
Title of Thesis

**Neural Mechanism of Visual Symmetry Perception:
Psychophysical and Visual Evoked Potentials Study**

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Abstract

In everyday life, most of things in environment were symmetrical. For example, butterfly are horizontal symmetry, wheel is central symmetry, the leaf are asymmetric. Symmetry perception holds a particular fascination as symmetry is so closely related to beauty. However, the neural mechanism of visual symmetry processing in human visual system is not completely clear.

The dissertation contains descriptions of the four experiments and a general discussion briefly introduced below.

Chapter 1 describes the concept of visual system and visual symmetry, related previous studies, Electroencephalogram (EEG) analysis, and the method of event-related potential (ERP) analysis in visual symmetry studies. Additionally, the aim and contents of the thesis are also briefly described.

Chapter 2 describes the first experiment. Previous studies have showed a special symmetry processing in human visual system. However, where and how visual symmetry processing is not clear at all. Furthermore, the temporal characteristic of visual symmetry processing is also unclear. In the present study, visual discrimination task was used to measure the relationship between psychical index of symmetry and perceived symmetry. An ERP method was used to evaluate temporal characteristic of

different visual symmetry figures.

Chapter 3 describes the second experiment. Whether the magnitude of eccentricity will affect the processing of visual symmetry. We measured the processing of symmetrical stimulus (diagonal) and asymmetrical stimulus (control) with two levels of intensity by measured visual evoked potential (VEP).

Chapter 4 describes the third experiment. Previous studies have showed a different directions of symmetry axis seem to have an impact on symmetry cognition. But the existence of this change in the brain is unclear. In the current study, we asked three questions. First, how does the number of symmetry axes modulate the brain response? Second, Whether the difference of visual field will also affect the recognition of symmetry. Third, does the direction of the symmetry axis affect the recognition of symmetry? To investigate these three questions, an electrophysiological method was used to examine brain activity with different symmetry axes.

Chapter 5 describes the fourth experiment. The symmetry axes of a stimulus are a critical determinant of visual perception. Although much is known about the effects of a single symmetry axis on perception, the effects of multiple symmetry axes are still poorly understood. Here, we investigated the influence of the number of symmetry axes on brain activity using event-related potentials (ERPs).

Chapter 6 Provides a general conclusion based on the findings of the

four experiments and future challenges.

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Chapter 1 Introduction

Summary

This chapter introduces the concept of visual perception and symmetry. The previous studies of visual symmetry have also been summarized here. Additionally, the technique of visual evoked potential (VEP) and event-related potential (ERP) have been introduced. At last, the purpose and contents of the thesis are briefly described.

1.1 Visual symmetry

Vision is the most dependent feeling in our daily life, Visual perception of an object is instantly connected with an idea of what we see. From the thalamus, visual input travels to the visual cortex, located at the rear of our brains. The visual cortex is one of the most-studied parts of the mammalian brain, and it is here that the elementary building blocks of our vision – detection of contrast, colour and movement – are combined to produce our rich and complete visual perception.

In everyday life, most of things in environment were symmetrical. For example, butterfly are horizontal symmetry, wheel is central symmetry, the leaf are asymmetric. Symmetry perception holds a particular fascination as symmetry is so closely related to beauty. Since Mach brought our attention to the symmetry perception [1], such as the difference between formal measures of regularity: reflection symmetry, translation symmetry, and rotation symmetry. Symmetry has frequently been used to investigate aspects of visual processing, such as perceptual organization [28], identification of objects against a background [53], face recognition [35; 40; 64], and 3-D reconstruction [67; 75]

1.2 Previous study

In previous studies, visual symmetry was often manipulated with a mathematical structure, the proportion of symmetry/noise, or the number of symmetry axes [8; 27; 30; 37; 41; 49; 62; 66; 73]. Symmetry driven by a mathematical structure often uses reflection, translation or rotation symmetry. Psychophysical studies have confirmed that reflection symmetry elicits a response more easily and rapidly than other symmetrical (translation or rotation symmetry) and asymmetrical stimuli [8; 27; 30; 37; 41; 62]. Symmetry driven by the proportion of symmetry/noise, that is, the amounts of structure-pairs in the sides of the symmetry axes divided by the totals of structures in the stimulus. Research on the proportion of symmetry/noise has revealed that behavioral performance is enhanced in response to stimuli with a higher proportion of symmetry/noise [8; 26; 42]. Conversely, symmetry driven by the number of symmetry axes, that is, the structure on the sides of each symmetry axis was paired (always 100% symmetry). Similar to the proportion of symmetry, the behavioral performance with multiple symmetry axes was more straightforward and faster; more specifically, the response to the stimulus with 4 axes was faster than to that with 2 axes or 1 axis [5; 76].

Furthermore, detection of vertical reflection symmetric pattern is more efficient than other orientation, such as horizontal or oblique reflection patterns [5; 8; 20; 30; 31; 41], perhaps because of the anatomical symmetry

of the human visual system (the callosal hypothesis) [79]. However, recent reviews suggest that the strong version of the callosal hypothesis is unlikely to be correct. Symmetry can be detected when the axis does not match the anatomical midline, and even when patterns are presented entirely to one hemisphere [41]. Neuroimaging work has shown that visual symmetry activates extrastriate brain areas, most consistently the lateral occipital complex (LOC). Recently, Zaira Cattaneo et al. (2017) used fMRI-guided transcranial magnetic stimulation (TMS) over LOC occipital face area and found clearer difference effects on detection of vertical than horizontal symmetry. Taken together, these studies suggest there may be some partially differences in the neural underpinnings of axis orientations based on distinct cortical networks.

1.3 Event-related potentials (ERPs)

1.3.1 Event-related potentials (ERPs)

ERPs are measured by means of electroencephalography (EEG), EEG is noninvasive, with the electrodes placed along the scalp and reflects the summed postsynaptic activity in the underlying cortical regions. EEG measures voltage fluctuations resulting from ionic current within the neurons of the brain. The EEG patterns change when external stimuli (such as sounds or pictures) are presented, whereas ERPs is the measured brain response that is the direct result of a specific sensory, cognitive, or motor event by non-invasive method.

Figure 1 shows recorded EEG data. EEG recordings show the overall activity of the millions of neurons in the brain. The recording shows fluctuations with time that are often rhythmic in the sense that they alternate regularly. The EEG patterns change when external stimuli (such as sounds or pictures) are presented.



Figure 1.1 Experiment of recorded EEG data.

1.3.2 Analysis method of ERPs data in the visual symmetry study

The ERPs elicited by the task-irrelative stimuli were analyzed. The data were band-pass filtered from 0.1 - 60 Hz during recording at a sample rate of 500 Hz. The data were divided into epochs, from -200 ms before to 1000 ms after the stimulus onset, and baseline corrections were made against a -200 ms to 0 ms time interval before stimuli onset. Trials with horizontal eyeball movements (horizontal EOG amplitudes exceeding ± 25 mV), vertical eye movements and eye blinks (vertical EOG amplitudes exceeding ± 100 mV), or other artifacts (a voltage exceeding ± 80 mV relative to baseline) were rejected automatically from the analysis. In addition, the data associated with a false alarm were excluded. The data were then averaged for each stimulus type, following digital filtering with a band-pass filter of 0.01 - 30 Hz, and the grand-averaged data were obtained across all participants for each stimulus type in each electrode.

1.4 The purpose of the present dissertation

The natural to take the vision system as the information processing for recognizing symmetrical things. Psychological and brain science research shows that there is an information processing process corresponding to the theory of "unity of symmetrical things (elements)" in human visual system. However, it is not clear in which brain area symmetrical information processing is carried out. This study aims to clarify this topic and analyze

the relationship between "symmetry physical index", "symmetry perception" and (event-related potential: ERP) by manipulating symmetry intensity.

1.5 The contents of the dissertation

The main aim of this present thesis was to investigate the visual symmetry processing in human visual perception system by visual stimulation through behavioral and event-related potential (ERP) experiments.

Chapter 1 Introduces the concept of visual system and visual symmetry, related previous studies, Electroencephalogram (EEG) analysis, and the method of event-related potential (ERP) analysis in visual symmetry studies. Additionally, the aim and contents of the thesis are also briefly described.

Chapter 2 Describes the first experiment. Previous studies have showed a special symmetry processing in human visual system. However, where and how visual symmetry processing is not clear at all. Furthermore, the temporal characteristic of visual symmetry processing is also unclear. In the present study, visual discrimination task was used to measure the relationship between psychical index of symmetry and perceived symmetry. An ERP method was used to evaluate temporal characteristic of different visual symmetry figures.

Chapter 3 Describes the second experiment. Whether the magnitude of eccentricity will affect the processing of visual symmetry. We measured the processing of symmetrical stimulus (diagonal) and asymmetrical stimulus (control) with two levels of intensity by measured visual evoked potential (VEP).

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Chapter 5 Describes the fourth experiment. The symmetry axes of a stimulus are a critical determinant of visual perception. Although much is known about the effects of a single symmetry axis on perception, the effects of multiple symmetry axes are still poorly understood. Here, we investigated the influence of the number of symmetry axes on brain activity using event-related potentials (ERPs).

Chapter 6 Provides a general conclusion based on the findings of the four experiments and future challenges.

Chapter 2 Visual evoked potentials study on the effects of symmetry and good continuity on Figure-Ground segment

Summary

In the everyday life, most of the things is symmetrical and visual system is extremely sensitive to symmetry. Several electroencephalography (EEG) studies have shown the amplitude is more negative for symmetrical than random patterns, from around 200 ms after stimulus onset. However, the mechanism of symmetrical intensity on visual processing was not well understood. In this study, Firstly, we measure the processing of symmetrical intensity with three levels of symmetry: 100% (full symmetry), 50% (8 Gabor is changed), 20% (16 Gabor is changed). Secondly, we measure the processing of symmetrical type with three types, vertical symmetry, horizontal symmetry and center symmetry. Our results showed that both symmetrical intensity and symmetrical type influenced visual processing. We found that with the intensity of symmetry decreased, the negative amplitude became small and the positive amplitude was increasing. Furthermore, negative amplitude was sensitive to vertical and horizontal symmetry, and positive was sensitive to center symmetry.

2.1 Background

It is well established that many of things in environment were symmetrical. For example, book are horizontal symmetry, wheel is central symmetry, the face are asymmetric. Therefore, further study of visual symmetry processing is important.

Previous studies have shown that symmetry contributes to the perception of graphics. Their results showed brain activity for central symmetry (blue) was stronger than that for others (black, red, green) in V1d, V2d, V3 [16]. But the symmetry of the strength of the graphics is not aware of whether the relevant.

