beginning of each scanning session, a high-resolution, three-dimensional T1-weighted anatomical image volume of the whole brain was collected. Functional image data were then collected using a T2*-weighted sequence with BOLD contrasts (Kwong, et al., 1992; Ogawa, et al., 1992). Whole brain image volumes were constructed from 32 contiguous axial slices (for further details, see study III and IV).

9.8.1.2 Functional MRI image preprocessing

In order to allow for statistical analysis, fMRI data needs to be preprocessed. In studies III and IV, all fMRI image volumes were realigned and unwarped (motion correction via spatial matching of voxels acquired at different time points) (Ashburner & Friston, 1997), coregistered to each individual's T1-weighted image (Ashburner & Friston, 1997), segmented (into grey matter, white matter and cerebrospinal fluid) and normalized into a standard space which allows data to be averaged across participants (Friston, et al., 1995) and finally spatially smoothed with an isotropic Gaussian filter.

10 DATA ANALYSIS

10.1 ANALYSIS OF DIVERGENT THINKING AND PET DATA

In study I, the putative relationship between dopamine D2BP and divergent thinking was investigated.

In order to process and analyze the PET-images in study I, MR-images were first acquired and realigned to the anterior–posterior commissural plane using the SPM2 software (Wellcome Department of Imaging Neuroscience, London, UK). PET images were then coregistered to the MR image using the normalized mutual information method implemented in SPM2. For determination of regional radioligand binding, region-of-interests (ROIs) were manually delineated on each individual MR-image using the Human Brain Atlas software. In study I, the selection of ROIs was limited to the thalamus and frontal cortex for [^{11}C]FLB 457 examinations, and to the striatum for [^{11}C]raclopride examinations. In an extended anatomical analysis of the striatum, ROIs for striatal subregions were defined according to a method described in the literature (Martinez, et al., 2003; Mawlawi, et al., 2001) in which striatum is divided into ventral, associative and sensorimotor subregions based on the differential connectivity of the striatum (Joel & Weiner, 2000). ROIs for the thalamus were defined using a modified version of a procedure described previously (Buchsbaum, et al., 1996; Gilbert, et al., 2001; Yasuno, et al., 2004). Finally, a ROI for cerebellum was drawn below the petrosal bone using five slices, corresponding to a thickness of 10 mm. The ROIs were transferred to the series of PET images to generate time–activity curves. D2BP values were calculated using the SRTM with the cerebellum as reference region. The SRTM has previously been validated for both [^{11}C]raclopride and [^{11}C]FLB 457 (Lammertsma & Hume, 1996; Olsson, Halldin, Swahn, & Farde, 1999).

The association between D2BP and divergent thinking was analyzed using Statistica 8.0 (StatSoft). Partial correlations between regional thalamic D2BP, striatal D2BP, intelligence and divergent thinking were then performed, keeping participant age constant. For the thalamus and the striatum, one-tailed significance tests were used, since negative and positive directions of the correlations were predicted for these regions respectively. Significance levels were Bonferroni corrected (n = 3; thalamus/ striatum/frontal cortex). Striatal subregions were analyzed separately in an extended analysis, also using one-tailed significance tests.

10.2 ANALYSIS OF FLOW AND PSYCHOPHYSIOLOGICAL MEASURES

The purpose of the data analysis in study II, was to investigate if changes in subjectively experienced flow were matched by changes in psychophysiological measures.

All psychophysiological measures were averaged over each trial for each participant. EMG was measured over the ZM and CS muscles as the root-mean-square (mV) of obtained activity. In the case of head movements, three measures were computed: movement amplitude (mV), based on the sum of amplitudes in three spatial dimensions; frequency (Hz), averaged over three spatial dimensions; and root-mean-square (mV), summed over three spatial dimensions. Three measures were obtained for respiration: respiratory rate (bpm), respiratory depth (V), and respiratory cycle duration

(s). The Chart 5 heart rate variability (HRV) module was used to detect interbeat intervals based on waveform peaks in the pulse signal and compute normalized interbeat (N-N) intervals, upon which subsequent analysis was performed. Drop beats and N-N intervals deviating more than three standard deviations from the mean interval were excluded and replaced with values calculated by linear interpolation between adjacent normal N-N intervals, using a custom made script in MATLAB. Heart period (HP; ms) was based on mean N-N across each trial. A spectral analysis, using a Fast Fourier transform (size 1024; Welch window; [1/2] overlap), was performed to divide the HRV power spectrum into two frequency bands and obtain power within each band: Low frequency (LF), 0.04–0.15 Hz (ms^2), and high frequency (HF), 0.15–0.5 Hz (ms^2). Power was corrected for HP by dividing the square root of the power value with the mean N-N. HF was corrected for respiratory rate and respiratory depth as is commonly recommended (Berntson, et al., 1997; Grossman & Taylor, 2007), by performing a multiple regression (within participant) to obtain the residual HF, which was then used as a measure of respiratory sinus arrhythmia (RSA). Total power and LF/HF ratio were also analyzed. The Chart 5 blood pressure module was used to attain measures of minimum, maximum, and range of pulse wave amplitude (V). Full-width-half-maximum (ms) was calculated through the use of a custom made script in MATLAB. A similar script was also used to remove and replace BP related values beyond three standard deviations from the mean with values based on linear interpolation between adjacent normal values. Trial duration (s) was measured as the time interval between the first and the last keystroke of the performance. Flow was operationalized as the average self-reported magnitude across the nine dimensions (Flow9D). An additional measure was created (Flow3D) combining the average response on the dimensions challenge-skill balance, concentration, and autotelic—the three dimensions that arguably corresponds most directly to (task) expertise, attention, and emotional experience, respectively. Three important points had to be taken into consideration when choosing the proper test for statistical analysis: First, the baselines for rated flow and physiological response might differ between individuals. This means that it would be wrong to simply pool data across individuals. Instead, a second level analysis would be required, evaluating the association between flow and physiology first within and then between subjects. Second, the number of trials and sample size were fairly small. Third, even though responses on the flow state scale are based on a Likert-scale and such responses are by convention thought to fall on an interval scale, there are in this case no empirical observations that can confirm this, which means that it can only be correct to assume an ordinal scale. Together, these points rule out the use of a parametric test. The Page Test for Ordered Alternatives, however, does accommodate all these points by testing if the rank order of measures ($\Phi_1, \Phi_2, \ldots \Phi_k$) of a dependent variable matches the rank order of measures of an independent variable (Siegel & Castellan Jr., 1988). The null hypothesis can thus be stated as:

