Metacontrol in the brain: investigating neural mechanisms of persistence and flexibility states during meditation and creative thinking using EEG and fMRI techniques

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Chapter 1

General Introduction

INTRODUCTION

Assume you have just landed on Mars. Survival on this alien planet poses numerous new challenges, and the Martian environment differs significantly from Earth's, presenting you with unprecedented problems. In the face of this new environment and its unique challenges, what would you do?

Would you firstly try to concentrate on the knowledge which you already have to solve the problems? What if your knowledge and approach are insufficient? Maybe you would open your eyes and mind to explore new information? Once you have gathered a lot of information, you may come back to focus on the problem and see if you can solve it. Through repeated transitions between focusing on the problem and opening to information, you might suddenly experience a moment of insight, leading you to discover a final solution.

Human survival and societal continuity both revolve around the continuous adaptation to new environments and the resolution of novel problems. For this, human beings have developed different cognitive and neural mechanisms of cognitive control to adapt between a more focused or persistent state to face the problem and a more open and flexible state to collect new information. This ability which regulates different cognitive control states, especially persistence vs. flexibility, has been named metacontrol (Hommel, 2015)

It seems that metacontrol most commonly comes into play when facing a new problem and utilizing creativity to solve it. Interestingly, creative thinking has two core components which are related to metacontrol, namely convergent thinking and divergent thinking (Hommel, 2015; W. Zhang et al., 2020). Convergent thinking is a type of thinking to find the only correct solution for a well-defined problem, which requires focus or persistence (Cropley, 2010; Guilford, 1956). Divergent thinking allows for generating multiple ideas without clear criteria for right and wrong, which requires openness and flexibility (Guilford, 1956; Runco, 2010;

Runco & Yoruk, 2014). Therefore, on Mars your creative problem-solving for your new life seems to need both convergent and divergent thinking, and thus, this would also involve both flexibility and persistence metacontrol states.

Persistence and flexibility, as different types of cognitive states, could be influenced or altered by different factors, such as meditation. Interestingly, there are also two types of meditation that are likely metacontrol-related, which are focused-attention meditation (FAM) and open monitoring meditation (OMM). FAM calls for sustaining selective attention on a specific object with a fairly narrow focus, which implies persistence, while OMM calls for attentive monitoring of anything that occurs in experience, which implies flexibility (Hommel & Colzato, 2017a; Lutz et al., 2008). In order to enhance your ability of metacontrol living on Mars, it would be useful for you to learn how to meditate, how to enhance your persistence using FAM when you need to focus on the problem, and how to enhance your flexibility using OMM when you need to collect information. Importantly, you need to learn how to quickly adapt between the two metacontrol states because there is not only one problem on Mars waiting for you.

After you have settled on Mars, it is time for you to select some people from earth to come to Mars to help you, and you want them to be good at both persistence and flexibility, or have good performances on both convergent and divergent thinking tests, which might indicate adaptability to a new environment.

This dissertation will serve as a preliminary exploration of the neurocognitive mechanisms of metacontrol. First, I studied the neural mechanisms of the metacontrol states (persistence vs. flexibility) induced by different types of creative thinking (convergent thinking vs. divergent thinking) and meditation (FAM vs. OMM). Second, I validated a test for convergent and divergent thinking as an indicator for adaptivity of metacontrol.

To better comprehend the neural mechanisms of a phenomenon, common brain research methods such EEG (electroencephalography) and fMRI (functional magnetic resonance imaging) have been employed. EEG offers high temporal resolution, providing valuable insights into the brain's temporal processes, while fMRI offers excellent spatial resolution, allowing for the detailed analysis of specific brain regions. In this dissertation I used both EEG and fMRI methods to investigate the neural mechanism of the metacontrol states.

In the next section, I will provide a detailed introduction to the definition of metacontrol and its relationship with creativity and meditation, as well as potential neural mechanisms. I will also outline the specific research objectives of all the chapters in this dissertation. Notably, the story of Mars, which serves as a clue to help the reader quickly understand and apply the content of this dissertation, will only be mentioned again at the end of this document.