However, the mechanism of symmetrical intensity on visual processing was not well understood. In this study, Firstly, we measure the processing of symmetrical intensity with three levels of symmetry: 100% (full symmetry), 50% (8 Gabor is changed), 20% (16 Gabor is changed). Secondly, we measure the processing of symmetrical type with three types, vertical symmetry, horizontal symmetry and center symmetry. Our results showed that both symmetrical intensity and symmetrical type influenced visual processing. We found that with the intensity of symmetry decreased, the negative amplitude became small and the positive amplitude was increasing. Furthermore, negative amplitude was sensitive to vertical and horizontal symmetry, and positive was sensitive to center symmetry.

2.2 Methods

2.2.1 Participants

Fifteen students from Okayama University take part in this experiment, and the age is range from 24 to 34 years (mean age 26.5 years). All participants with normal or corrected-to-normal vision are right-handed. They had no neurological/psychiatric disorders and no hearing problems. They have provided written informed consent for their participation in this experiment, which was previously approved by the ethics committee of Okayama University.

2.2.2 Stimuli

The stimulus was an array of 497 non-overlapping Gabor elements on a gray background. Control the direction of 20 gabors to form a semicircle gabor (SN0) ; randomly change the direction of 8 gabors (SN0.4) ; randomly change the direction of 16 gabors (SN0.8) . see figure 2.1.

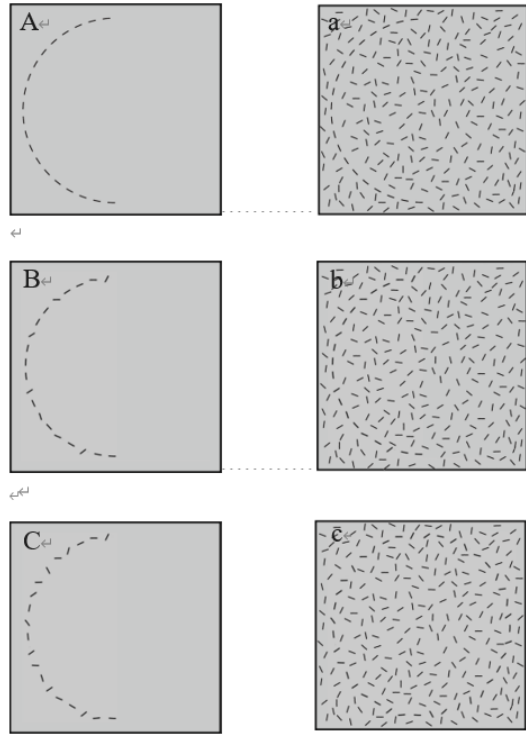


Figure 2.1 (A) Sample stimuli used in the experiment: Semicircle of 20 Gabor. (B) Sample stimuli used in the experiment, with changing the orientation of 8 Gabor. (C) Sample stimuli used in the experiment, with changing the orientation of 16 Gabor.

2.2.3 Procedure

Figure 2.2 showed the experiments include three parts as follows. Fixation present for 1200-1800 ms randomly, then stimuli will present for 150 ms. Vertical symmetry task: left and right semicircles were presented randomly. Subjects were instructed to press 1 of the keyboard when semicircle was left, and press 2 of the keyboard when semicircle was right. Horizontal symmetry task: Subjects were instructed to press 1 of the keyboard when semicircle was up, and press 2 of the keyboard when semicircle was down. Central symmetry task: Subjects were instructed to press 1 of the keyboard when stimulus was right-up & left-down, and 2 of

the keyboard when stimulus was left-up & right-down.

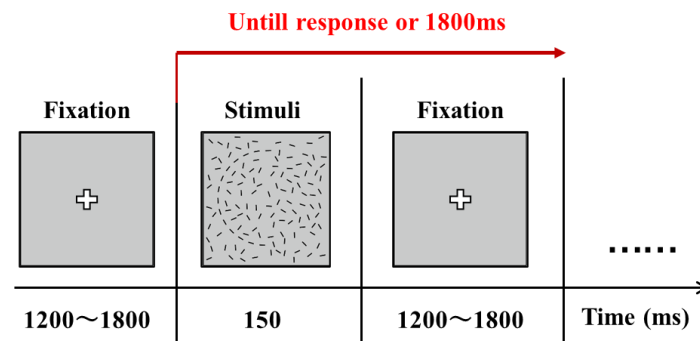


Figure 2.2 Time Course for Experiment. First, a fixation point of 1200 ms to 1800 ms is displayed, and then a stimulation image of 150 ms is presented. After that, the fixation point of 1200 ms to 1800 ms is again displayed, and then the next stimulus image is presented, and the fixation point and the stimulation image are alternately presented. Response: The subjects answered whether they found irritation.

2.2.4 Apparatus

The stimuli were generated and controlled using MTLAB with Psychophysics Toolbox for Windows 7 and Electroencephalographic (EEG) signals were recorded at a sampling rate of 500 Hz from 30 scalp electrodes. To detect blinks and eye movements, a horizontal bipolar electrode (HEOG) was placed approximately 1 cm from the outer canthi of the left eye, and a vertical bipolar electrode (VEOG) was placed approximately 1.5 cm below the subject's left eye.

2.2.5 Data analysis

The ERPs elicited by the task stimuli were analyzed by using the Brain Vision Analyzer software (version 1.05, Brain Products GmbH, Munich,

Germany). Then data was segmented into epochs of 100 ms pre- to 500 ms post-stimulus. Eyeblinks and horizontal eye-movements were corrected using the algorithm of Gratton et al. During the experiment, impedance was maintained below 5 k Ω . Raw signals were digitized using a sample frequency of 500 Hz, and all data were stored digitally for offline analysis.

2.3 Results

Figure 2.3 showed the reaction time: the response to central symmetry was significant slower than that to vertical or horizontal symmetry ($p < 0.01$). However, there are no significant difference was found between vertical and horizontal ($p > 0.05$). Accuracy: all accuracy was higher than 85%, and no significant difference was found (all $p > 0.05$).

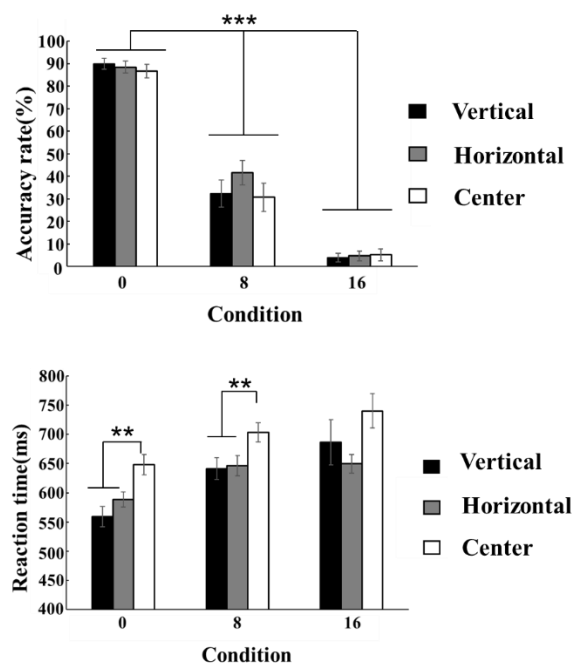


Figure 2.3 Mean reaction time and of hit rate ERP Experiment ($p < 0.01$) .

Figure 2.4 ERPs displayed between -100 and 500 ms and recorded at electrode of Fp1, Fz, Fp2, O1, Oz and O2. In the forehead (Fp1, Fp2 and Fz), significant difference was observed between central symmetry condition and line symmetry conditions after 250 ms in all electrodes. Similarly, in the visual cortex (O1, Oz and O2), significant difference was also found between central symmetry condition and line symmetry conditions after 250 ms.

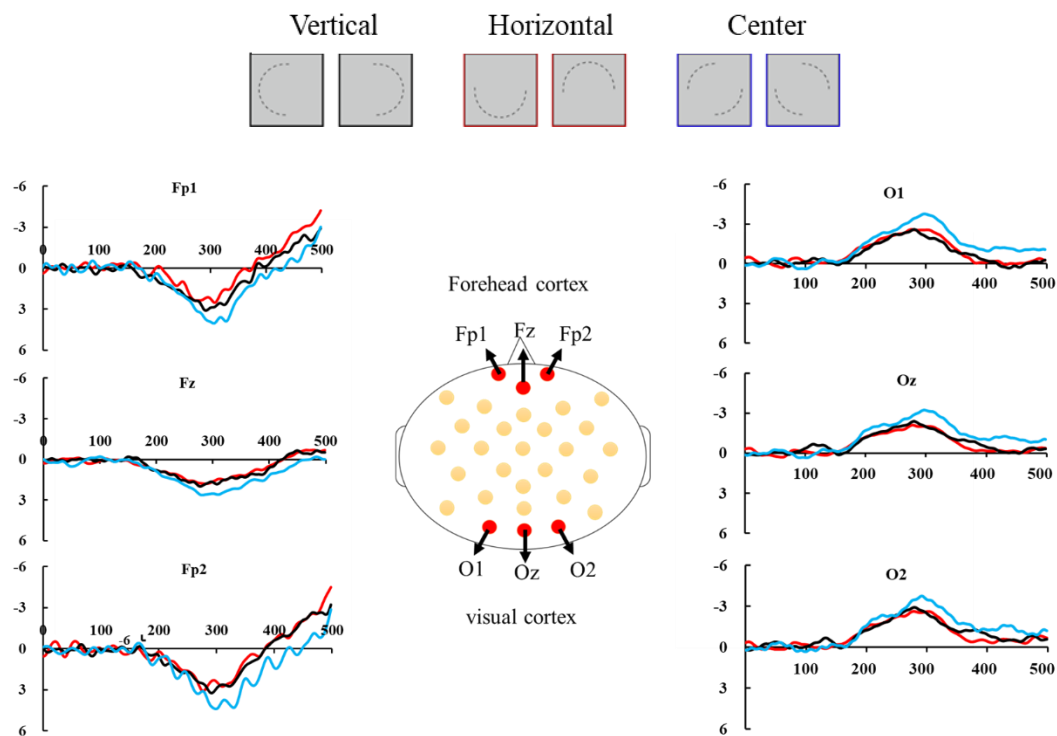


Figure 2.4 event-related potentials. Comparison of wave from vertical, Horizontal and Center at Forehead cortex and Visual cortex.

Figure 2.5 ERPs displayed between -100 and 500 ms recorded at electrode. we focused our analysis on eight regions of interest (ROIs): L-Frontal (Fp1, F3 and F7), R-Frontal (Fp2, F4 and F8), L-Temporal (FC5, T7 and C3), Central (Fz, Cz, FC1, FC2, CP1, CP2 and Pz), R-Temporal (FC6, T8 and C4), L- Parietal (Cp5, P7 and P3 and), R- Parietal (Cp6, P4 and P8), and Occipital (POz, O1, Oz and O2). The signal from each of the eight ROIs was measured as the mean of the signals from adjacent electrodes. Significant difference was observed between SN0 condition and SN0.4, SN0.8 conditions after 220 ms in all electrodes.

