3D shape and orientation representation in the human cortical areas

論 文 内 容 の 要 旨

The ability of human to perceive three-dimensional (3D) shape and orientation of in the real world is vital in daily life. For example, when someone attempts to pick up a pencil on a desk or insert a key into a lock, the procedure depends on the above-mentioned abilities. The images projected onto the retina of the eyes are two dimensional (2D), but what we perceived is a 3D world. How the human brain actual achieve 3D is an intriguing question. There are a variety of depth cues that can be used to extract 3D perception by human brain: binocular disparity, perspective, motion parallax, texture and so on. Although there are a lot of studies about how brain extract information from these cues to perceive the shape and orientation of 3D object, the underlying neural mechanisms have not been fully investigated. The visual information is considered to be processed progressively in a hierarchical manner from early visual areas to higher visual areas, with each area processing information based on the results of previous areas. It is possible there is a generalized representation of 3D shape and orientation during the processing in some areas. To this end, we adopted functional magnetic resonance imaging (fMRI) method which can measure blood oxygenation level-dependent (BOLD) signal of the brain. The BOLD signal can indirectly reflect the underlying neural activity of cortices. Multi-voxel pattern analysis (MVPA) method was used to judge whether activity pattern of neurons reflect particular attribute of stimuli. Support Vector Machine (SVM) was used as the classifier for classification. Furthermore, by transfer classification in which we trained a classifier on one type of stimuli and test the classifier on another type of stimuli, we investigated whether common representation of different type of stimuli is involved in regions of interest (ROIs). The ROIs in our study include early visual areas which were defined by standard retinotopic mapping procedure and higher visual areas which were defined by standard localizers. In this research, we focused on two kinds of depth cues: binocular disparity and perspective. Two topics were investigated:

In the first topic, binocular disparity cue was investigated. We investigate convex–concave shape representation and horizontal–vertical orientation representation of stereoscopic surface. Random dot stereogram (RDS) stimuli which comprised of random black and white dots were generated using Psychotoolbox 3 in MATLAB. They depicted four surface types as follows: the horizontal convex and concave curved surfaces and vertical convex and concave surfaces. Surfaces were simulated in two depth positions. Stimuli selected from a set of eight conditions (4 types × 2 positions) were presented using a block design. Participants viewed the stimuli while BOLD signal was measured. After each stimulus block, the participant was required to make a judgement of the shape of the surface by pressing the corresponding button on a key pad. A series of classification were performed.
(1) To investigate representation of convex–concave shape defined by disparity among ROIs, three types of convex–concave shape classification were performed with the first type using same-type stimuli and the second and the third types using data of different types of stimuli. The first type is "same-type stimuli convex–concave classification." In this type classification, SVM was trained and tested using the same type of data. It was used to verify whether neurons are selective to convex–concave stereoscopic surface shapes in ROIs. The second type is "transfer convex–concave classification of surfaces at the same depth position." In this type of classification, the training and testing data were selected from blocks when surfaces were shown at the same depth position and "transfer" indicates that the data used for training and testing had different attributes in terms of orientation (horizontal or vertical). It was used to verify whether some ROIs are involved in generalized representation of convex–concave curved stereoscopic surface irrespective of surface

orientation. The third type is "transfer convex–concave classification of surfaces at different depth position." In this type of classification, the "transfer" indicates that the data used for training and testing has different attributes in terms of both depth position and orientation. It was used to verify whether some ROIs are involved in generalized representation of shapes irrespective the orientation and depth position of stereoscopic surface. Results showed that: for the first type of classification, the V1; V2; dorsal areas V3d, V3A, V7, and KO; ventral area LOC; and parietal area VIPS exhibited a classification accuracy higher than the baseline of statistical significance, suggesting that the activity patterns of neurons in these areas are selective to the shape of curved surfaces. For the second type of classification, in the higher dorsal areas V3A and KO, ventral area LOC, and parietal area VIPS, the fMRI responses evoked by one type of surfaces (horizontal or vertical) could allow the convex–concave shape classification of responses evoked by the other type of surface (vertical or horizontal, respectively). Because the disparity patterns of the surfaces used for training and testing were different, this result was probably related to more generalized processing of the convex–concave stereoscopic shapes irrespective of orientation of surfaces. For the third type of classification, only the classification accuracy for V3A was higher than the baseline of statistical significance. As for all the three types of classification, accuracy in V3 was higher than the baseline of statistical significance, this indicate that it is possible that V3A is involved in more generalized representation of stereoscopic shapes irrespective of orientation and depth position of surfaces.
(2) Similarly, to investigate horizontal–vertical orientation representation of stereoscopic curved surface, two types of horizontal–vertical classification were performed: the first type of classification is "same type stimuli horizontal–vertical classification," and the second type of classification is "transfer horizontal–vertical classification on surfaces of different shape at same depth position". In both two types of classification, the SVM was trained to classify whether a stimulus shown to a participant was horizontal or vertical. For the first classification, the SVM was trained and tested using the same type of data, and this was used to verify whether neurons are selective to horizontal–vertical orientation of stereoscopic surface in ROIs. For the second type of classification, the data used for training and testing have different shapes but at the same depth position. This was used to verify whether ROIs are involved in generalized representation of orientation irrespective of the shapes of surfaces. Results showed that for the first type of classification, accuracies for distinguishing horizontal versus vertical orientation among all areas were higher than the baseline of statistical significance, indicating that all these ROIs contained robust information for orientation classification. For the second type of classification, results showed that in the dorsal areas V3A and V7, higher ventral area LOC, and parietal areas VIPS and POIPS, the fMRI responses evoked by one type (convex or concave) of horizontal–vertical surface and allow the classification of the response evoked by another type (concave or concave, respectively) of horizontal–vertical surface at the same depth position. This finding suggests that these areas are related to the generalized processing of orientation of stereoscopic surfaces irrespective of shape of surfaces.

