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 6

General Discussion

The primary objective of this dissertation was to investigate the neural mechanisms underlying the metacontrol states of persistence and flexibility. In this general discussion section, the findings of each chapter will be summarized, and efforts will be made to establish connections between these findings to answer the research questions concerning the neural mechanisms of metacontrol states.

SUMMARY OF THE MAIN FINDINGS

Chapter 2 provided a comprehensive review of previous behavioural and neuroscientific research on convergent thinking (CT) and divergent thinking (DT) and proposed a neurocognitive framework of metacontrol of creative cognition, namely Meta-Control of Creativity (MCC) model, which proposes that creative cognition in divergent- and convergent-thinking heavy tasks is modulated by metacontrol states, where divergent thinking and insight solutions in convergent-thinking tasks seem to benefit from metacontrol biases towards flexibility, whereas convergent, analytical thinking seems to benefit from metacontrol biases towards persistence. These particular biases seem to be reflected by specific cortical brain-activation patterns, involving left dorsolateral prefrontal cortex (DLPFC), left inferior frontal cortex (lIFG) and right temporal/parietal networks (T/PC), especially right superior temporal gyrus (STG) and right posterior parietal gyrus (PPC). Specifically, flexibility in creative cognition is promoted by weak activation of the left DLPFC and right T/PC together with a strongly activated left IFG, whereas persistence would be characterized by the opposite pattern.

In Chapter 3, EEG technology was utilized to compare the task-related power changes in alpha band during the idea generation phase (2 seconds before responding) in the Remote Associates Task (RAT) and the Alternative Uses Task (AUT) to investigate the neural mechanisms of metacontrol, and the MCC model proposed in Chapter 2 was also examined. Because the three brain areas proposed by the MCC model were summarized from various EEG and fMRI studies, we mainly examined the predictions from the MCC that are suitable for EEG. Specifically, we expected the right T/PC would show higher alpha synchronization during AUT than RAT, and the right STG would show a decrease in alpha power in the process of insight, which is consistent with our findings. In general, we also found AUT was associated with higher alpha power than RAT throughout the entire brain, suggesting different levels of top-down control and competition between ideas, as implied by the assumption of task-specific metacontrol states. Additionally, we found that insight solutions, but not non-insight solutions, were positively correlated with AUT scores, suggesting that insight is closely associated with flexibility. However, this association was not unequivocally supported by other EEG results. Taken together, Chapter 3 provides first evidence in favor of the MCC, even though the neural underpinnings of the difference between insight and non-insight trials need more clarification.

In Chapter 4, we employed fMRI technique to investigate the neural mechanisms of metacontrol induced by creativity tasks (RAT vs. AUT) and meditation (FAM vs. OMM). The brain areas fueled by frontal and striatal dopamine (which are thought to relate persistence and flexibility, respectively) and proposed in the MCC models were examined specifically. We also conducted conjunction analysis between creativity and meditation tasks to locate common mechanisms of metacontrol. Our findings suggest that metacontrol persistence is associated with activation in the PFC, ACC, and the BG, while metacontrol flexibility is linked to activation of the DMN. However, this pattern was much clearer in the analysis of brain activation related to the two creativity tasks than in the brain activation associated with the two types of meditation. Meditation may be a good method to induce particular metacontrol states, but to assess the impact of these states on information processing, it would need to be associated with particular task performance, which we did not study here. With regard to the MCC model, we found supporting evidence with regard to predictions related to PPC and, partially, PFC, but no significant findings were observed for STG and the findings for lIFG where exactly opposite of what was predicted. More research will be necessary to determine whether it is absolute or relative activation of lIFG that matters for metacontrol, and whether lIFG is really part of the flexibility network, as suggested by the MCC model, or rather part of the persistence network.

In Chapter 5, a validation analysis of the Picture Concept Task (PCT) was conducted, and the results suggest that both the sub-tests of PCT are insufficient for accurately measuring convergent thinking (CT; measured by PCTc meaning PCT for CT) and divergent thinking (DT; measured by PCTd meaning PCT for DT). However, there is a positive finding regarding the scoring dimension of fluency in PCTd, which appears to be a reliable indicator of the fluency of divergent thinking. This implies that the PCTd could potentially serve as a useful tool for assessing divergent thinking skills, provided further improvements are made to enhance its validity. Additionally, we identified the scoring method for the dimension of originality as an area that requires improvement. With refinements to the scoring process for originality, the PCTd holds promise to become a valid test specifically designed for measuring divergent thinking. We will not be discussing Chapter 5 in the following sections as it does not contribute to the main research question of this dissertation.