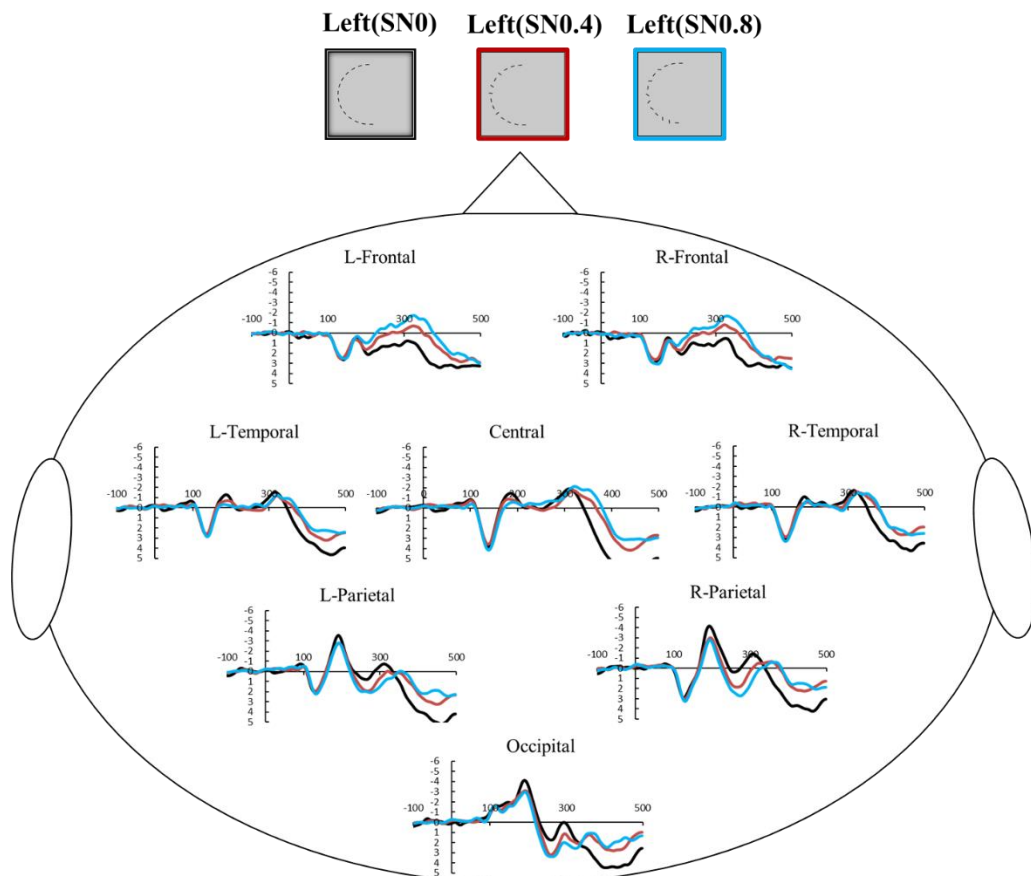


Figure 2.5 Grand average ERPs in the eight ROIs.

2.4 Discussion

Our behavioral results showed the response to central symmetry was significant slower than that to vertical or horizontal symmetry, consisted with previous studies [78]. In agreement with previous studies, our ERP results showed that the brain activity for central symmetry was stronger than that for vertical or horizontal after 250 ms in whole brain. Our results showed that RTs for central symmetry was delayed. One of the most possible reason is that stimulus was presented at both left visual field and right visual field, and attention was divided into left and right, resulting in longer RTs. This finding was consistent with previous visual studies, see Figure 2.6.

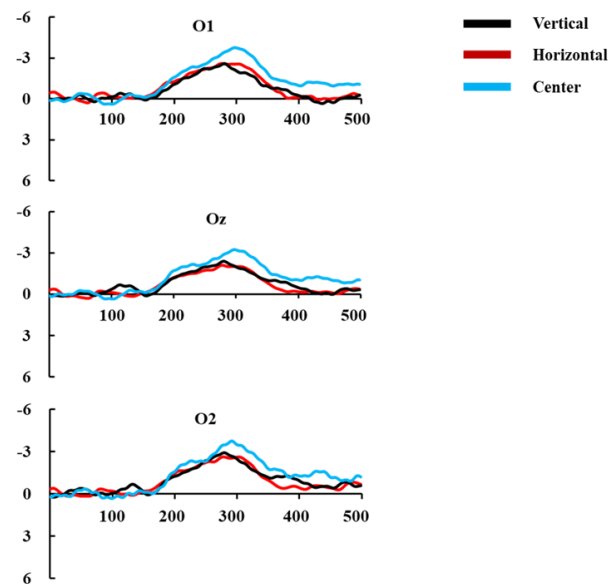


Figure 2.6 Comparison of wave from vertical, Horizontal and Center at O1, Oz and O2.

Regarding the continuity effects, our results showed that the amplitudes of P2 within posterior areas decreased linearly as the noise increased. These results suggest that the discriminating power of continuity increases as the amplitude of the P2 component decreases. It should be mentioned here that the order of the size of the amplitude is reversed between 220ms-340ms and 340ms-500ms. In 340ms to 500ms, SN0 deviates significantly downward compared to SN0.4 and SN0.8. These reversed properties suggest that the P2 and the subsequent potentials may involve two different components.

In the previous studies through button pressing task paradigm, it has been reported that button pressing causes larger positive potentials in the mid-head and occipital electrodes(C3, Cz, C4, TCP1, TCP2, Pz , in the paper and C3, C4,T5,T6,Cz, Pz, O1, O2 in the paper [83; 84].

In our experiment based on this figure 2.5, we employed button pressing task paradigm. The frequency of button pressing is different for three conditions. The SN0 condition is 88%, SN0.4 and SN0.8 conditions are less than 35% and 5% respectively. Thus, the SN0 stimuli may yield the larger effect of button pressing, causing the larger positively potential shift than the SN0.4 and SN0.8 stimuli. In fact, Fig.2.5 shows that the potentials of all electrodes are positively larger in the range of 300ms to 500ms for the SN0 than for SN0.4 and SN0.8 conditions. This finding is consistent the findings in the previous studies through button pressing task paradigm.

In summary, visual signal SN0 yield larger negative potential in the range of 250 ms to 300 ms and large positive potential in the range of 300 ms to 500 ms than SN0.4 and SN0.8 signals.

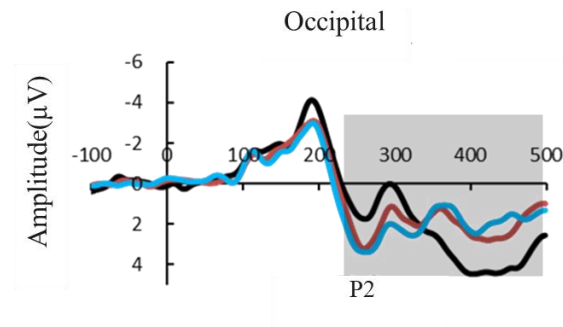


Figure 2.7 Comparison of wave from Left(SN0), Left(SN0.4) and Left(SN0.8) at Occipital.

2.5 Conclusions

In the present study, we measured the diversity of visual stimuli processing with different symmetry by ERP method. The results revealed that response of the central symmetry was slower, and brain activity was stronger than vertical symmetric stimulus and horizontal incompatible stimuli at after 250 ms. The continuity affects visual discrimination. The effect of discriminating power of continuity corresponded to the negative change of P2 component around the range of 250ms to 300ms.

Chapter 3 The effect of visual eccentricity on symmetry perception: an VEP study

Summary

Although symmetry is known to be an important determinant of visual processing and an appreciation of visual symmetry has been studied in several electroencephalography (EEG) experiments, it remains not well clear the mechanism of visual symmetry processing. To investigate this, we measured the processing of symmetrical stimulus (diagonal) and asymmetrical stimulus (control) with two levels of intensity by measured visual evoked potential (VEP). Our results showed significant difference in P8, P4 and O2, the right hemisphere for symmetry processing. In addition, the activity of visual related cortex for diagonal was weaker than that for control during the period of (160-190 ms), whereas the relationship was inverse during the period of (220-280 ms) in all intensity. This work provides a new account of neural mechanisms involved in visual symmetry perception.

3.1 Background

In everyday life, most of things in environment were symmetrical. For example, butterfly are horizontal symmetry, wheel is central symmetry, the glasses are asymmetric. Symmetry perception holds a particular fascination as symmetry is so closely related to beauty. Therefore, it is important to understand the mechanism of visual symmetry processing.

Since initially introduced by Weyl, H. et al. (1953) [1], the symmetry has been widely investigated as a case of visual symmetry perception [2-4]. One typical hypothesis proposed that the visual symmetry perception originates from the perceptual stage of processing. Previous psychological studies have showed that symmetry object is detected more quickly than other irregular objects. such as the research conducted by Palmer, S.E., & Hemenway, K. (1978), their results suggested that the perception of symmetrical shape was faster than near symmetries shape [5]. In addition, the symmetry perception was modulated by the symmetrical intensity. Royer, F. L. (1981) conducted three experiments to measure the time to detect symmetries in square field patterns. Their results showed that the response times were faster for multiple symmetric patterns than for singly symmetric ones, Horizontal–vertical symmetry was faster than diagonal, which was faster than centric [3]. Furthermore, Hiroshi Ban et al. (2006) found that the symmetry perception was also modulated by the

symmetrical type by ERP method [6]. These researches suggesting that "irrelevant" symmetry facilitated symmetry performance.

Additionally, Bertamini and Makin (2014) have reviewed the existing neuroimaging work with symmetry perception [7]. Functional magnetic resonance (fMRI) and Trans-cranial Magnetic Stimulation (TMS) studies have revealed that the lateral occipital complex (LOC) is causally involved in symmetry detection. their results found symmetry-related activations in extrastriate visual areas such as V3a, V4, V7 and the lateral occipital complex (LOC), but not in V1 or V2 [8]. Furthermore, there have also been several ERP studies on symmetry perception. Damien Wright et al. (2015) found that right-lateralized alpha desynchronization during regularity discrimination. This could reflect temporary enhancement of contralateral visual inputs and specifically a shift of attention to the left, or right hemisphere specialization for regularity discrimination. However, they did not attribute this hemispheric specialization to symmetry processing due to spatial attention [9]. To investigated this problem, Damien Wright et al. (2017) directly compared responses to symmetry presented to the left or the right hemifield. They found a symmetry sensitive network of extrastriate areas can be activated independently in each cerebral hemisphere. However, despite pervious work and prior plausibility, they did not find much evidence in support for a strong right lateralization of the symmetry response in this series of experiments. Right lateralization of

the symmetry response was found in Experiment 1, but not in Experiments 2 or 3. Therefore, the mechanism of the visual symmetry perception is still not well clear so far [10].

