論 文 内 容 の 要 旨

Orientation processing in humans plays a crucial role in manipulating objects in daily life. Numerous studies have investigated the neural mechanisms underlying orientation processing, spanning from early visual areas to more action-related regions. These studies have highlighted the significance of orientation information in action-related process, as it provides essential spatial cues for successful task performance, particularly when actions are guided by real-time visual feedback. However, how the orientation information is processed during the visually occluded action towards an object remains unclear. To investigate this process, we used functional magnetic resonance imaging (fMRI) techniques to record blood-oxygenation-level-dependent (BOLD) signals during occluded action tasks. The multivariate pattern analysis (MVPA) was used to examine the cortical patterns of BOLD signals associated with orientation processing during occluded grasp. The classification of cortical patterns using MVPA was performed on the selected regions of interest (ROIs). The classification result from ROI was defined as the decoded orientation representation of that area. Additionally, we utilized transfer-type classification or cross-decoding methods to identify shared orientation cortical patterns across conditions. The study focused on two primary research directions in orientation processing. Firstly, we aimed to understand the influence of different types of visually occluded grasping actions on the orientation process. Secondly, we investigated the role of non-visual sensory information and action-related processes in grasping tasks without online visual feedback.

The first research approach examined the influence of visually occluded actions on orientation processing in the visual areas of the brain. Participants were engaged in tasks that involved observing an object and performing a grasping action while their visual input of the object was occluded. The object presented in the experiment had four different orientations. Participants were instructed to perform either a precision grasp, which involved using two fingers and a thumb to hold the object with precision (e.g., holding a pen or pencil), or a coarse grasp, which required using all five fingers to firmly hold the object. The BOLD signal was recorded during both the visual observation phase and the occluded action phase to investigate the representation of orientation information in the visual areas. The aim was to identify the specific visual cortices that encode orientation in different types of grasping actions and to reveal a generalized representation of the orientation process. MVPA classification was utilized to decode orientation information from selected ROIs within the visual cortices. The same-type classification was applied to determine the ROI that represents the orientation in each grasping type. Transfer-type classification was performed to identify a generalized representation of orientation that is independent of specific grasping types. This approach involved training the classifier using data from one grasping type, such as precision grasp, and then testing it on the data from another grasping type, such as coarse grasp and vice versa. By applying the trained classifier to different grasping types, we aimed to uncover a shared representation of orientation that transcends specific action contexts. The results demonstrated that orientation information can be decoded in early visual areas during visually occluded actions, specifically in area V3d for both coarse and precision grasps. Moreover, the results indicated that orientation can only be decoded from coarse grasping in V1 and V2. Transfer classification analysis revealed that the generalized representation of orientation in V3d is significant during visual observation but not during occluded action. This suggested that the processing of orientation information in early visual areas may differ depending on the action context. Overall, the study provides evidence of a representation of vision-related orientation in V1 and V2 and action-related orientation in V3d, with high classification accuracy for each action type. The results suggest that action-related orientation information may rely on proprioceptive information and/or feedback signals from higher motor areas, depending on the type of action.

The second approach of this study investigated the mechanisms underlying orientation processing in the visual cortices, considering the influence of non-visual sensory input and action-related process. Specifically, we examined the role of tactile and proprioceptive sensations as non-visual sensory inputs, as well as the impact of planned and unplanned grasping processes on orientation representation as the action related process. In this study, we examined BOLD signals in four distinct action conditions: direct grasp, air grasp, non-grasp, and uninformed grasp. Participants were presented with images of a cylindrical object, each having one of two orientations. They subsequently performed one of the four conditions and later judged the orientation across all conditions. Notably, all grasping actions were executed without real-time visual feedback, enabling us to investigate the contribution of tactile input, proprioceptive input, and action-related processes to the

processing of orientation information. MVPA was used to examine the differences in cortical patterns among the four action conditions. In addition, transfer-type classification, also known as cross-decoding, was performed to identify shared patterns across action conditions related to the orientation process. Significance in the transfer classification results suggests the presence of a generalized representation within an area, encompassing either input sensory-related or output action-related information. The results demonstrated significant decoding accuracy above chance level for direct grasp in most areas. During air grasp, only early visual areas showed significant accuracy, suggesting that tactile feedback from the object influences orientation processing in higher visual areas while the early areas utilized visual information of object that previously observed. The non-grasp condition showed no statistical significance in any area, indicating that without the grasping action, visual information does not contribute to cortical pattern representation. Interestingly, only the dorsal and ventral divisions of the third visual area (V3d and V3v) exhibited significant decoding accuracy during uninformed grasp, despite the absence of visual instructions. This suggests that the orientation representation in V3d is derived from action-related processes, while V3v is involved in the visual recognition process of object visualization. The processing of orientation information during non-visually guided grasping relies on non-visual sources and is specifically divided based on the purpose of action or recognition.

In summary, this doctoral dissertation provides a comprehensive investigation into the processing of orientation information in the human visual cortex during visually occluded actions. The combination of the two research topics sheds light on the neural mechanisms underlying orientation processing in the absence of visual input. The findings contribute to the field by revealing the role of early visual areas in decoding orientation during visually occluded actions, as well as the influence of non-visual sources on orientation representation in higher visual areas. The study highlights the importance of proprioceptive information, tactile feedback, and action-related processes in the processing of orientation information during grasping actions. These insights deepen our understanding of how the human brain integrates non-visual sensory input and feedback from motor system during orientation processing, thereby facilitating action planning and execution.

Keywords:orientation, visually occluded, fMRI, MVPA, action, tactile, proprioception