氏　　名　南條 啓孝

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学 位 論 文 題 目　Neural substrates of metacognitive processes under sequential perceptual decision-making

論 文 審 査 委 員　主　査　北城 圭一
生理科学コース 教授
吉村 由美子
生理科学コース 教授
磯田 昌岐
生理科学コース 教授
松田 哲也
玉川大学 脳科学研究所 教授

博士論文の要旨

氏　　名　南條啓孝

論文題目　Neural substrates of metacognitive processes under sequential perceptual decision-making

The higher-level cognition works to monitor and control one's own cognition, which is known as metacognition. For instance, most people might have an experience of the feeling-of-knowing state as a consequence of monitoring our memory (metacognitive monitoring), even though we cannot recall it at that time. One strategy to recall is to control retrieval time (metacognitive control). This type of metacognition has functional roles in improving learning and decisions.

In neural substrates of metacognition, studies first focused on metacognitive monitoring. To assess metacognitive monitoring, confidence has been measured as a metric in which subjects rate their confidence on how accurate their choice would be. Based on confidence to the accuracy of choices correctly reflecting external sensory states, the neural activity and structure of the lateral prefrontal cortex (lPFC) have been shown to be related to the metacognitive sensitivity using the perceptual decision-making paradigm. However, this focus on metacognitive monitoring overlooks the inherent role of metacognition in sequential decision-making processes.

The other parts of prefrontal cortex (PFC) is also thought to play a crucial role in this higher cognitive function, especially its control functions. In neural mechanisms underlying control, the anterior cingulate cortex (ACC) in the medial PFC (mPFC) is related to cognitive control and executive functions. It is thought that the mPFC has an important role in controlling our cognition and its implementation process. Moreover, damage to the PFC due to disease or injury results in the dissociation of knowledge (monitoring) and execution (control). Hence, the different views on the neural substrates of metacognition have not been completely resolved yet, considering both

metacognitive monitoring and control.

This study then investigates 1) the role of metacognition in influencing subsequent decision-making, 2) the representation of metacognitive monitoring in the PFC, 3) the neural distinction of subsequent control from metacognitive monitoring, and 4) the neural interaction of these processes. To address these issues, a task-based functional magnetic resonance imaging (fMRI) experiment was conducted with 34 Japanese general subjects. They underwent visual size discrimination task with two-alternative forced choice paradigm, which involved sequential decision-making and rating confidence. This experimental task was designed to investigate how initial confidence influences subsequent decision-making, whether to change their choice. Each subject was required to discriminate which of the two visual stimuli presented (stimulus size was composed of four steps) was bigger and to rate how confident they were in their judgement at the time subsequently. The same stimuli were presented twice in each trial.

This task allows me to investigate whether initial decision was switched or stayed in subsequent decision-making processes. However, confidence is known to be influenced by external evidence. To examine the influences of internally-driven components of metacognition on subsequent decision-making, I classified all trials into high/low confidence trials in each stimulus difference according to median of initial confidence within each subject. I then calculated the proportion of change of mind in each confidence level.

I first, analyzed the behavioral data to elucidate whether initial confidence influences on subsequent decision-making in comparison with the proportion of change of mind between low and high-confidence trials. I found that when people were highly confident on their initial choice, they persisted initial choice. Second, I examined whether initial confidence has a functional role in error detection and correction. I also revealed that when they made an error on their initial decision given low confidence,

they more frequently changed their initial choice compared to an error decision given high confidence. Both effects showed that internally-driven components of metacognition have a functional role in influencing subsequent control.

Next, regression analysis was performed on the fMRI data, comparing behaviorally identified variables against the BOLD signals recorded across the whole brain. To investigate the metacognitive monitoring-related activity on the initial decision, I compared the activity of the high confidence with the low confidence trial and found that the anterior part of the mPFC was highly activated. Subsequently, to identify brain regions associated with change of mind, I compared the activity of the switch with the stay trial on the subsequent decision. This analysis revealed significantly higher activation mainly in the dorsal ACC. These neural results suggest that there is a dissociation representing initial confidence generation and subsequent control process. However, behavioral results showed that there was a relationship between metacognitive monitoring and subsequent control. To investigate whether a connection existed between the two processes, I finally performed a conjunction analysis between the change of mind and metacognitive monitoring related activity. Through this analysis, I uncovered a common brain region between metacognitive monitoring and change of mind in the perigenual ACC. These regions work as a coordinated system, providing new insights into human metacognition.

（別紙１ Separate Sheet 1）

Results of the doctoral thesis defense

博士論文審査結果

Name in Full
氏 名　　南條　啓孝

Title
論文題目　　Neural substrates of metacognitive processes under sequential perceptual decision-making

出願者南條氏は、メタ認知の一種である確信度という観点から、自分の知覚的な意思決定について、どの程度確信度があるかどうかを推定するメタ認知的モニタリングと、その情報をもとに後続する行動をフィードバックなしに制御するメタ認知的コントロールという２つの過程に着目した。先行研究の多くは、確信度のメタ認知的モニタリング過程に着目しており、後続する知覚的意思決定の行動制御であるメタ認知的コントロールの神経基盤にアプローチしている研究はあまり報告されていない。そこで、南條氏は、確信度に関するメタ認知の行動制御における機能的な役割の実証とその神経基盤を明らかにすることを目的に、２つの円を視覚的に呈示して、大小の判断をする系列的な２試行からなる知覚的意思決定課題を用いて、１試行目の意思決定の確信度が、後続する意思決定に与える影響とその神経基盤を fMRI 実験により調べた。

南條氏は、まず、確信度がその後の行動へどのような影響を与えるかを調べるため、確信度の高低で試行群を２分割し、行動データを解析した。その結果として、１回目の試行での確信度が高い時より低い時の方が、２回目の試行で判断をより変更すること示した。さらに、確信度とメタ認知の行動制御に関連する神経基盤を調べるために fMRI のデータを解析し、１回目の意思決定での確信度が高いときには低いときに比べて、内側前頭前野前方部の活動が高まり、２回目の試行において、１回目の判断を変更したときには、変更しないときに比べて、背側前帯状皮質等の活動が高まることを明らかにした。確信度に基づき１回目の判断を適切に変更した試行に加え、１回目の判断を適切に維持した試行も解析し、一次視覚野を中心とした賦活を観察した。また、メタ認知的モニタリング時と２回目の試行における判断を変更したときの双方の過程で、前帯状皮質の一部の領域(perigenual ACC)の活動がみられた。さらに、メタ認知的モニタリングとメタ認知的コントロールのいずれか、あるいは双方の過程で活動がみられた perigenual ACC、背側前帯状皮質と内側前頭前野前方部との間の機能結合についても解析し、perigenual ACC と他の脳領域は機能結合が高いことを示した。Perigenual ACC は確信度に関してのメタ認知的モニタリングとコントロール過程においてネットワークとしてのハブ、あるいは、中核的に働いている脳領域であると解釈した。南條氏はこれらの結果から、メタ認知の後続する行動に与える機能的な役割を実証し、メタ認知的モニタリングとコントロールに関する神経基盤を明らかにしたと結論付けた。審査委員会では、発表と質疑応答を通じて、メタ認知的コントロールに着目してその神経基盤を明らかにした本研究には十分な新規性が認められると判断した。審査委員会では、以上の理由により、本論文が学位の授与に値すると判断した。