Despite these important findings, the above studies can't rule out the possibility that other psychophysiological measures might be sensitive to spontaneous evaluation [8; 11; 12]. In the present study, we compared responses to diagonal and control stimuli directly to test the mechanism of visual symmetry processing.

3.2 Methods

3.2.1 Participants

Ten students from Okayama University take part in this experiment, and the age is range from 22 to 29 years (mean age 23.9 years). All participants with normal or corrected-to-normal vision are right-handed. They had no neurological/psychiatric disorders and no hearing problems. They have provided written informed consent for their participation in this experiment, which was previously approved by the ethics committee of Okayama University.

3.2.2 Stimuli

The experiment was conducted in a dimly lit, sound-attenuated room. Visual stimuli were presented centrally on a black background monitor 60 cm from the subject. The stimulus consists of a quarter circle with a background gray of 120 pixels and a stimulus grayscale of 150 pixels. Two quarter arcs aligned with symmetrical, diagonal about a fixation point (diagonal), and asymmetrical (control), see figure 3.1.

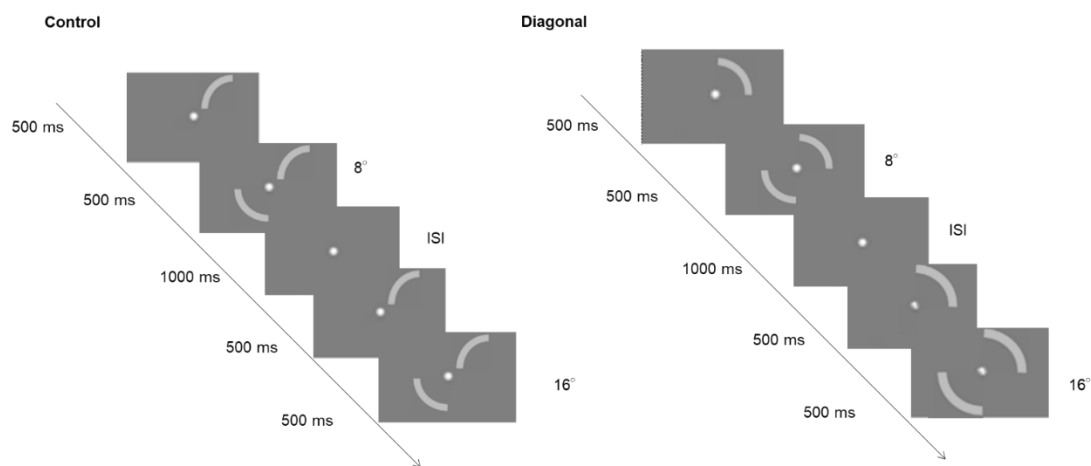


Figure 3.1 Experimental design. Subjects sat approximately 60 cm from the screen. The subjects keep eyes on center. Stimulus were presented in the front screen and presented 500 ms. There were four kinds of visual Stimulus. In one block, the participant's task when the fixation point turns red, the subjects respond by pressing a button.

3.2.3 Procedure

During the experiment participants were instructed to focus on the central fixation point, when the fixation point is red, the subject presses a button. There are 856 stimuli in total. Participant completed 12 blocks in

all, every block takes about 5 minutes. Between each set, proceed with the operation of the experimenter.

3.2.4 Apparatus

Electroencephalographic (EEG) signals were recorded at a sampling rate of 500 Hz from 30 scalp electrodes. The electrodes were referred to the left and right earlobes. Horizontal and vertical eye movements were also recorded by deriving the electrooculogram (EOG) [13]. The impedance of all electrodes was below 5 k Ω . Brain Vision Analyzer software (version 1.05, Brain Products GmbH, Munich, Bavaria, Germany) was used to analyze the ERPs, which were averaged separately for each stimulus type off-line. It is a sintered silver chloride ring electrode (Electrodes) B10-S-200 made by Easy Cap used for brain wave measurement (outer diameter 12 mm, inner diameter 6 mm). A signal measured from the electrode was used as an Analog Input and Output Box (Analog Input and Output Box) manufactured by Brain Product. The digital signal and the trigger signal were transmitted to the measuring PC via the optical fiber cable (Optical Fiber) and USB 2 Adapter by Brain Product. It is amplified by sending it to the brain wave voltage amplifier BrainAmp MRplus manufactured by Brain Product Company. The amplified signal is converted into a digital signal within the voltage amplifier. Subjects washed the hair and scalp before the experiment started, dried and placed in a clean state, and then

attached with electrophysiology cap attachment cap (Electrode cap). When attaching the electrodes, Skin prepping Gel and Abrasive Electrolyte-Gel manufactured by Easy Cap were used. After drying and making it clean, attach the electrophysiology electrode attachment cap (Electrode cap).

2.2.5 Data analysis

The EEG data of the standard stimuli were filtered off-line (0.1–30 Hz). Then data was segmented into epochs of 100 ms pre- to 600 ms post-stimulus. Eyeblinks and horizontal eye-movements were corrected using the algorithm of Gratton et al. All electrodes were re-referenced to an average reference. This reference was the average of activity between left and right earlobes [8]. The epochs were then baseline corrected, by subtracting the voltage measured during a pre-stimulus window (-100 ms to 0 ms relative to the stimulus onset) from the entire waveform, so that the waveform reflects the voltage relative to the average pre-stimulus voltage [14]. Epochs that contained EEG artifacts were rejected from the data. Artifacts were defined by a voltage change ranging from -80 μ V to +80 μ V per sampling point. Furthermore, trials during which the subject response incorrectly stimulus onset, as coded using the stimulus, were discarded [15]. Separate ERP averages were computed for all subjects, for all conditions.

Firstly, point-wise running t-tests (two-tailed) were used to compare

diagonal with control. In the present data, periods of significant difference were plotted when alpha criterion was less than 0.05 and then only when this criterion was exceeded for at least 12 consecutive data points (12 data point = 24 ms at a 500 Hz digitization rate) [6]. Based on previous research, we expected activity to be maximal at visual cortex during the peaks of interest, which was confirmed for both conditions in the present study by visual inspection of ERP waves. Then, mean amplitudes were automatically detected for the time intervals that were selected based on an overview of the significant differences in the first phase of analysis. These mean amplitudes were analyzed using repeated measures ANOVA with symmetric type (diagonal and control) and electrode (P4, P8, O2) as within-subject variable [6]. The level of significant was fixed s at corrected $p < 0.05$.

3.3 Results

ERPs of stimuli in both conditions were characterized by a P1 (peaking approximately 100 ms post-stimulus) with a temporal scalp distribution, an N1 (peaking approximately 170 ms) with a fronto-central distribution, and a late positivity (200–400 ms) with a central-to-parietal scalp distribution [8]. Although the latencies of measured P1/N1 components are long, the scalp distributions of P1/N1 are consistent with previous studies, the latency of P1/N1 can be affected by such visual stimulus parameters, as

size, intensity, and eccentricity.

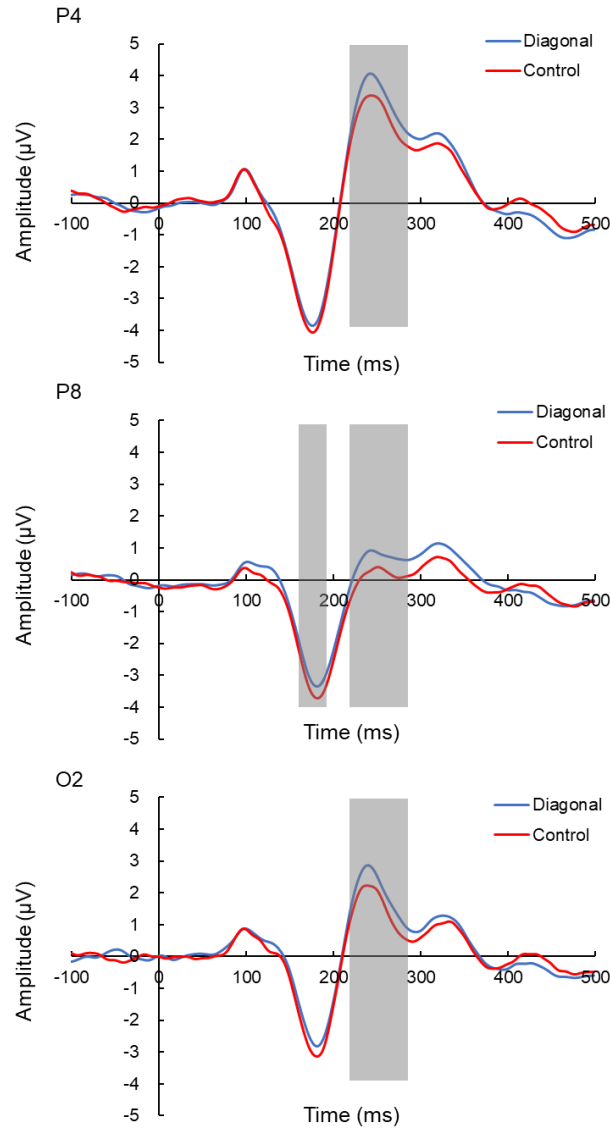


Figure 3.2 Grand averaged ERPs displayed between -100 and 500 ms and recorded at electrode of p4, P8 and O2. The analysis time window for N1 (160–190 ms) is shaded gray on P8 electrode. The analysis time window for late positivity (220–280 ms) is shaded gray on all electrodes.

The results of the point wise running t-tests (diagonal vs control) in electrodes which show significant difference. Based on previous research [18]. we expected different brain activity at visual related cortex (P3, P4, P7, P6, POz, O1, Oz, O2 electrodes). However, we found significant

difference from two stages, early stages range from 160 to 190 ms at electrode of P8, middle stages range from 220 to 280 ms at electrodes of P4, P8 and O2, as shown in Figure 3.2.

(A) N1 component (160–190 ms)

Figure 2.3 showed the difference between symmetric type by the mean amplitude for 160-190 stages. [6]. Results of the repeated-measure ANOVA on mean amplitude revealed no significant main effect for symmetric type, [$F(1, 8) = 3.08$; $p = 0.117$; $\eta^2 = 0.28$], but the mean amplitude for control was larger than that for diagonal at P8 electrode [19]. However, no main effect of electrode [$F(1, 8) = 2.40$; $p = 0.124$; $\eta^2 = 0.23$] or interaction [$F(1, 8) = 0.55$; $p = 0.589$; $\eta^2 = 0.06$] were found.