$$H_0: \Phi_1 = \Phi_2 = \ldots \Phi_k,$$

and the alternative hypothesis:

$$H_2: \Phi_1 \leq \Phi_2 \leq \ldots \Phi_k,$$

where the difference between at least two measurements is a strict inequality (<).

Hence, if the null hypothesis is rejected, there is an association between the two variables in the prespecified direction. This nonparametric test allows for a mixed effects analysis in which relative flow is first compared to physiology within participant across trials before checking if a potential relationship holds across participants; rank orders are pooled instead of raw data, thus avoiding the problem of individual baselines (Siegel & Castellan Jr., 1988). The statistical test and analysis were implemented and performed in the MATLAB environment. Rank orders for each subject were computed based on absolute physiological values during piano playing. This was considered preferable in relation to using change scores from periods before each trial because such baseline measurements would be dependent on the previous active condition, given the short inter-trial period.

10.3 ANALYSIS OF PIANO IMPROVISATIONS AND FMRI DATA

10.3.1 Brief introduction to fMRI data analysis

The MRI data in studies III and IV were processed and analyzed using the SPM5 software package (Wellcome Department of Imaging Neuroscience, London, UK). The fMRI data was modeled using the General Linear Model (GLM). The aim of GLM is to explain the variation of the time course of activity in each voxel in terms of a linear combination of explanatory variables (experimental conditions) and an error term. The statistical model is then estimated to assess the regional brain activity associated with each condition, which can subsequently be compared. Statistical thresholding is finally used to account for spatial and temporal autocorrelations and the use of multiple tests.

10.3.2 Improvisation of melody and rhythm

In order to explore a regional difference in brain activity between melodic and rhythmic improvisation study III was designed as a two-by-two factorial design with the two factors Melodic Structure (Specified or Improvised) and Rhythmic Structure (Specified or Improvised). There were thus four active conditions where rhythm and melody were either notated, or unspecified with need for improvisation: Notes (Specified Melodic Structure, Specified Rhythmic Structure), Melody (Improvised Melodic Structure, Specified Rhythmic Structure), Rhythm (Improvised Rhythmic Structure, Specified Melodic Structure), and Free (Improvised Rhythmic Structure, Improvised Melodic Structure).

10.3.2.1 Analysis of behavioral data

In the analysis of behavioral data measures of the accuracy of the recorded piano performance in the different experimental conditions were computed. This was done by calculating the Levenshtein distance (LD) between a performed melody or rhythm and the corresponding target structure presented in the visual stimuli (Bengtsson, et al., 2007; Levenshtein, 1966). To investigate if the melodic accuracy differed between Notes and Rhythm, a repeated measures ANOVA was performed, using the participant median melodic LD as dependent variable. To test if the rhythmic accuracy differed between Notes and Melody, the corresponding test was performed using the median rhythmic LD.

Secondly, melodic and rhythmic complexity were estimated by calculating the binary melodic and rhythmic entropy of each trial. To determine if there were

differences in complexity between conditions, two-by-two factorial ANOVAs were employed. The median number of notes, melodic entropy or rhythmic entropy was used as dependent variable; Rhythmic Structure and Melodic Structure were used as factors, each with two levels (Specified and Improvised).

10.3.2.2 Analysis of fMRI data

In study III, a ROI analysis was used. A ROI analysis requires an a priori hypothesis about involved regions. In this analysis the pre-SMA and PMD were defined as ROIs, based on a hypothesis in Bengtsson (2007), postulating that the pre-SMA and PMD are predominantly involved in rhythmic and melodic processing, respectively.

The fMRI data were modeled using a general linear model, defined by four conditions of interest, corresponding to the periods in each epoch during which the participants played the piano (i.e. the last 17.5 s of the 22.5 s epochs); one regressor representing the preparatory periods (first 5 s of each epoch); and one regressor controlling for melodic entropy, as the analysis of behavioral data showed that melodic entropy was somewhat lower in Melody than in the other conditions (see Results). Rest was modeled as part of the implicit baseline.