INTEGRATING THE FINDINGS:

CURRENT INSIGHTS INTO THE RESEARCH QUESTION

Neural mechanisms of metacontrol states

In the next, I will explain the neural mechanisms of metacontrol from three perspectives: (1) the MCC model; (2) the dopamine theory (3) the general findings from the EEG and fMRI studies.

The MCC model, as originally proposed in Chapter 2 of this dissertation, underwent examination using EEG and fMRI methods in Chapter 3 and Chapter 4, respectively. The MCC model postulates that biases in creativity-related metacontrol during creativity tasks are reflected in task-specific activation patterns of three key brain areas: (1) the left inferior frontal gyrus (lIFG), (2) the left dorsolateral prefrontal cortex (lDLPFC), and (3) the right temporal and/or parietal cortex (rT/PC), particularly the right superior temporal gyrus (rSTG) and the right posterior parietal gyrus (rPPC). Based on previous EEG and fMRI studies related to convergent and divergent thinking, the MCC model suggests that two activation patterns (lIFG+, lDLPFC-, rT/PC- vs. lIFG-, lDLPFC+, rT/PC+) reflect metacontrol states biased toward flexibility and persistence, respectively. In Chapter 3, which employed EEG methods, the primary focus was on the rT/PC, and we observed that there was more pronounced alpha synchronization or higher alpha power in this area for the flexibility state than for the persistence state. This indicates lower brain activation ((Scheeringa et al., 2011, 2016)), which aligns with the MCC model. This was further supported by findings from insight trials of RAT, which are considered a transition from flexibility to persistence, as alpha power decreased in the right temporal region. In Chapter 4, all the brain areas from the MCC model were examined during both creativity and meditation. Supporting evidence was found for predictions related to rPPC (in line with the EEG results of rT/PC in Chapter 3) and, to some extent, lDLPFC (only in the context of creativity, not meditation). However, no significant findings were observed for STG, and the findings for lIFG were exactly the opposite of what was predicted. When combining the results from Chapter 3 and Chapter 4, preliminary evidence in favor of the MCC model was found. Nevertheless, further research is needed to clarify the predictions for lIFG.

The dopamine theory mentioned in this dissertation suggests that metacontrol is strongly related to frontal and striatal dopaminergic pathways (Durstewitz & Seamans, 2008; Cools, 2016; Cools & D'Esposito, 2011), which deliver dopamine to its receptors in prefrontal cortex

(PFC) and basal ganglia (BG), respectively. There are two views to understand the relationship between the dopamine pathways and metacontrol. Firstly, based on the views of Cools (2016; Cools & D'Esposito, 2011), we assume the frontal dopaminergic pathway is a system that promotes persistence and the striatal pathway is a system that promotes flexibility, so persistence would be accompanied by stronger activation of the areas (PFC and/or anterior cingulate cortex, ACC) fueled by the frontal dopaminergic pathway, while flexibility would be associated with stronger activation of the areas (BG) fueled by the striatal dopaminergic pathway. Secondly, the views of Durstewitz and Seamans (2008) implies that both regions of interest (PFC/ACC and BG) might be involved in implementing a particular balance between persistence and flexibility, even though the receptor types that are promoting the activities in these regions might differ. Chapter 4 examined the dopamine theory by comparing the brain activation in the regions of interest between different metacontrol states induced by creativity tasks and meditation, and it was found that the brain areas fueled by both frontal and striatal dopamine were activated in the persistence state induced by both RAT and FAM. In previous studies on stability and flexibility (Armbruster et al., 2012) and neuroanatomic considerations regarding metacontrol (Cools, 2016; Cools & D'Esposito, 2011), striatal structures including the basal ganglia have commonly been thought to be associated with flexibility, rather than persistence. If so, our findings do not support a scenario of the interaction between frontal and striatal structures in which the activation of frontal structures promotes persistence, and the activation of striatal structures promotes flexibility. Rather, it seems that both kinds of structures continuously interact to negotiate the current degree of persistence versus flexibility. In other words, persistence and flexibility do not reflect the isolated activation of a corresponding neural structure but, rather, emerge from the continuous interactions between frontal and striatal components of a distributed but well-integrated metacontrol system. This integrated system may operate along the lines of Durstewitz and Seamans (2008), who have claimed that D1 and D2 receptors in both kinds of structures are biasing metacontrol towards persistence or flexibility, respectively. But other scenarios are possible. For instance, the interaction between frontal and striatal structures might be steered by tuning the productivity of the VTA and the substantia nigra, which are fueling the frontal and the striatal dopaminergic system. Another, not mutually exclusive possibility is that the balance between the frontal and the striatal dopaminergic pathway is moderated by serotonergic input (Prochazkova et al., 2018b), which has been demonstrated to have that ability (De Deurwaerdère et al., 2021). No matter in what cases, the brain areas modulated by frontal and striatal dopamine are found to be involved in the regulation of the metacontrol states.