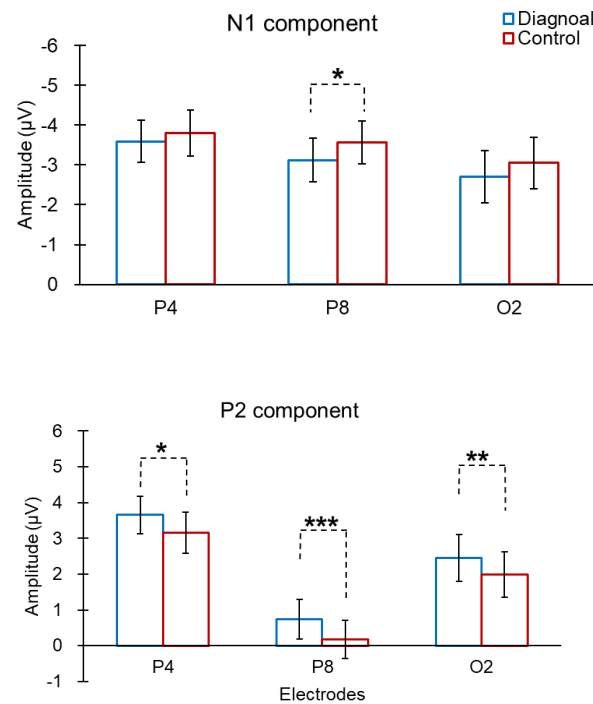


Figure 3.3 Mean amplitudes measured: diagonal and control for two components

(B) P2 component (220–280 ms)

Figure 3.3 also showed the different between symmetric type by the mean amplitude for 220-280 stages. Results of the repeated-measure ANOVA on mean amplitude revealed a significant main effect for symmetric type, [$F(1, 8) = 19.00$; $p < 0.001$; $\eta^2 = 0.63$], showed that the mean amplitude for control was larger than that for diagonal over all electrodes. Also revealed a significant main electrode effect, [$F(1, 8) = 24.87$; $p < 0.001$; $\eta^2 = 0.69$], revealed that the mean amplitude for P4 was significant larger than O2 and P8, and O2 was larger than P8 ($P4 > O2 > P8$). However, there is no difference between the symmetric type and electrode, [$F(1, 8) = 0.26$; $p = 0.800$; $\eta^2 = 0.02$].

3.4 Discussion

In the present study, we used ERP methods to examine the effects of symmetry on visual processing [20]. Our results showed that the activity of visual related cortex for diagonal was weaker than that for control during the period of (160-190 ms), whereas the relationship was inverse during the period of (220-280 ms) [21]. Most importantly, the present ERP results showed a stronger right hemisphere lateraled in symmetry processing, see figure 3.4.

Our results showed the response to central symmetry was significant

slower than that to vertical or horizontal symmetry, consisted with previous studies [22]. This result is likely to be due to symmetry, because subjects are faster to recognize Diagonal. Our results showed that RTs for central symmetry was delayed [23]. One of the most possible reason is that stimulus was presented at both left visual field and right visual field, and attention was divided into left and right, resulting in longer RTs. This finding was consisted with previous visual studies, see figure 3.3.

As discussed above, symmetry is a nonfatal nature. The impression of symmetry is most likely to be caused by real (symmetric) objects [24]. In fact, complete bilateral mirror symmetry as viewed from a non-orthogonal point of view can cause distorted symmetry in the projected retinal image and use distorted symmetry to infer mirror symmetry [8, 9]. In the stimulus of this experiment, symmetry was defined only at the overall composition level.

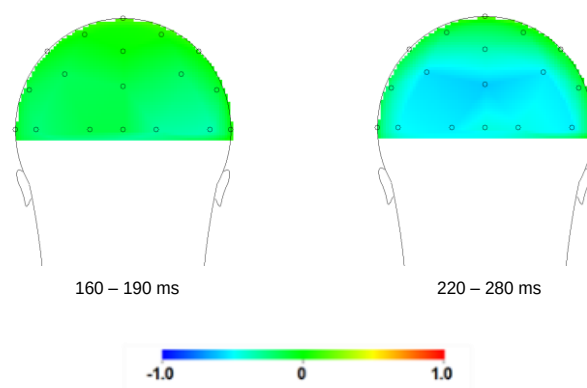


Figure 3.4. Topographical representations of brain activity evoked by the difference between diagonal and control stimuli.

There is no local symmetry in the position of quarterly circle. Therefore, detection of global symmetry can only follow local grouping based on position of quarter circle [25]. Therefore, careful detection of symmetry was impossible in our experiments. Perhaps symmetry only works in interaction with other group compound diagrams that (in part) precede symmetry grouping. Interactive view similar to interrelationships between more local or semi-local groups at the element level at the object or object / part level and more global or semi-global groups, fragmented contour discrimination. Bootstrap model. In this view, the advantage of symmetry becomes most pronounced if grouping based on other clues is too late, or if that grouping leads to an ambiguous interpretation of the visual input. To test this premise, more research is needed.

3.5 Conclusions

In summary, our findings extend previous reports of early sensory processing in extrastriate visual area is not affected by visual symmetry, the symmetry processing main occurred from a later stage range from 220-280 ms [26]. However, this intriguing result was not anticipated from existing reaction time or fMRI and warrants further investigation. In the human visual system, psychological and brain science studies show that there exists an information processing process corresponding to the Gestalt rule of "Symmetrical things (elements) are gathered". In this research, in order to elucidate this problem, we analyzed the relationship between "symmetry physical index", "symmetry perception" and (event related potential: ERP) by manipulating the strength of symmetry.

Chapter 4 Electrophysiological response to symmetry axis orientation

Summary

The recognition of human symmetric figures is influenced by the strength of different symmetry. In the current study, we are concerned with the neural mechanism of visual symmetry processing with different symmetry axes. We asked three questions. First, how does the number of symmetry axes modulate the brain response? Second, whether the difference of visual field will also affect the recognition of symmetry. Third, does the direction of the symmetry axis affect the recognition of symmetry? To investigate these three questions, an electrophysiological method was used to examine brain activity with different symmetry axes. By two experiments, the influence of the direction of the symmetry axis on the recognition of symmetry is in component P2, and the late component SPN has an influence.

4.1 Background

The visual system is extremely sensitive to symmetry. Symmetry was first introduced by Mach et al. [2], who identified three types of symmetry: reflection symmetry, translation symmetry, and rotation symmetry. Symmetry has frequently been used to investigate aspects of visual processing, such as perceptual organization [28], identification of objects against a background [53], face recognition [35; 40; 64], and 3-D reconstruction [67; 75].

The recognition of human symmetric figures is influenced by the strength of different symmetry. In previous studies, visual symmetry was often manipulated with a mathematical structure, the proportion of symmetry/noise, or the number of symmetry axes [8; 27; 30; 37; 41; 49; 62; 66; 73]. Symmetry driven by a mathematical structure often uses reflection, translation or rotation symmetry. Psychophysical studies have confirmed that reflection symmetry elicits a response more easily and rapidly than other symmetrical (translation or rotation symmetry) and asymmetrical stimuli [8; 27; 30; 37; 41; 62]. Symmetry is driven by the proportion of symmetry/noise, that is, the amounts of structure-pairs in the sides of the symmetry axes divided by the totals of structures in the stimulus. Research on symmetry driven by the proportion of symmetry/noise has revealed behavioral performance is enhanced in response to stimuli with a higher proportion of symmetry/noise [8; 26;

42]. Conversely, symmetry was driven by the number of symmetry axes, and the structure on the sides of each symmetry axis was paired (always 100% symmetry). Similar to the proportion of symmetry, the behavioral performance with multiple symmetry axes stimulus was more straightforward and faster; more specifically, the response to the symmetry with 4 axes was faster than to that with 2 axes or 1 axis [5; 76].

Effects of symmetry on visual recognition of symmetric figures. Sasaki et al. conclude that a symmetry-sensitive network of extrastriate areas can be activated independently in each cerebral hemisphere [10]. Levine et al. Proved in 2005 that the visual perception intensity of the upper half field and the lower half field is different [80]. Whether the difference of the field of view also affects the recognition of symmetry is still unclear.

Far more research has focused on the perception of symmetry, especially mirror symmetry, at different axis orientations. Mach (1886, 1959) was among the first to notice the salience of vertical symmetry. Vertical bilateral symmetry has in several studies since been confirmed as more easily detected than symmetries at other orientations [2]. Corballis and Roldan (1975) asked subjects to discriminate reflected from translated dot patterns with an explicit symmetry axis drawn. They found responding was quickest to vertical, followed by oblique

orientations and then horizontal. The results suggested a mental rotation of the patterns to the vertical. These evidences suggest that different directions of symmetry axis seem to have an impact on symmetry cognition. But the existence of this change in the brain is unclear.

In the current study, we are concerned with the neural mechanism of visual symmetry processing with different symmetry axes. We asked three questions. First, how does the number of symmetry axes modulate the brain response? Second, whether the difference of visual field will also affect the recognition of symmetry. Third, does the direction of the symmetry axis affect the recognition of symmetry? To investigate these three questions, an electrophysiological method was used to examine brain activity with different symmetry axes. By two experiments, the influence of the direction of the symmetry axis on the recognition of symmetry is in component P2, and the late component SPN has an influence.

4.2 Methods

4.2.1 Participants

A total of thirteen participants (8 males and 4 females ; mean age = 28; SD = 3.1) with normal or corrected-to-normal vision from Okayama University volunteered for the experiments. They provided written

informed consent for their participation in this study, which was previously approved by the ethics committee of Okayama University.

4.2.2 Stimuli

We used Matlab (v 7.1; The MathWorks, Natick, MA) and GERT, the Grouping Elements Rendering Toolbox (Demeyer & Machilsen, 2011), to construct arrays of Gabor elements on a grey (50%) background (Figure 4.1). The arrays comprised 496×496 pixels. Each Gabor element was defined as the product of an oriented sine-wave luminance grating (spatial frequency of 3 cycles per degree) and a circular Gaussian envelope (standard deviation of 5.4 arc min). In The experiment, these elements had orientations parallel to the local tangent of the shape outline (curvilinear contour elements). We placed 12 Gabor elements on a 7° circle contour to generate two kinds of symmetry stimuli: axis symmetry and center symmetry (figure 4.1B). We positioned 12 Gabors on equidistant locations along a half of circle contour to obtain axis symmetry stimulus, and there were upper, down, left and right four kinds of axis symmetry stimulus by change the locations. For center axis symmetry stimulus, the 12 Gabor elements were segmented into two equal parts, 6 Gabors in each part were positioned equidistant locations along a quarter of circle contour, and the two parts were mirror symmetry. Like axis symmetry, there were four

kinds of center symmetry stimulus by adjust Gabor location, see figure 1A.