What is Metacontrol?

To explain metacontrol, the concept of cognitive control needs to be understood first. Cognitive control, also known as executive function, is the process by which goals or plans influence behavior. This process can inhibit automatic responses and affect working memory. Cognitive control enables us to respond flexibly and adaptively to goals and engage in complex, goal-directed thinking (Diamond, 2013). Research on cognitive control encompasses various cognitive processes such as attentional control, cognitive inhibition, inhibitory control, working memory, and cognitive flexibility (Diamond, 2013). However, in recent decades, psychological research has largely focused on these control processes themselves, such as maintaining goals and suppressing interference in tasks like the Stroop test (Posner & Snyder, 2004) or flexibly switching between two simple tasks (e.g., categorizing numbers vs. letters) (Arrington & Logan, 2004). Yet, there has been little attention to how we control cognitive control itself, which is known as metacontrol.

In general, metacontrol is defined as a subset of control mechanisms responsible for the monitoring and regulation of cognitive control itself (Eppinger et al., 2021). For example, one type of metacontrol process is cognitive stability or persistence which is to maintain attention on a specific goal or some mental representations. Another is cognitive flexibility, allowing attention to switch between different goals or mental representations. The concept of metacontrol is crucial because the external environment is constantly changing, and different situations or contexts require different states of cognitive control. Moreover, some cognitive control states may be antagonistic or contradictory, with varying effects on adapting to the current environment, such as stability versus flexibility. For instance, when faced with new challenges in the environment, if the goal for addressing these challenges is clear, individuals tend to enter a stable or goal-maintenance state to tackle the issues. However, when the environment or goals change, flexibility becomes crucial for adaptation. To describe the regulation of the metacontrol states between persistence versus flexibility, the Metacontrol States Model (MSM) has been proposed (Hommel, 2015; Hommel & Wiers, 2017). The MSM is based on the widely accepted scenario that multiple goal-related representations compete for selection according to a winner-takes-all principle, so that increasing the activation of one alternative reduces the activation of others (Bogacz, 2007). However, in the MSM, the degree to which alternatives compete and to which they are biased by the current goal is determined by the present metacontrol state, which varies between persistence and flexibility. Extreme persistence would consist of (1) strong mutual competition between alternatives and (2) strong top-down bias towards certain alternatives, whereas extreme flexibility would consist of (1) weak competition and (2) weak top-down bias allowing flexible switching between alternatives (Hommel, 2015).

From an evolutionary or adaptive perspective, persistence and flexibility might address two specific types of situations related to environmental changes and problem solving: (1) In situations where problems and goals are clearly defined based on the environment, information processing or decision-making is carried out to achieve specific objectives or solve specific problems. In this scenario, the goals have a significant top-down influence on information processing, with information more relevant to the goals being weighted more heavily, while irrelevant information is inhibited. This is similar to cognitive processes such as goal maintenance and distraction inhibition. This situation is suitable for a persistence state, as excessive flexibility may hinder problem-solving efficiency due to interference from irrelevant information. (2) When the environment changes, leading to unclear problems and goals based on the new environment, information processing occurs. On one hand, it is necessary to clarify goals and problems; on the other hand, information gathering is needed based on goals and problems that are not yet clear. Thus, both the goals and problems, as well as their related information, are subject to change. Therefore, strong cognitive flexibility is required. In this scenario, a flexibility state is appropriate, as excessive persistence may result in spending too much time on incorrect goals and problems, thereby affecting problem-solving efficiency.