Besides the results revealed by theory-driven explorations guided by the MCC and the dopamine theory, the EEG findings in Chapter 3 show that flexibility exhibits higher alpha power than persistence through entire brain, and the fMRI findings in Chapter 4 show that persistence is associated with activation in the PFC, ACC, and BG, while flexibility is associated with activation of the areas in the default mode network (DMN). Firstly, regarding persistence, the activations in the PFC, ACC, and BG are commonly assumed to create selectivity in attention and action control: The PFC is key in providing goal-contingent top-down support for goal-related representations (Miller & Cohen, 2001), the ACC is assumed to be a crucial hub in monitoring internal conflict and signaling the need for stronger goal-support from the PFC (Botvinick et al., 2004), and the BG are considered to bias stimulus and response selection according to expected rewards (Johnston et al., 2007; Richter & Yeung, 2015; Yehene et al., 2008). Accordingly, the joint activation of these three components is likely to reflect the degree of selectivity of information processing, which according to metacontrol theory corresponds to a strong persistence bias (Hommel & Colzato, 2017c). Secondly, note that flexibility's higher alpha power (form Chapter 3) matches with its brain activation in DMN (from Chapter 4). The increased alpha power through the entire brain suggests reduced working memory retention and monitoring process (Carp & Compton, 2009; S. Tang et al., 2021; Wianda & Ross, 2019), which suggests an inactive Executive Control Network (ECN), which is negatively correlated with the activation of DMN. The DMN, a task-negative or resting-state network, is known to be negatively correlated with executive control function and cognitive control (Raichle, 2015), and positively associated with cognitive flexibility (Vatansever et al., 2016). Hence, the DMN is activated by the absence of concrete task constraints and in the absence of the need to be selective with respect to stimuli or responses, which is exactly the state that metacontrol envisions for strong biases towards flexibility.

CONCLUSION

In conclusion, to investigate the neural mechanisms of metacontrol induced by creativity tasks and/or meditation, this dissertation employed both EEG and fMRI methods. These investigations were guided by the MCC model proposed within this dissertation and the dopamine theory established in previous studies.The EEG findings in this dissertation suggest that flexibility is associated with higher alpha power or alpha synchronization compared to persistence, particularly in the right temporal and parietal regions. This observation points to varying levels of top-down control and competition between ideas, as implied by the concept of task-specific metacontrol states. The fMRI findings indicate that persistence is linked to activations in the PFC, ACC, and BG, signifying a strong goal-related top-down control and selectivity in information processing (competition between alternatives). On the other hand, flexibility is associated with the activation of the default mode network (DMN), suggesting a reduction in top-down control and competition.

LIMITATIONS AND FUTURE DIRECTIONS

Although creativity tasks and meditation techniques have been shown to induce metacontrol states, they are not direct measurements of these states, and their brain activations might also involve other cognitive functions unrelated to metacontrol. Moreover, while we used dopamine-related theorizing and the MCC theory for a goal-related, focused analysis of metacontrol, this approach may overlook some metacontrol-related areas beyond this scope. In addition, in our EEG study conducted in Chapter 3, we attempted to examine the MCC model. However, due to the fact that the patterns predicted by the MCC are specific to brain activation, and our EEG study only focused on alpha band power, we were unable to accurately and effectively test the MCC. This limitation underscores the need for further research utilizing comprehensive brain imaging techniques. Nevertheless, in Chapter 4, we utilized fMRI to validate the MCC, and the evidence partially supported this model.

For future research, firstly, Chapter 4 of this dissertation calls for a revision of the MCC model to clarify the role of lIFG in metacontrol. Secondly, Chapter 4 also provides some regions of interest for further investigation into the brain networks of metacontrol. Thirdly, as previous studies suggest an association between brain variability (noise) and metacontrol (Armbruster-Genç et al., 2016; C. Zhang et al., 2022), future research could compare the brain variability between the metacontrol states to explore this potential relationship.