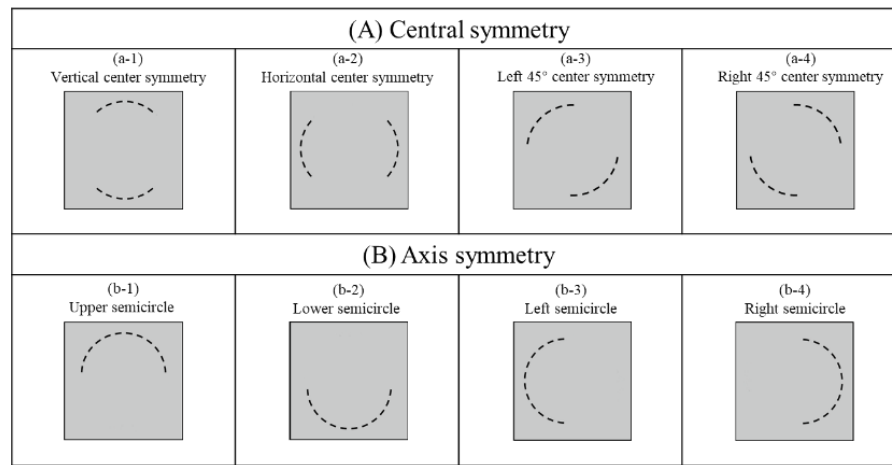


Figure 4.1 Stimulus display in the experiment

4.2.3 Procedure

We measured visual neural activity in a passive viewing task in the present study. To ensure that participants' attention was kept to the displays, the participants were instructed to perform an orthogonal catch detection task in a dimly lit, electrically shielded and sound-attenuated room (laboratory room, Okayama University, Japan) with their head positioned on a chin rest. The experiment consisted of a total of 2000 trials, catch trials (frequency = 0.2) were randomly intermixed in the stimulus sequence. Sixteen sessions were conducted, with each session lasting approximately 7 min. Each session consisted of 25 catch stimuli and 100 symmetry stimuli which were presented randomly. For each stimulus, the subjects were

presented with a fixation cross for 1 s, the stimulus that was displayed for 2s, followed by the 0.5s blank display. During the stimulus, the participants were asked to press “1” key of the keyboard when a white circle was presented in stimulus (figure 4.3). In order to prevent participants from focusing their attention on a small part of the display, we randomly assigned 8 types of circle positions in the fishing experiment. Catch trials were not included in the analyses.

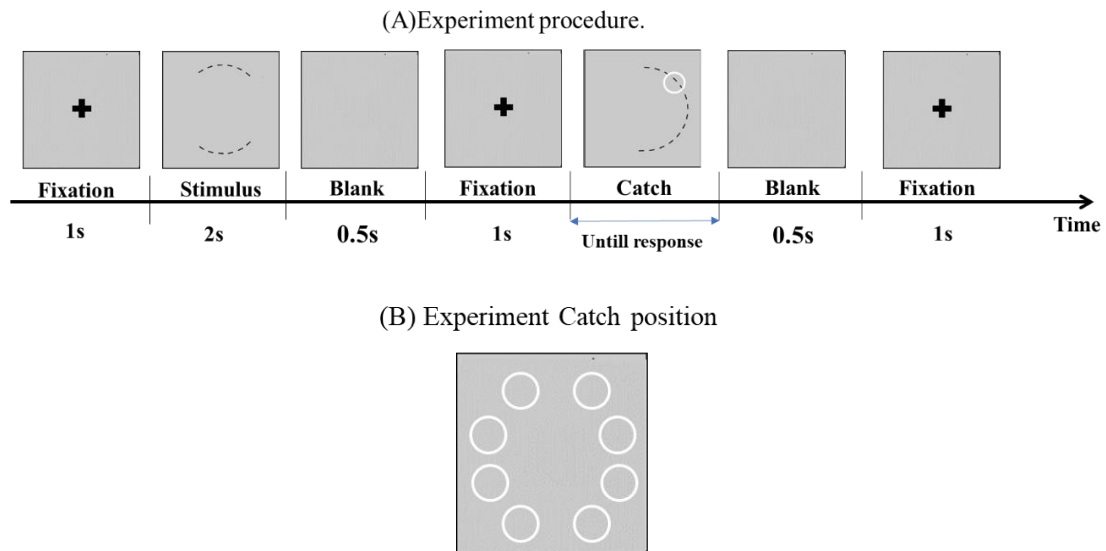


Figure4.3 experiment procedure and task. (A)Experiment procedure. (B)8 kinds of Catch positions, randomly prompted during the experiment.

4.2.4 Apparatus

Participants sat 70 cm from the monitor ($1,024 \times 768$; 85 Hz, Mitsubishi, Tokyo, Japan) with their head stabilized with a chin rest. Stimuli were presented on a CRT monitor and controlled with opensource

Psychophysics Toolbox (Brainard and Vision 1997). An EEG system (BrainAmp MR plus, Gilching, Germany) was used to record EEG signals through 32 AgCl electrodes mounted on an electrode cap (Easy-cap, Herrsching Breitbrunn, Germany) according to the international 10-20 system. All signals were referenced to the left and right earlobes. In order to detect blinks and eye movements, horizontal bipolar electrode (HEOG) was placed approximately 1 cm from the outer canthi of the left eye, vertical bipolar electrode (VEOG) was placed approximately 1 cm below the subject's left eye. During the experiment, the impedance was maintained below 5 k Ω . Raw signals were digitized using a sample frequency of 500 Hz, and all data were stored digitally for off-line analysis. The ERP analysis was using Brain Vision Analyzer software (version 1.05, Brain Products GmbH, Munich, Bavaria, Germany).

4.2.5 Data analysis

The EEG signals which elicited by the task-irrelative stimuli were analyzed separately in the time domain (as averaged ERPs) and in the time-frequency domain using wavelets. For both analyses, the EEG signals were time-locked to the visual stimulus onset. The data were bandpass filtered from 0.1–30 Hz during recording at a sample rate of 500 Hz. The data were divided into 1 s epochs, from -0.2 s to 0.8 s after the stimulus onset with a -0.2 s pre-stimulus baseline. Epochs contaminated by artifacts (e.g., eye

blinks, eye movements, muscle activity, or false alarm) were rejected automatically from the analysis based on a threshold of $\pm 100 \mu\text{V}$ in both EEG and EOG channels before averaging, leaving 150 ± 12 (mean ± 1 SE) valid epochs for axis symmetry trials, 150 ± 11 epochs for central symmetry trials, respectively. The average proportion of excluded trials did not differ significantly between the two conditions, $F(1,11) = 2.475$, $p = .069$, $\eta^2 = .279$. The ground-averaged ERPs across all participants in experiment. we can clearly observe that evoked amplitudes in N1(150-190 ms), P2 (240-320 ms) and SPN (400-800 ms) were difference. Therefore, to explore these differences in detail, separate 2 hemisphere (left, right) * 2 stimulus type (symmetry, baseline) * 4 orientation(0° , 45° , 90° , 135°) repeated measures ANOVA for each component is presented below. A Greenhouse-Geisser corrections with corrected degrees of freedom. The statistical analyses were performed using SPSS 19.

4.3 Results

N1 component. Fig. 4.4 displays symmetry and baseline ERPs at the two Hemispheres. Amplitude in the 150 to 190 ms window was analyzed with a Hemisphere (left, right) $\times$ Stimulus type (symmetry, baseline) $\times$ Orientation (0° , 45° , 90° , 135°). As expected, there was a significant main effect for Stimulus type, $F(1,12) = 13.333$, $p = 0.004$, $\eta^2 = 0.507$, the amplitude for symmetry ($M = -5.66 \mu\text{V}$, $SE = 1.02 \mu\text{V}$) condition was

significantly negative than that for baseline ($M = -4.43 \mu V$, $SE = 0.79 \mu V$) condition. The only other significant effect was the interaction between Hemisphere and Stimulus type, $F(1,12) = 6.286$, $p = 0.028$, $\eta^2 = 0.344$. To explore this interaction, we analyzed left and right hemisphere separately. The effect of symmetry was significant in both hemispheres, but smaller on the left hemisphere (left: $F(1,12) = 12.826$, $p = 0.004$, $\eta^2 = 0.517$; right: $F(1,12) = 16.463$, $p = 0.002$, $\eta^2 = 0.578$). However, there was no significant effects involving axis orientation in the main analysis.

For P2 component, mean amplitude in the 240-320 ms window was examined, and showed a significant main Orientation, $F(3,36) = 8.439$, $p = 0.001$, $\eta^2 = 0.413$. We found that the amplitude with 90° ($M = 3.88 \mu V$, $SE = 0.87 \mu V$) was smaller than amplitude with 45° ($M = 4.66 \mu V$, $SE = 0.89 \mu V$; $p = 0.013$) and 135° ($M = 4.60 \mu V$, $SE = 0.89 \mu V$; $p = 0.031$), but not 0° ($M = 4.15 \mu V$, $SE = 0.82 \mu V$; $p > 0.05$), see figure 4.4. There was interaction of Stimulus type $\times$ Orientation was significant, $F(3,36) = 4.599$, $p = 0.011$, $\eta^2 = 0.277$. We analyzed symmetry and baseline condition separately. The effect of Orientation was significant only in symmetry condition, $F(3,36) = 4.841$, $p = 0.025$, $\eta^2 = 0.592$. Further comparison found that significant difference between 90° ($M = 3.54 \mu V$, $SE = 0.87 \mu V$) and 45° ($M = 5.04 \mu V$, $SE = 0.97 \mu V$; $p = 0.009$), 90° and 135° ($M = 4.71 \mu V$, $SE = 0.92 \mu V$; $p = 0.021$) and a board difference between 45° and 0° ($M = 4.14 \mu V$, $SE = 0.89 \mu V$; $p = 0.076$). In addition, the interaction of

Hemisphere $\times$ Orientation was also significant, $F(3,36) = 4.567$, $p = 0.014$, $\eta^2 = 0.276$. To explore this interaction, we analyzed left and right hemisphere separately, the main effect of Orientation was significant in both hemispheres (left: $F(3,36) = 7.676$, $p = 0.003$, $\eta^2 = 0.390$; right: $F(3,36) = 7.195$, $p = 0.002$, $\eta^2 = 0.375$). Further comparison found that significant difference between 135° ($M = 4.90 \mu V$, $SE = 0.96 \mu V$) and 90° ($M = 4.92 \mu V$, $SE = 0.92 \mu V$; $p = 0.017$), 135° and 45° ($M = 4.59 \mu V$, $SE = 0.93 \mu V$; $p = 0.031$) in the left hemisphere, whereas only significant difference was found between 90° ($M = 3.83 \mu V$, $SE = 0.86 \mu V$) and 45° ($M = 4.74 \mu V$, $SE = 0.90 \mu V$; $p = 0.005$) in right hemisphere. There were no other main effect or interactions.