As distinct and opposing cognitive control states, persistence and flexibility are likely to involve different neural mechanisms, particularly related to dopamine modulation and its interaction with the prefrontal cortex (PFC) and basal ganglia (BG). Dopamine binds to five different dopamine receptors, which fall into two main receptor types: the dopamine D1 receptor family (D1R) with subtypes D1 and D5, and the dopamine D2 receptor family with subtypes D2, D3, and D4. In the PFC, D1Rs are expressed in all cortical layers and are approximately 10-fold more abundant than D2Rs (Ott & Nieder, 2019). The dual-state theory (Durstewitz & Seamans, 2008) proposes that in a D1R-dominated state, dopamine stabilizes prefrontal representations by increasing sustained responses during working memory (Durstewitz et al., 2000; Durstewitz & Seamans, 2002), which is likely associated with persistence. In contrast, a D2R-dominated state renders prefrontal representations unstable, thus enabling switching between representations (flexible state) via a D2R mechanism, which is opposite to D1R (Durstewitz & Seamans, 2008). Additionally, dopamine synthesized in the midbrain can transmit not only to the PFC (through the mesocortical pathway) but also to the striatum, which is a part of the BG (through the nigrostriatal pathway), and the D2Rs are omnipresent in the striatum (Beaulieu & Gainetdinov, 2011; Gallo, 2019). Accumulating evidence reveals that striatal dopamine plays a key role in attentional gating or shifting in response to unexpected and behaviorally important stimuli (Cools & D'Esposito, 2011; van Schouwenburg et al., 2010), which could be associated with flexibility. Furthermore, dopamine is thought to modulate its balance in the PFC and striatum to manage the trade-off between cognitive stability and flexibility through a so-called fronto-striatal circuit (McNab & Klingberg, 2008), and neuroimaging studies have also demonstrated that brain activation in the dorsolateral PFC (DLPFC) is related to working memory and information maintenance (Andrews et al., 2011) which are associated with persistence, while brain activation in the BG is related to task switching (Yehene et al., 2008) which is associated with cognitive flexibility. These neural mechanisms above could potentially underlie stability/persistence and flexibility, but remain unclear. Notably, in this dissertation we did not derive dopamine as the cause from the conclusions of fMRI; rather, it is because previous research has indicated that stability and flexibility are related to dopamine and its associated brain regions. Therefore, we aimed to verify whether persistence and flexibility are also related to these two brain regions.

Creativity and Metacontrol

Creativity is a complex and elusive phenomenon that has been the subject of research since around the 1950s (Guilford, 1956), spanning over 70 years. Despite this extensive duration of study, there is still no comprehensive understanding of it. However, researchers currently hold some consensus: Firstly, concerning its outcomes, creativity is defined as the ability to produce novel and useful products (Runco & Jaeger, 2012). Secondly, regarding its processes, creativity involves dual processes (Kleinmintz et al., 2019; Nijstad et al., 2010), which are frequently mentioned in various aspects of creative research. For instance, engaging in creative activities involves both idea generation and idea evaluation (Kleinmintz et al., 2019). The creative thinking process encompasses divergent and convergent thinking (Cropley, 2010; Jones & Estes, 2015). Additionally, a mysterious and unique phenomenon known as insight is crucial in creativity, wherein answers spontaneously emerge during problem-solving, accompanied by a strong sense of certainty and joy (Kounios & Beeman, 2014). There has been significant controversy surrounding how to accurately measure creativity. Currently, the Torrance Tests of Creative Thinking (TTCT) are widely accepted and used (Said-Metwaly et al., 2019). Various tests tailored to different aspects of creativity exist, such as the alternative uses task for measuring divergent thinking (Runco & Yoruk, 2014), remote associates tasks for measuring remote associative ability (Cropley, 2010), and insight problems(Luo & Niki, 2003), among others. According to recent research progress, the cognitive framework of creativity comprises three important cognitive factors: attention, memory, and cognitive control (Benedek & Fink, 2019). Among these, cognitive control is particularly relevant to the research topic of this paper. In creative problem-solving, flexible mental set shifting and persistent goal-oriented processes are equally important(Nagy et al., 2023), which are highly relevant to metacontrol flexibility and persistence. There are two core components related to creative thinking: divergent thinking requires more flexibility, while convergent thinking requires more persistence (Hommel, 2015).

Divergent thinking (DT) represents a style of thinking that allows idea generation, in a context where the selection criteria are relatively vague and more than one solution is correct—which has been taken to require cognitive flexibility (Hommel, 2015; W. Zhang et al., 2020). In contrast, convergent thinking (CT) represents a style of thinking that allows finding a single solution to a well-defined problem, which requires persistence and focus (Cropley, 2010; Guilford, 1967).