The main effect in brain activity for Improvised Melodic Structure was investigated with the contrast (Free + Melody) – (Rhythm + Notes). The main effect for Improvised Rhythmic Structure was investigated with the contrast (Free + Rhythm) – (Melody + Notes). Interaction effects were explored with the two contrasts (Free + Notes) - (Rhythm + Melody) and (Rhythm + Melody) - (Free + Notes).

10.3.3 Improvisation and pseudorandom generation

The main purpose of data analysis in study IV was to compare free musical improvisation with the generation of pseudorandom key presses. To that end, the experimental paradigm consisted of three main conditions: production of pseudo-random key presses (Random), musical improvisation (Improvise) and a baseline sight-reading task (Notes). Each of these conditions was in different trials performed on 2, 6 or 12 keys. Thus, brain activity could be compared between the main conditions and in addition it was possible to explore if these conditions were parametrically modulated by the response space/number of keys played.

10.3.3.1 Analysis of behavioral data

The accuracy of the piano performance during the Notes conditions was computed in the same way as in study III, using the calculating the LD between the pitch sequences of the performed melody and the target melody presented in the visual stimuli.

Secondly, structural differences in output between the conditions were investigated, with the main aim to determine if the participants followed the instructions in the free generation conditions, i.e. if they produced a more "musical" output in Improvise than in Random. We selected mean interval size as a basic measure, since across musical cultures melodies tend to move in small intervals with few large leaps (Dowling and Harwood, 1986). Differences in interval size between conditions were tested with mean interval size of each trial as dependent variable and condition as within-participant independent variable in a repeated measures ANOVA. The Tukey HSD was used as post-hoc test.

10.3.3.2 Analysis of fMRI data

The fMRI data were modeled using a general linear model, defined by three conditions of interest, corresponding to the periods in each epoch during which the participants played the piano (i.e. the last 20 s of the 25 s epochs). For each of these three regressors there was an additional regressor which corresponded to the parametric modulation of effects associated with the number of keys played. Preparatory periods (the first 5 s of each epoch), which were of no interest in the present study, were represented by one separate regressor. Rest was not explicitly modeled in the design matrix, but made part of the implicit baseline.

The following contrasts were used: Improvise-Notes, Improvise-Random, Random-Notes and Random-Improvise. Parametric modulation of regional brain activity with regard to the number of keys used (2, 6, or 12), was also investigated for each of these contrasts.

11 SUMMARY, RESULTS AND BRIEF DISCUSSION

11.1 STUDY I

As reviewed in the introduction (see chapter 1), several lines of evidence support that dopaminergic neurotransmission plays a role in creative thought and behavior. Thus, in study I, the relationship between creative ability and dopamine D2 receptor expression was explored in healthy individuals, with a focus on regions where aberrations in dopaminergic function have previously been associated with psychotic symptoms and a genetic liability to schizophrenia. Scores on divergent thinking tests (Inventiveness battery, Berliner Intelligenz Struktur Test) were correlated with regional D2 receptor densities, as measured by Positron Emission Tomography, and the radioligands [^{11}C]raclopride and [^{11}C]FLB 457.

The results showed a negative correlation between divergent thinking scores and D2 density in the thalamus (r = 2.64, p = .013), also when controlling for age and general cognitive ability (see Figure 2).

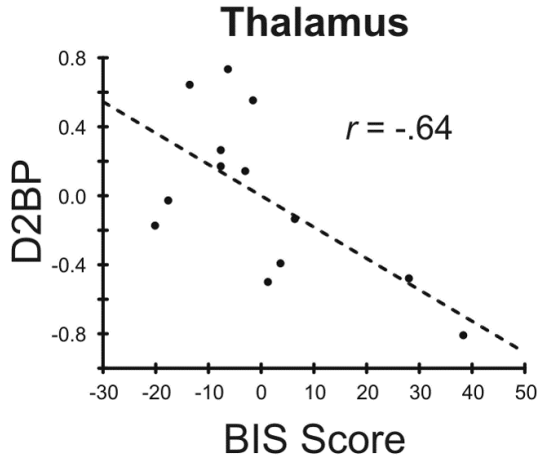

Figure 2. Correlation between thalamic D2 binding potential (D2BP) and divergent thinking (BIS score).

Hence, the results of study I demonstrate that the D2 receptor system, and specifically thalamic function, is important for creative performance, and may be one crucial link between creativity and psychopathology. Decreased D2 receptor densities in the thalamus may lower thalamic gating thresholds, thus increasing thalamocortical information flow. In healthy individuals, who do not suffer from the detrimental effects of psychiatric disease, this may increase performance on divergent thinking tests. In combination with the cognitive functions of higher order cortical networks, this could constitute a basis for the generative and selective processes that underlie real life creativity.

11.2 STUDY II

Expert performance is commonly accompanied by a subjective state of optimal experience called flow. Previous research has shown positive correlations between flow and quality of performance and suggests that flow may function as a reward signal that promotes practice. In study II, piano playing was used as a flow-inducing behavior in

order to analyze the relationship between subjective flow reports and psychophysiological measures. Study II introduces the notion that flow is the subjective experience of an interaction between positive valence and high attention during performance of a nontrivial task whose difficulty is on par with the skill level of the subject, which is facilitated by a certain level of expertise. Thus, same physiological response to flow was expected as predicted by these cognitive states. Flow was operationalized as the average self-reported magnitude across nine dimensions (Flow9D) (see section 5 – Flow and creativity). Based on the description of flow in terms of emotion, attention and expertise, an additional measure was created (Flow3D), which combined the average response on the dimensions challenge-skill balance, concentration, and autotelic, i.e. the three dimensions that arguably corresponds most directly to (task) expertise, attention, and emotional experience, respectively.