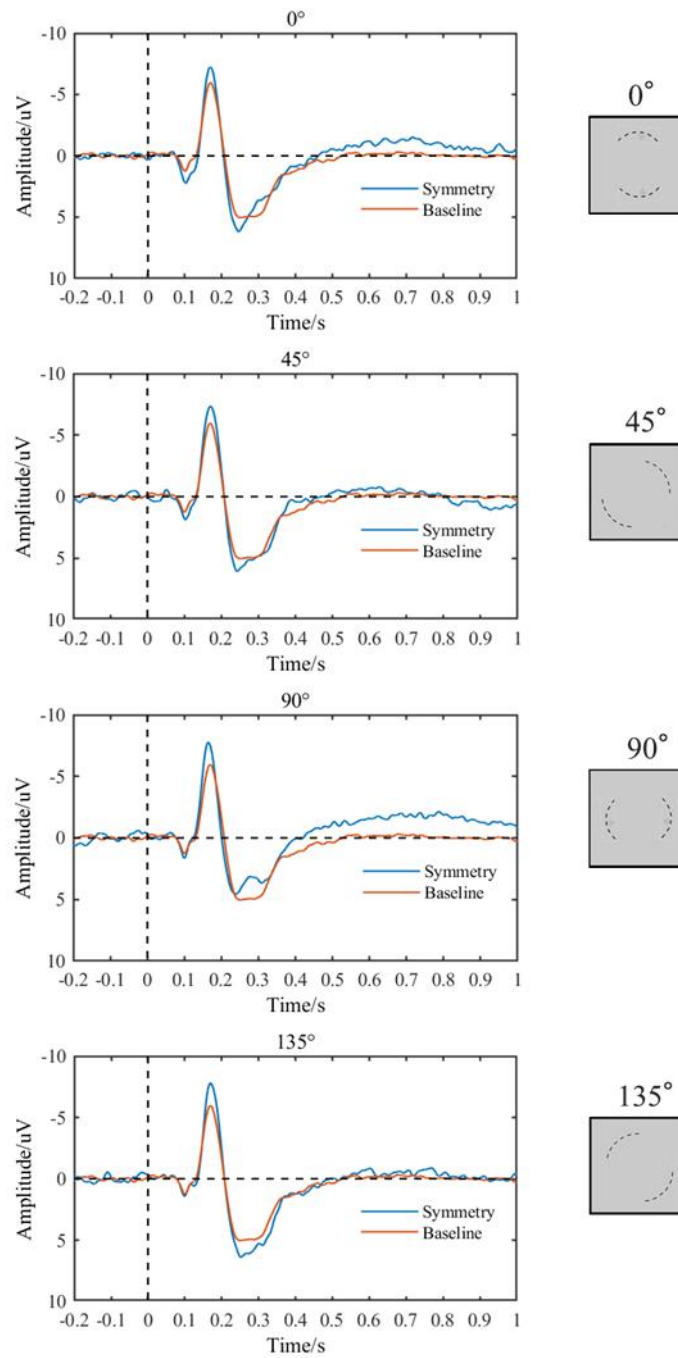


Figure 4.4 Event-related potentials.

SPN amplitude in the 350-600ms interval was examined, see figure 4.5.

As expected, there was a significant main effect for Stimulus type, $F(1,12)$

= 10.222, $p = 0.008$, $\eta^2 = 0.460$, the amplitude for symmetry ($M = -0.37 \mu V$, $SE = 0.43 \mu V$) condition was significantly negative than that for baseline ($M = 0.12 \mu V$, $SE = 0.43 \mu V$) condition. The only other significant effect was the three-way interaction with Hemisphere $\times$ Stimulus type $\times$ Orientation, $F(3,36) = 4.595$, $p = 0.014$, $\eta^2 = 0.277$. This interaction was followed up with separately analyzed. The effect of symmetry was significant in both hemispheres (left: $F(1,12) = 5.509$, $p = 0.037$, $\eta^2 = 0.315$; right: $F(1,12) = 14.321$, $p = 0.003$, $\eta^2 = 0.544$), but smaller on the left hemisphere (left: $M = 0.42 \mu V$, $SE = 0.18 \mu V$; right: $M = 0.57 \mu V$, $SE = 0.15 \mu V$). However, there was no significant effects involving axis orientation in the main analysis.

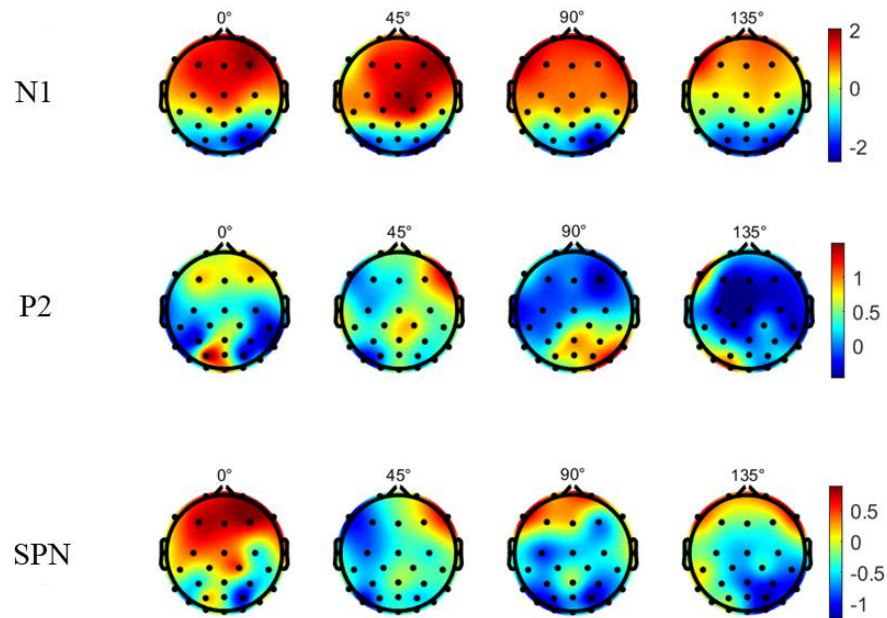


Figure 4.5 Mean amplitude in the experiment: N1, P2 and SPN.

4.4 Discussion and conclusions

Our ERP results showed a significant difference was found between central symmetry and axial symmetry. It was found that the amplitude of central symmetry (black) is larger than the amplitude of axial symmetry (red) for N1, P1 components, see Figure 4.6. The difference between central symmetry and axial symmetry may be influenced by the intensity of midpoint representation. According to the theory of Tonder et al. (2003) and Kovacs et al. (1997), the skeleton of the shape is generated in the early stage of visual processing, and the skeleton of this shape is composed of points of symmetric center, and the intensity of the center point of central symmetry axis (0.86) is greater than that of axial symmetry center point (0.831).

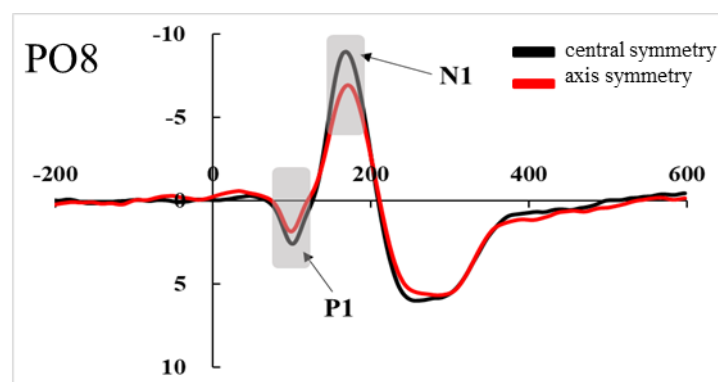


Figure 4.6 event-related potentials. The amplitude of central symmetry (black) is larger than the amplitude of axial symmetry (red) for N1, P1 components.

The reason for this difference is the number of symmetry axes. The

central symmetric stimulus in the experiment has two symmetry axes, so the symmetry is stronger. The results are consistent with those of Makin et al. (2015).

In summary, amplitude of strength in EEG component P2: “Vertical central” < “Horizontal central” < “Right 45 ° central”. This result is consistent with the result of Wenderoth et al. (2000). The effect of the direction of the axis of symmetry on the cognition of symmetry lies in component P2, and the late component SPN has an effect.

Chapter 5 Electrophysiological response to visual symmetry: Effects of the number of symmetry axes

Summary

The symmetry axes of a stimulus are a critical determinant of visual perception. Although much is known about the effects of a single symmetry axis on perception, the effects of multiple symmetry axes are still poorly understood. Here, we investigated the influence of the number of symmetry axes on brain activity using event-related potentials (ERPs). Our results showed that altering the number of symmetry axes affects both the amplitude and the latency of ERPs. Specifically, the amplitude of ERP components increased as the number of symmetry axes increased, starting at the N1 (165-175 ms) component and lasting until the P2 (230-250 ms) component in the bilateral posterior areas and until the N2 (340 ms) component in the frontal-central areas. Importantly, the latency of ERP components was reduced when the number of symmetry axes increased, starting at the N1 in the right posterior area and lasting until the P2 component in the bilateral posterior areas. The temporal and spatial differences in these effects imply that activity related to symmetry axes gradually changes throughout the ventral visual streams in the human brain.

5.1 Background

Mach highlighted a key element of symmetry perception [51]: the difference between perceptual salience and formal measures of regularity, including reflection symmetry, translational symmetry, and rotational symmetry. Symmetry has frequently been used to investigate various aspects of visual processing, such as perceptual organization [28], identification of objects against a background [15], face recognition [35; 40; 64], and 3-D reconstruction [67; 75].

Visual symmetry is often manipulated in terms of the mathematical structure, the ratio of symmetry/noise, or the number of symmetry axes. Symmetry driven by a mathematical structure often involve reflection, translation or rotation [27; 41; 62]. Psychophysical studies have confirmed that stimuli with reflection symmetry elicit responses more easily and rapidly than stimuli with other forms of symmetry (translational or rotational) or without symmetry. Symmetry can also be driven by the ratio of symmetry/noise, that is, the number of paired structures on the sides of the symmetry axes divided by the total number of structures in the stimulus. Research has revealed that behavioral performance is enhanced in response to stimuli with higher symmetry/noise ratios [8; 42; 81]. In contrast, in paradigms where symmetry is driven by the number of symmetry axes, the structures on the sides of each symmetry axis are paired (always 100%

symmetry). As with the symmetry/noise ratio, the number of symmetry axes of a stimulus is positively associated with behavioral responses [62].

Two models have been proposed to explain this behavioral facilitation associated with symmetry. The transformational model argues that the perceptual benefit increases with the number of structure-preserving transformations, that is, the number of axes in reflection symmetry, the number of turns in rotational symmetry or the number of repeats in a repetitive pattern [46]. Furthermore, Vander Helm (2011) quantified the predictions of a transformational model (T) as a function of the number of symmetry axes (F): $T = 1 - (1/2F)$ [71]. According to this model, the perceptual benefit should monotonically increase with the number of symmetry axes; however, this model cannot completely explain why reflection confers a greater perceptual benefit than repetition or rotation. Alternatively, the holographic model proposed by Vander Helm holds that when stimuli are subdivided into smaller pieces, all pieces share the same type of regularity [72]. The holographic model (H) states that $H = E/N$, where E is the number of holographic identities in the pattern and N is the total amount of information. According to this model, the perceptual benefit should increase nonmonotonically with the number of symmetry axes. In addition, all reflection, rotation, repetition, and Glass patterns have this holographic property[42; 69]. Despite the proposal of these models regarding perceptual facilitation of behavior, there is little evidence about

the role of perceptual facilitation in the neural processing of symmetry.