The prototypical convergent thinking task is the Remote Associates Task (RAT; Mednick, 1968), in which the participant needs to find the only correct common association (e.g., "party") of three presented, otherwise unrelated words (e.g., "cocktail, dress, birthday"). Even though the RAT does need some degree of flexibility in searching through memory for possible solutions, the task requires various processes that rely on persistence: potential answers being generated need to be monitored continuously and evaluated immediately (higher top-down bias); and evaluating one potential answer is likely to inhibit other answers (higher competition). Accordingly, it comes without surprise that engaging in RAT increases goal-related impact and reduces crosstalk in dual-task performance (Fischer & Hommel, 2012).

The prototypical divergent thinking task, in turn, is the Alternative Uses Task (AUT; Guilford, 1967), in which the participant is presented with a common object (e.g., brick) and required to generate as many novel uses of this object as possible. Since there is not just one correct answer in the AUT, the ideas being generated are influenced less by monitoring and evaluating processes (lower top-down bias) and have lower competition between each other, which are the characteristics defined by metacontrol flexibility (Hommel, 2015). Previous studies have found that engaging in AUT can induce positive mood (Akbari Chermahini & Hommel, 2012), and AUT performance is related to the spontaneous eyeblink rate, a marker of striatal dopamine (Akbari Chermahini & Hommel, 2010), which associates the AUT with flexibility.

Therefore, the AUT and RAT tapping on divergent and convergent thinking, respectively (Guilford, 1956), are thought to induce or rely on different metacontrol states (Akbari Chermahini & Hommel, 2012a, 2012b; Colzato et al., 2012; Fischer & Hommel, 2012). Although there are other tests for measuring divergent and convergent thinking, the Remote Associates Test (RAT) and Alternative Uses Task (AUT) have been empirically demonstrated to be associated with persistence and flexibility, which is why we chose these two tests.

As a complex psychological phenomenon, creativity involves intricate brain activity, implicating numerous brain regions. Although creativity tasks involve executive functions, leading to relatively active prefrontal cortex (PFC), particularly the inferior frontal gyrus (IFG) (Kounios & Beeman, 2014; Runco & Yoruk, 2014), divergent thinking or mental wandering plays a crucial role in creative problem-solving, and it is associated with increased alpha power and activation of the default mode network (DMN) (Beaty et al., 2015). If inducing persistence and flexibility states by manipulating creativity is considered, we expect to observe the aforementioned relevant brain activities.

Meditation and Metacontrol

Meditation has existed for at least 2500 years, originating from religious traditions, each with its own methods and purposes (West, 2016). However, from a modern perspective, meditation is defined as a series of practices related to the integration of mind and body, aimed at increasing awareness of the present moment and self-control, as well as enhancing emotional stability and well-being (Tang et al., 2015). Particularly, with the development of modern psychology, meditation is increasingly used to promote psychological well-being and improving mental problems, such as anxiety (Woodruff et al., 2014), post-traumatic stress disorder (Wahbeh, 2014), chronic illness (Pagnini et al., 2014), eating disorders (Kristeller & Epel, 2014), and stress (Crum & Lyddy, 2014). Common meditation practices include mindfulness meditations (Wielgosz et al., 2019), mantra meditations (Álvarez-Pérez et al., 2022), movement meditations (Payne & Crane-Godreau, 2013), loving-kindness meditations (Hofmann et al., 2011), and many others. Among the meditation practices, mindfulness is gaining more popularity in modern research and practice. Mindfulness meditation is defined as "paying attention with purpose, non-judgmentally, and while in the present moment" (Kabat-Zinn, 2005). This mindful practice comprises four elements: (1) Awareness of all possible experiences such as sensations in the body, thoughts, emotions, sights, and sounds. (2)

Sustained attention. (3) Focus on the present moment. (4) Non-judgmental acceptance—this involves not making judgments about experience (West, 2016). Based on these elements, mindfulness practices can be categorized into two main types: Focused Attention Meditation (FAM) and Open Monitoring Meditation (OMM) (Lutz et al., 2008), which may be related to the metacontrol states under investigation in our study (Hommel & Colzato, 2017a).