Professional classical pianists were asked to play a musical piece and then rate state flow. The performance was repeated five times in order to induce a variation in flow, keeping other factors constant, while recording the arterial pulse pressure waveform, respiration, head movements, and activity from the CS and ZM facial muscles. A significant relation was found between flow and heart period, blood pressure, heart rate variability, activity of the ZM muscle, and respiratory depth (see Table 1).

Table 1. Page Test Results: Physiological Measures vs. Flow Measures

		z_L	
Variable	*N*	*Flow9D*	*Flow3D*
EMG ZM	15	6.02^{***}	4.57^{***}
EMG CS	17	0.82	0.24
HP	19	1.90^{a*}	2.75^{a**}
FWHM	19	1.17^{a}	2.25^{a**}
MinP	19	1.58^{+}	2.89^{**}
MaxP	19	0.94^{a}	2.48^{a**}
MaxP-MinP	19	1.17^{a}	2.84^{a**}
RSA	17	2.35^{a**}	1.65^{a*}
LF/HF	19	1.67^{*}	1.79^{*}
Total power	19	2.32^{**}	2.29^{**}
RD	18	2.33^{**}	2.38^{**}
RR	18	0.33^{a}	1.34
Rcycle	18	0.38	0.82
Head Amp	14	0.69	1.07
Head Fq	14	0.59	0.37
Head RMS	14	0.27^{a}	0.86
Trial duration	21	0.70	0.26

Note: *N* = number of participants, z_L = page test statistic, EMG ZM = zygomaticus major activation, EMG CS = corrugator supercilii, HP = heart period, FWHM = full-width-half-maximum of the arterial pulse pressure waveform, MinP = minimum estimated blood pressure, MaxP = maximum estimated blood pressure, MaxP-MinP = estimated pulse pressure, RSA = respiratory sinus arrhythmia, LF/HF = low frequency heart rate variability/high frequency heart rate variability, Total power = total heart rate variability, RD = respiratory depth, RR = respiratory rate, Head Amp = head movement amplitude, Head Fq = head movement frequency, Head RMS = head movement root-mean-square.

$^{+}$ trend at $p \leq 0.06$; * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$

^{a} Signifies an inverse relationship between flow measure and physiological measure

The results confirm that flow manifests in physiological processes. Furthermore, the findings suggest that during a physically and cognitively demanding task, an increased activation of the sympathetic branch of the autonomic nervous system in combination with deep breathing and activation of the ZM might potentially be used as an indicator and flow. Flow appears to be a state of effortless attention, which arises through an interaction between positive affect and high attention.

11.3 STUDY III

Musical improvisation has been used previously as a model for studying the neural basis of creative cognition. A suggestion from an earlier study in the research group is that the PMDr, which has been consistently implicated in cognitive aspects of motor planning and selection of ordinal action sequences may have particular involvement in the generation of melodic sequences; whereas the pre-SMA, which shows increased activation during perception, learning and reproduction of temporal sequences, may contribute more to the generation of rhythmic structures. Study III tests this hypothesis. Brain activity during improvisation in professional pianists was measured using fMRI. Four experimental conditions were arranged in a two-by-two factorial design with two factors Melodic Structure (Specified/Improvised) and Rhythmic Structure (Notated/Improvised). Main effect contrasts for Melody and Rhythm were investigated using a ROI analysis for the pre-SMA and the PMDr. The ROI analysis partly confirmed our hypothesis: Melodic improvisation loaded more on the PMDr than did rhythmic improvisation; activity in the pre-SMA was, as predicted, related to rhythmic improvisation, but also active for melodic improvisation (see Figure 3, next page).