In the second topic, binocular disparity cue and perspective cue were investigated. The main purpose of this topic is to investigate whether ROIs are involved in representation of convex–concave 3D shapes from binocular disparity or perspective and investigate whether common representation of shapes from these two different cues is involved in ROIs. Stimuli were convex–concave shape consisted of two slanted planes which were defined by binocular disparity and perspective respectively. In detail, three types of stimuli were used: shapes defined by RDS, shapes defined by black–white dotted lines with perspective and shapes defined by black–white dotted lines with disparity. Two different disparity stimuli types (RDS and black-white dotted lines with disparity) were adopted to verify whether shapes from disparity but different elements share common representation. Two main types of classification were performed: (I) Same cue type stimuli convex–concave classification. In this type of classification, the SVM was trained and tested using data of same cue type. Corresponding to the three types of stimuli, this type of classification includes three sub types of classification: same cue type stimuli convex–concave classification using data of RDS, same cue type stimuli convex–concave classification using data of lines with perspective, and same cue type stimuli convex–concave classification using data of lines with disparity. The purpose of this type of classification was to verify whether neurons in ROIs are selective to convex–concave shape defined by one of these three types of stimuli. (II) Transfer convex–concave classification using stimuli of different cues. In this type of classification, convex–concave classifications were performed between combinations of different types of stimuli. Corresponding to these three types of stimuli, this type of classification also includes three sub classification: transfer convex–concave classification between data of RDS and lines with perspective, transfer convex–concave classification between data of lines with perspective and lines with disparity, and transfer convex–concave classification between data of RDS and lines with disparity. The purpose of this type of classification is to investigate whether a common neural activity pattern is involved for each ROI in the processing of shapes from the two different types of stimuli. If classification accuracy is higher than the baseline of significance level in one ROI, we can say that the neural activity pattern in this ROI for the shape from one type of stimuli is similar to the neural activity pattern for the shape from the other type of stimuli. Results showed that early and middle visual areas had a tendency to be high classification accuracy in the "same cue type stimuli convex–concave classification," and for some higher visual areas, in particular the area dorsal intraparietal sulcus (DIPS), classification accuracy had a tendency to be high in both "same cue type stimuli convex–concave classification" and "transfer convex–concave classification using stimuli of different cues. The possible reason to the results is as follows: (1) neurons in the early and middle visual areas are traditionally considered to be selective to some simple features of stimuli including binocular disparity and orientation of lines. And for same cue type convex–concave classification using data of RDS or using data of lines with disparity, the disparity patterns between convex–concave shapes were different; and for same cue type convex–concave classification using data of lines with perspective, the orientation of the element lines were different between the convex and concave shapes. it is therefore reasonable for the early and middle areas showed high accuracies in "same cue type stimuli convex–concave classification". (2) There are evidence showing IPS areas are involved in processing of 3D shapes, and these areas are thought to be related to vision for actions. It is possible the high accuracies in DIPS in most types of classification was caused by the visual information used for guiding action, and this information is more generalized which reflect the shapes of stimuli and does not depend on the concrete cue types.

In summary, our research investigated generalized representation of convex–concave shape and horizontal–vertical orientation of curved surfaces defined by binocular disparity, and we also investigated common representation convex–concave representation of shapes which consisted of slanted planes defined by binocular disparity and perspective, respectively. This dissertation provides a better understanding on the neural representation of shape and orientation of 3D object among human cortical areas.