FAM typically calls for sustaining selective attention moment-by-moment on a specific object with a fairly narrow focus, which implies persistence, while OMM calls for the attentive monitoring of anything that occurs in experience without focusing on any explicit object (Hommel & Colzato, 2017a; Lutz et al., 2008), which implies flexibility. Interestingly for present purposes, FAM and OMM have been found to facilitate RAT and AUT performance, respectively (Colzato et al., 2012, 2014).

Studying the neural mechanisms of the metacontrol states induced by creativity tasks and meditation

Although it appears that the mentioned creativity tasks (RAT vs. AUT) and the meditation techniques (FAM vs. OMM) are related to persistence and flexibility, the degree of their relationship and whether they can truly induce the state still requires further discussion. Below, we will link these concepts in a more specific manner: First, the Metacontrol States Model (MSM) describes a situation of general decision-making, in which multiple alternatives compete for selection biased by the current goal. In this situation, the differences between persistence and flexibility are characterized by their different levels of (1) top-down control to alternatives biased by the goal and (2) competition between different alternatives. In the persistence state, certain goal-relevant and competitive alternatives are held for selection biased by the goal, while irrelevant alternatives are inhibited, and switching to another alternative is difficult. In the flexibility state, the top-down impact from the goal is weak, which might be because the task requirement is easy or vague. Therefore, while certain alternatives are held for selection, other alternatives are not strongly inhibited, and switching between different alternatives is easy. Based on the above, the creativity tasks and the metacontrol states will be discussed as follows: the RAT has a clearly defined problem, that is, to come up with a word that matches with three other words, and there is only one correct answer, so the goal has a strong impact on alternatives, and the more relevant the alternatives are to the question, the more they will be valued, and the less relevant they are, the more they will be strongly inhibited. The problem of AUT does not have a single correct answer, that is, to come up with a novel use for a common object, and the participants can freely imagine ideas related to their own lives, because the task requirements do not explicitly limit the categories. Therefore, the current goal has little influence on different alternatives, and after the participants come up with an idea, they will immediately think of another idea, and there is little mutual inhibition between various alternatives. Secondly, regarding the meditation techniques, the goal of FAM is to focus attention on the breath and inhibit other internal and external thoughts and stimuli, so the breath as a competing alternative will be strongly biased by the goal, and other alternatives will be inhibited. In the OMM, the goal is to focus on the present moment, being aware of everything entering consciousness, but not being completely occupied by any one thought or stimulus, so there will be no specific alternative strongly held by the goal's influence and no other alternatives strongly inhibited. Therefore, if we look at the specific situations described by MSM, the selected creativity tasks and meditation techniques are highly consistent with the definitions of persistence and flexibility states. Although these creativity tasks and meditation techniques have differences in other aspects, based on previous theoretical and empirical research, they are relatively effective manipulations for studying persistence and flexibility states.

Considering the connections between the metacontrol states and the processes of creativity and meditation, it thus makes sense to assume that during RAT and FAM, the brain would be more likely to establish a state of persistence, while during AUT and OMM, it would be more likely to establish a state of flexibility. Therefore, we thought that comparing the brain activity while performing the RAT vs. AUT and comparing the brain activity while engaging in FAM vs. OMM, could help reveal the neural mechanisms underlying the metacontrol states of persistence and flexibility.

OUTLINE OF THIS DISSERTATION

As shown in Figure 1, the primary focus of this dissertation is to investigate the neural mechanisms of metacontrol states, specifically of persistence and flexibility (Fig. 1A). These metacontrol states can be induced by various creativity tasks (RAT and AUT), as well as different meditation types (FAM and OMM) (Fig. 1B). Furthermore, these states are believed to be related to specific brain regions modulated by frontal and striatal dopamine (Fig. 1C).