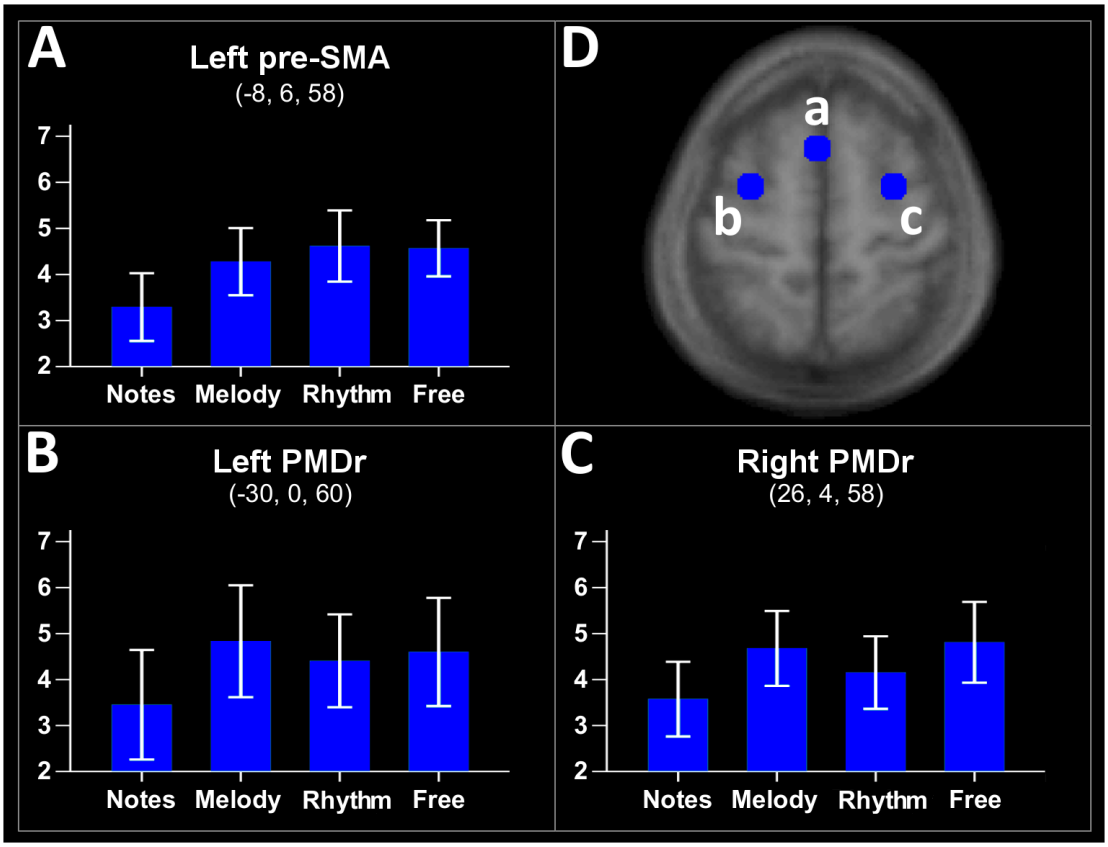

Figure 3. Fitted responses of active conditions in peak voxels reported in the main effects analysis (Melody and Rhythm). The bars illustrate the adjusted hemodynamic response (% signal change) for each condition relative the implicit baseline in one local peak voxel: Panel A – Left pre-SMA, in coordinates *x* = -8, *y* = 6 *z* = 58; Panel B – Left PMDr, in coordinates *x* = -30, *y* = 0 *z* = 60; Panel C – Right PMDr, in coordinates *x* = 26, *y* = 4 *z* = 58. Panel D displays the ROIs for the Left pre-SMA and bilateral PMDr, superimposed on the normalized group T1w image: a = Left pre-SMA, b = Left PMDr, c = Right PMDr. Error bars represent the spread of the data +/- 1 standard error.

Given that the PMD and pre-SMA are also involved in the perception and performance of music, the results additionally suggest that perception, performance, and free generation share neural mechanisms and underscores that the function of the premotor regions is highly flexible and dependent on task goals.

11.4 STUDY IV

Research on willed action has been criticized for not capturing the context of natural human volition. Study IV presents an fMRI paradigm aimed at contrasting free generation and selection in an experimental task to an ecologically valid example of willed action: musical improvisation. Professional classical pianists performed improvisation of melodies, pseudo-random key presses and sight-reading, using either two, six or twelve keys on a piano keyboard. When comparing the internal generation of melodies to the externally cued reproduction of musical scores, largely the same set of regions in the lateral, dorsolateral and medial prefrontal cortices were found, which have been identified using simpler models of willed action (see Figure 4). Improvisation did not activate any region over and above pseudo-random generation, which further demonstrates that creative behavior originates from similar cortical networks as other forms of volition; and that adding a musical context does not engage additional neural processing. Pseudo-random generation however, induced greater activity than improvisation in several cortical regions, which illustrates the complexity of this task and effect of expertise. Varying the response set did not alter brain activity,

which indicates that there is not a simple relationship between set-size and neural processing at the abstract level of motor planning.

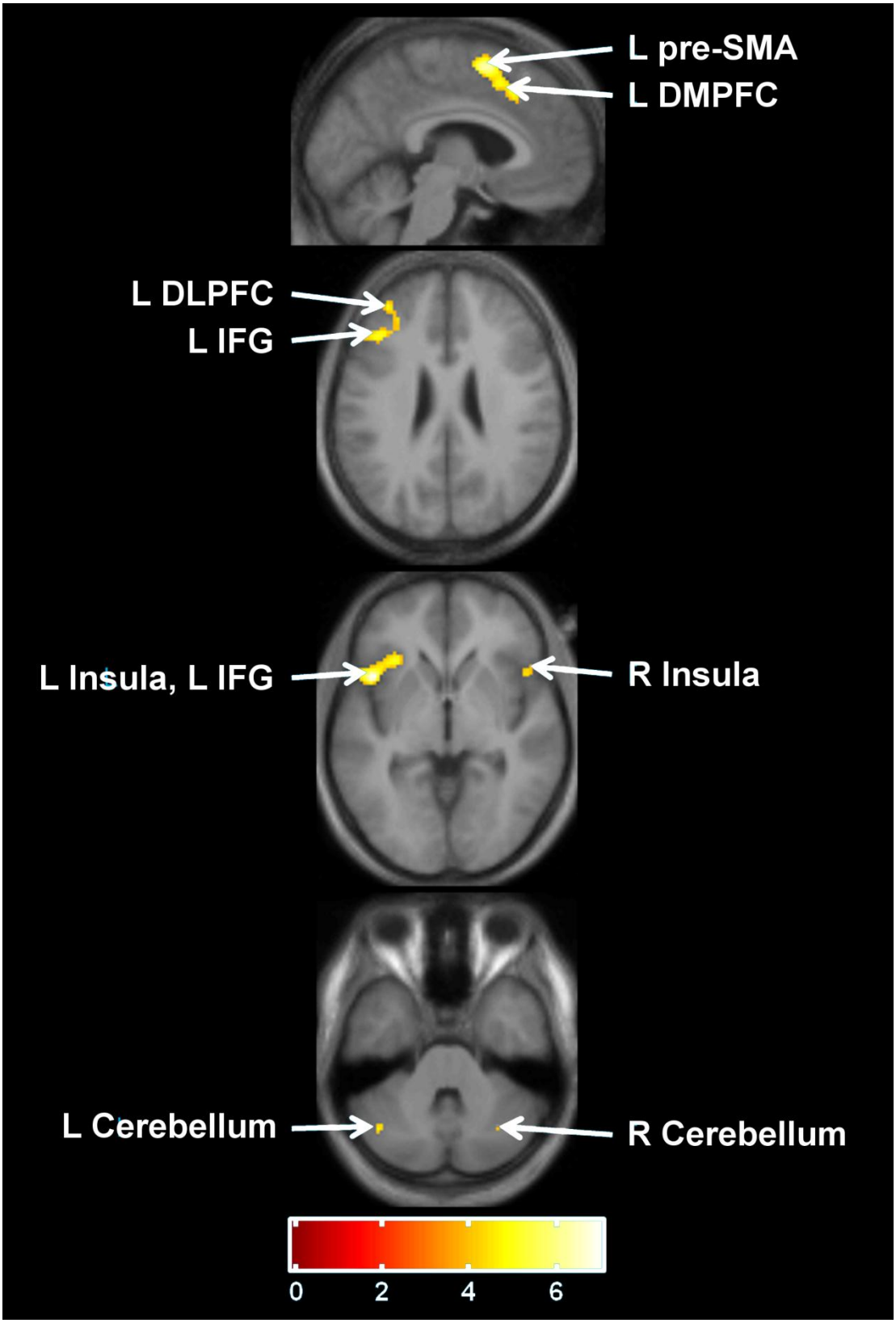

Figure 4. Brain activity associated with the internal generation of action sequences during both pseudorandom key presses and piano improvisation. The activity in a conjunction between the (Improvise – Notes) and (Random – Notes) contrasts is shown. DMPFC = dorsomedial prefrontal cortex, DLPFC = dorsolateral prefrontal cortex, IFG = inferior frontal gyrus, pre-SMA = pre-supplementary motor area. Color bar represents t-values.

12 GENERAL DISCUSSION AND REFLECTION

12.1 A BIOLOGICAL LINK BETWEEN CREATIVITY AND MENTAL ILLNESS

The main finding in the study I was a negative correlation between divergent thinking and D2BP in the thalamus. Decreased D2BP in the thalamus has been suggested, firstly, to be related to lower thalamic gating thresholds, resulting in decreased filtering and autoregulation of information flow (Yasuno, et al., 2004) and, secondly, to increase excitation of cortical regions through decreased inhibition of prefrontal pyramidal neurons (Seamans, Gorelova, Durstewitz, & Yang, 2001; Seamans & Yang, 2004; Trantham-Davidson, Neely, Lavin, & Seamans, 2004). The decreased prefrontal signal-to-noise ratio may place networks of cortical neurons in a more labile state, allowing them to more easily switch between representations and process multiple stimuli across a wider association range (Floresco & Magyar, 2006). Besides carrying benefits related to fluency and switching, the decreased signal-to-noise ratio should be disadvantageous in relation to tasks that require high levels of selective attention. Some support for this prediction can be taken from Dorfman (Dorfman, Martindale, Gassimova, & Vartanian, 2007) who showed that the greater a person's divergent thinking scores, the slower his or her reaction times were on a negative priming task requiring the inhibition of interfering information. Furthermore, this state may also bring a risk of excessive excitatory signals from the thalamus overwhelming cortical neurotransmission, with ensuing cognitive disorganization and positive symptoms (Takahashi, Higuchi, & Suhara, 2006). It is thus tempting to suggest that dopaminergic modulation of neurotransmission mediated through dopamine D2-receptors could be one of the mechanisms which associate creativity with positive psychotic symptoms. It can be speculated that aberrant thalamic function may promote unusual associations, as well as improved performance on divergent thinking tests in healthy individuals, in the absence of the detrimental effects typically associated with psychiatric disorders.

Study I received a lot of attention in the media when it was published, and it has earned a F1000 "Must read". What seems to have triggered the main interest was the suggested biological link between creativity and mental illness. Obviously, this makes a good story to read. Nonetheless, the study is particular, in that it brings together two separate neuroscientific fields: psychopathology and creativity. This was not necessarily the idea from the beginning of the project, but something which came out of digging deeper into the literature. If dopaminergic function is related to both mental illness and creativity, and there already exists a body of neuroscientific studies on dopamine and psychopathology, why not make use of that to find a specific hypothesis about dopamine and creativity? Thus, the study is also important because of the theoretical approach which was used.