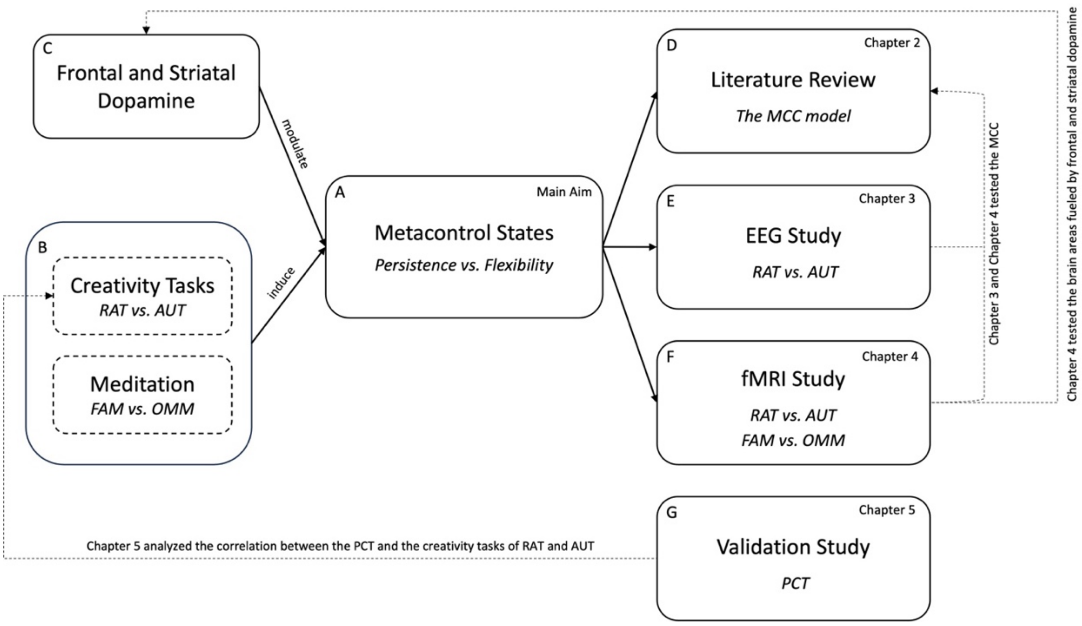

Fig.1 The structure of this dissertation

To understand the neural mechanisms of metacontrol, Chapter 2 (Fig. 1D) provides a comprehensive review of previous behavioral and neuroscientific studies related to convergent and divergent thinking. Based on the review, Chapter 2 proposed a neurocognitive framework, namely Meta-Control of Creativity (MCC) model, to describe how metacontrol biases in creativity tasks might be reflected by task-specific activation patterns of different brain areas.

In Chapter 3 (Fig. 1E), we employed the EEG technique and compared alpha activities between the RAT and AUT, which are thought to induce persistence and flexibility states, respectively, to investigate the neural mechanisms of metacontrol. Furthermore, we examined some predictions from the MCC model, which are suitable for the EEG methods.

Chapter 4 (Fig. 1F) involves using the fMRI technique to compare the metacontrol states (persistence vs. flexibility) induced by creativity tasks (RAT vs. AUT) and mediation (FAM vs. OMM). This study also attempted to explore potential overlaps in brain activation between creativity and meditation for finding common mechanisms of metacontrol. Furthermore, this study also examined the brain areas that are thought to be fueled by frontal and striatal dopamine, which are in turn hypothesized to be associated with persistence and flexibility. We as well examined the brain areas predicted by the MCC model.

Chapter 5 (Fig. 1G) is a validation study, in which we analyzed the Picture Concept Task, a creativity test for convergent and divergent thinking, which has been used in previous studies but has never been validated. Because this test was originally designed to measure fluid intelligence and was later applied to creativity, we did not expect it to be a good creativity test.

Finally, Chapter 6 serves as the concluding section of the dissertation. It summarizes and connects the findings from all the chapters, providing a comprehensive discussion of the neural mechanisms underlying the metacontrol states.