12.2 THE PSYCHOPHYSIOLOGY OF FLOW

In study II, EMG, cardiovascular, and respiratory measures were all significantly associated with self-reported flow. Increased flow was related to decreased heart period and respiratory sinus arrhythmia, increased LF/HF ratio, total HRV power, and respiratory depth. This suggests that during a physically and cognitively demanding task, an increased activation of the sympathetic branch of the autonomic nervous

system in combination with deep breathing and activation of the *zygomaticus major* muscle might potentially be used as an indicator of effortless attention and flow. Furthermore the results suggest that flow is associated with an increased parasympathetic modulation of sympathetic activity. Nonreciprocal coactivation of the sympathetic and parasympathetic systems has been observed in relation to critical events that induce high workload and require active coping (Backs, Lenneman, & Sicard, 1999). Berntson, Cacioppo, and Quigley (1991) suggested that coactivation provides precise control of both the response direction and magnitude, as well as fine tuning of target organ function. It might therefore be interesting to consider flow as a feedback reward signal, which signifies optimal coping. This would also explain why flow is associated with high performance levels. It is interesting to note that a concomitant increase in parasympathetic tone to counter sympathetic activation has also been found to occur during attention demanding meditative states that are characterized by a combination of restfulness and heightened concentration (see, e.g. Ditto, Eclache, & Goldman, 2006; Kubota, et al., 2001).

Study II was in many ways a tricky project. Flow is to begin with a quite intangible concept and it was not clear how to arrive at a hypothesis about physiological correlates. While contemplating on the elements of flow, it was realized that some pertain to individual factors (e.g. concentration, enjoyment) while others were external prerequisites (e.g. clear feedback, clear goals). While assessing the individual factors more closely, the idea came to try to describe these dimensions, and thus explain flow, in terms of more established psychological constructs (emotion, attention and expertise). Hence, the notion is introduced that flow is the subjective experience of an interaction between positive valence and high attention during task performance, when task difficulty is matched with individual skills. Hopefully, this will prove to be a valuable theoretical and conceptual advancement, firstly because it makes flow a more concrete concept, and secondly, because it allows a hypothesis about biological correlates of flow, derived from studies on emotion and attention. Thus, study II, in much the same way as study I – presents a novel theoretical approach, in addition to the empirical findings.

The initial experimental paradigm in study II consisted of two musical tasks which were expected to induce different levels of flow. However, this was not considered optimal, since differences in motor output could have confounded results. Realizing that repetitions of the same musical piece would probably also induce a variation in flow, while essentially controlling for all sensorimotor output was a breakthrough in the development of the experimental design. Another issue was how to preprocess and analyze the arterial pulse pressure data. Firstly, in the absence of a golden standard, the methods had to be developed in house. Secondly, with regard to analysis, many previous studies pooled data across subjects. This is obviously problematic, since between-subject baseline differences might then confound results. Thirdly, it cannot be taken for granted a certain magnitude of change in flow, gives the same magnitude of physiological response in all participants. Fourth, even though the flow questionnaire is using a Likert scale, there is no empirical evidence to show that participants judge the steps on this scale to be equal, i.e. the difference between e.g. 2-3 might be perceived differently from 4-5. Hence, it was critical to find a suitable statistical test. This was a time-consuming process, but after massive interrogations of the teaching staff at a statistical course, the Page Test for Ordered Alternatives was proposed, which does accommodate all the above points. Thus, the study could be finalized as the first peer-

reviewed study to show that the subjective flow state is linked to biological mechanisms in the human body.

12.3 MUSICAL CREATIVITY

Study III and IV were both aimed at elucidating the neural mechanisms of musical creativity using fMRI. The findings from the studies corroborate one another by largely identifying the same network of regions, including the pre-SMA, PMD, DLPFC, ACC, IFG, and cerebellum, to be involved in the free generation of musical structures.

Study III partly confirms the hypothesis stated by Bengtsson and colleagues (Bengtsson, et al., 2007); that the PMDr has a particular involvement in the generation of melodic sequences; whereas the preSMA contributes more to the generation of rhythmic structures. These findings are of interest, in that they suggest that at the level of the rostral premotor areas, free generation of music may utilize neural circuitry that is also used for perception, learning and production of the same type of structures, i.e. that the same neural representations – e.g. of sequential structures – can be used, parsimoniously, for both processing of sensory input and programming of movement, depending on task context. The findings in study III suggest that this functional versatility of the premotor areas should be extended to include free generation in the context of creative performance.

The overlap in neural correlates underscores that the improvisation of the rhythmic and melodic structure of a tune are highly integrated processes. Indeed, if a particular musical goal should be fulfilled, these aspects of a tune can obviously not be generated independently: the emotional character of a tune is determined by a complex interplay between these, and other, musical parameters (Gabrielsson & Lindström, 2001). The high degree of melody-rhythm integration in higher order musical processes such as improvisation fits a general, modular view of music processing in the brain, where temporal and spatial/melodic processing are separated at lower levels of perception and production but integrated in superordinate brain regions (Peretz & Coltheart, 2003). Presumably, in this context, the medial and lateral premotor regions are important for the representation of more abstract musical goals of the improvisation and the implementation of an overall action plan (Bengtsson, Csíkszentmihályi, & UIlén, 2007).

In study IV, brain activity during piano improvisations was compared to that during a pseudo-random generation task. The results suggest that a lot of the neural machinery underlying diverse free generation tasks, in different modalities and with different overall goals, may be common. However, it obviously remains possible that some of the regions found active in the conjunction contain spatially segregated circuits for processing in musical and non-musical contexts, which could not be distinguished due to the limited resolution of functional MRI. Nevertheless, the findings in study IV suggest that the network of regions which is illustrated in study III and IV can control both musical improvisation as well as non-musical generation tasks.

The difference in activity between pseudo-random generation and musical improvisation may have several explanations. Music is a human cultural universal, and the human brain is probably evolutionarily adapted to process music (Wallin, Merker, & Brown, 2000). Perhaps more importantly, the participants were expert musicians with many years of musical training. The high activity during pseudorandom generation in fronto-parietal networks could reflect that this behavior, far from being a

simple model of free choice, is a complex and novel task with high demands on attention, planning, working memory, and executive functions. During musical improvisation, in contrast, the load on prefrontal networks for superordinate control was lower, presumably since the participants could rely on highly automatized auditory-motor skills relevant for music performance. In line with this, studies have demonstrated that professional musicians show less activity in premotor and prefrontal regions during performance of musical tasks than do non-musicians (Bengtsson & Ullén, 2006; Jäncke, Loose, Lutz, Specht, & Shah, 2000).

No region was found in which brain activity was differentially modulated by the number of allowed notes. This was unexpected given that other studies have found activity in the DLPFC to vary with number of available responses in verbal generation tasks (Desmond, et al., 1998; Nathaniel-James & Frith, 2002). One explanation for the negative finding in the present study could be related to the expertise of the subjects. The six and twelve key conditions might have been represented by the pianists as a (truncated) F-major scale and a full chromatic scale, respectively. If such strategies were employed, there was no need to maintain online a specific set of responses and there would accordingly be no relation between number of available notes and brain activity level.

To further introduce the regions part of the 'musical creativity network', the DLPFC, which serves a central role in planning and performance of novel or complex behavioral sequences, including language and thought, has been attributed a great number of functions, such as attention to action, monitoring in working memory, response selection, and suppression of stereotype responses (Desmond, et al., 1998; Lau, et al., 2004; Nathaniel-James & Frith, 2002), by exerting top-down influences on subordinate premotor areas. All of these functions would be relevant to free improvisation. The IFG could conceivably be involved in several cognitive processes related to the creation of musical phrases, e.g. retrieval and selection of semantic information from long-term memory (Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Moss, et al., 2005), rule maintenance (Bunge, et al., 2005), and sequential control in general (Schubotz & von Cramon, 2004) including syntax processing (Minati, et al., 2008). The involvement of IFG, which is traditionally considered to be part of the language network, underscores the close relation between language and music, in that the two presumably share neural correlates also in generative tasks (Brown, et al., 2006). The ACC is known to activate during free choice paradigms and internal selection of behavioral goals (Mueller, Brass, Waszak, & Prinz, 2007), as well as in tasks requiring attention to spatial targeting (Isomura, Ito, Akazawa, Nambu, & Takada, 2003) and conflict monitoring (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999). Mueller (2007) suggested, based on findings supporting that the ACC is more active when behavioral goals are internally generated than when they are externally cued, that the ACC may play a particular role in action-effect anticipation. This function might be of particular importance for improvisation, during which, novel and appropriate responses must be rapidly and accurately selected from a continuous stream of information resulting from free association, to fit a musical context and to obtain an overall aesthetic goal. The cerebellum is highly important for sensorimotor adaptation and explicit timing of motor output (Spencer, Zelaznik, Diedrichsen, & Ivry, 2003). The results show that free improvisation, in contrast to sight-reading, induce activity in the lateral areas of the cerebellum, which are known to

participate in movement planning and cognitive aspects of motor performance (Hülsmann, Erb, & Grodd, 2003).

Both study III and IV provide systematic contributions to the understanding of the functional anatomy of musical creativity. In contrast to study I and II, the theoretical background and methodology used in these studies are more ‘mature’ and closer to what is found in mainstream neuroscientific literature. Most issues which had to be resolved during the process of conducting these studies were of a technical or administrative nature.

13 FUTURE DIRECTIONS

All of the studies in this thesis are each but one step on the way towards unraveling the biological mechanisms of creativity. However, each study has provided valuable clues that motivate further research. Study I, in which an association between divergent thinking and D2BP in the thalamus was demonstrated, gives rise to several new research topics in creativity research. Firstly, we need to better describe the functions of dopamine D2 receptors and the mechanisms through which D2 receptor density modulates creative thinking. Secondly, as described in the introduction (), both personality traits and environmental influences which are somehow linked to creativity, also appear to be related to dopaminergic function. Potentially, research on dopamine and creativity may partly unite the hitherto different strands of research on individual and environmental influences on creative function. Thus, the research should be expanded to include such factors as well.

Study II, is the first peer-reviewed study to show that flow may manifest in physiological functions. Given this finding, it is a natural step to investigate how flow manifests in neural processes. Such research may come to illustrate how flow influences creative thinking.

In study III, the findings suggest that similar regions are involved in both perception and production as well as in free generation of musical structures. How these regions may shift between externally cued and internally generated processing is however still unknown and further investigations are required to determine what regulatory processes are involved in this functional switching.

In study IV, in which brain activity during musical improvisation was compared to that during pseudo-random key-presses on a piano keyboard, it was shown that the pseudo-random task activated the brain to a much greater extent. Musical improvisation did however not activate any region to a greater degree than pseudo-random generation. Future research should further investigate the significance of using ecologically valid tasks to study creativity. Musical improvisation should also be compared to other ecologically valid creative behaviors. Moreover, the relationship between expertise and creativity has still not been studied using neuroscientific methods.

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