Neuroimaging studies have revealed a network of symmetry-sensitive areas in the extrastriate visual cortex, including the V3a, V4, V7, and lateral occipital complex (LOC), but not in V1 or V2 [8; 70]. The first study on this topic was conducted by Tyler et al. (2005) and focused on human brain activity in response to reflection and random stimuli; the study found that the response in the dorsal LOC was more activated in response to reflection symmetry [70]. In the same year, Sasaki et al. further investigated human and animal brain activity in response to reflection symmetry and found that the V3a, V4, V7 and LOC responded more strongly to symmetrical than asymmetrical stimuli [8]. Brain activity within these networks has been further confirmed to be positively correlated with symmetry; a greater number of symmetry axes in a stimulus is associated with more brain activity [8]. However, due to the low temporal resolution of functional magnetic resonance imaging (fMRI), it remains to be determined when and how these effects of symmetry occur.

Electrophysiological studies have shown that the sustained posterior negativity (SPN), an event-related potential (ERP) component thought to be generated by visual symmetry, is detectable starting at approximately 220 ms in the posterior electrodes [13; 59; 81]. Markin et al. (2013) manipulated the positions of dots on both sides of a vertical axis to form stimuli with different regularity (reflection, rotation, translation, and

random) in order to clarify their neural correlates[56]. Their results showed that the SPN was most pronounced for reflection, rotational and translational symmetry. Subsequently, Palumbo et al. (2015) reported that the SPN and the symmetry/noise ratio were positively correlated [56; 81]. These studies suggest that human electrophysiological activity is modulated by the mathematical structure of symmetry and the ratio of symmetry/noise [55; 56]. An important question remains: how does the brain respond to symmetry when there are different numbers of symmetry axes? Moreover, as mentioned above, most existing ERP studies have focused on the bilateral posterior areas; it is not known whether there an extended network from areas recorded by posterior electrodes to other higher areas, such as those recorded by the frontal and central electrodes. In addition, previous studies found that symmetry processing was sometimes slightly stronger in the right hemisphere when the symmetry involved a mathematical structure [57] and when the symmetry/noise ratio was high [58]. Thus, it is not clear whether the detection of symmetry about different numbers of axes involves different activity in the left and right hemispheres.

In the current study, the neural mechanism of visual symmetry processing with different numbers of symmetry axes was examined via electrophysiology. Regarding the two processing models, if the neural responses are correctly predicted by the transformation model, they should

increase monotonically with an increasing number of symmetry axes [71]; conversely, if the neural responses are predicted by the holographic model, then they should show a pattern corresponding to a quintic increase as the number of symmetry axes is increased, see Figure 5.2D.

5.2 Methods

5.2.1 Participants

Statistical power analysis in G*Power version 3.1 was performed for sample size estimation. The projected partial η^2 of the interaction in this experiment was set to 0.25, the two-tailed alpha level was set to 0.05, the power value was set to 0.8, the number of groups was set to 1, and the number of measurements was set to 6. The calculations indicated that a sample size of 19 would be required. Therefore, twenty participants (13 males; mean age $\pm$ SD: 27.6 $\pm$ 3.0 years) were recruited for the experiments. All participants had normal or corrected-to-normal vision and provided written informed consent for the procedure, which was previously approved by the Ethics Committee of Okayama University and was organized to ensure conformity to the Declaration of Helsinki

5.2.2 Stimuli

We used MATLAB (v 7.1; The MathWorks, Natick, MA) to construct the stimuli. The base pattern used in this study was a circular contour with a cross-sectional luminance profile defined by the radial fourth derivative of a Gaussian (D4). This pattern is the same as the one used by Wilkinson [35] (Figure 5.1). The equation for the circle is

$$D4(r) = C \times \exp\left(-\frac{(r-r_0)^2}{\sigma^2}\right) \times \left(1 - 4\frac{(r-r_0)^2}{\sigma^2} + \frac{4}{3}\frac{(r-r_0)^4}{\sigma^4}\right) \quad (5-1)$$

where C is the pattern contrast, which was set to 100%; r_0 is the mean radius of the stimulus, the center of which was located at the fixation point and set to 7.5deg; and σ represents the thickness of the cross-sectional profile, which was set to 0.5deg. To examine symmetry perception with different numbers of symmetry axes, we used a semicircle, with only 1-axis of symmetry, as one of the stimuli. Then, we divided the semicircle equally into two parts, producing 2-axes. We also divided the circle into three equal parts (3-axes), four equal parts (4-axes), five equal parts (5-axes) and six equal parts (6-axes), see Figure 5.2B.

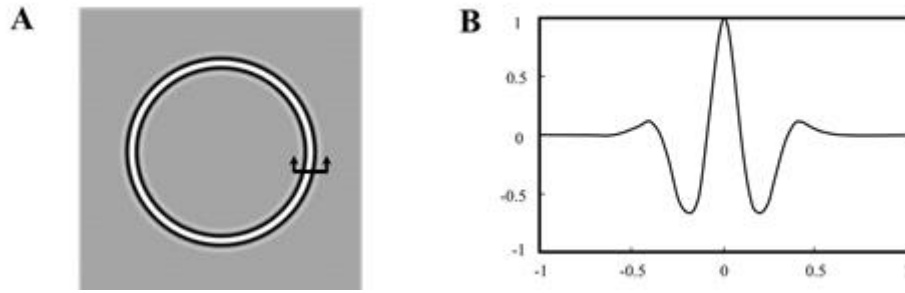


Figure 5.1 Base stimulus used in the experiment. (A) Example of the D4 circles. (B) Cross-sectional luminance profile of the D4 contour as indicated by the arrows in (A).

5.2.3 Procedure

Participants sat 70cm from a CRT monitor ($1,024 \times 768$; 85Hz), with the head stabilized by a chin rest, in a dimly lit, electrically shielded and sound-attenuated room. Stimuli were presented on the monitor under the control of the open-source Psychophysics Toolbox [29]. To ensure that the participants' attention remained focused on the displays, they were instructed to perform an orthogonal detection task with catch stimuli. The experiment consisted of six sessions of 125 trials each, with every session consisting of 25 trials containing catch stimuli randomly intermixed with 100 trials containing symmetrical stimuli. For each stimulus, the subjects were presented with a fixation cross for 1s, followed by the stimulus for 2s and then a blank display for 0.5s. During the experiment, the participants were asked to press the “1” key on the keyboard when a white circle was presented on the display. To prevent participants from focusing their

attention on a small part of the display, we randomly varied the location of the circle among 8 positions in the experiment (Figure 5.2).

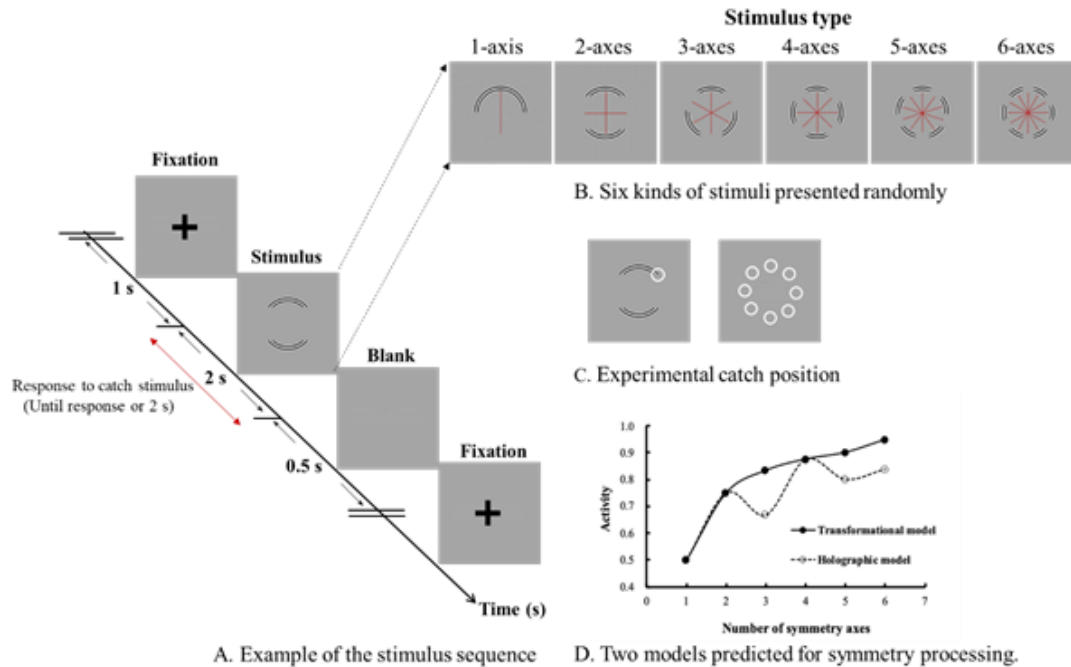


Figure 5.2 Trial structure of the experiment. (A) Experimental procedure. (B) Stimulus types. (C) Catch stimuli. (D) Predictions of two models for symmetry processing.

5.2.4 Apparatus

An electroencephalography (EEG) system (BrainAmp MR plus, Gilching, Germany) was used to record EEG signals through 32 AgCl electrodes mounted on an electrode cap according to the international 10-20 system. All signals were referenced to the left and right earlobes. To detect blinks and eye movements, a horizontal bipolar electrode was placed approximately 1cm from the outer canthus of the left eye, and a vertical

bipolar electrode was placed approximately 1.5cm below the subject's left eye. During the experiment, impedance was maintained below 5k Ω for all electrodes. Raw signals were digitized using a sampling frequency of 500Hz.

5.2.5 Data analysis

Offline preprocessing. The ERPs elicited by task-irrelevant stimuli were analyzed by using Brain Vision Analyzer software (Brain Products GmbH, Munich, Bavaria, Germany). The data were processed with a bandpass filter from 0.1 to 30Hz during recording at a sampling rate of 500Hz. The data were divided into 1.0s epochs [-0.2s to 0.8s], with the period from -0.2 to 0s used as the baseline. Epochs contaminated by artifacts (e.g., eye blinks, eye movements, muscle activity, or false alarms) were rejected automatically from the analysis if the amplitude exceeded a threshold of $\pm 100\mu\text{V}$ before averaging; the number of excluded trials did not differ significantly among conditions ($F(5,95) = 0.675$, $p = 0.615$, $\eta^2 = 0.034$). The grand average data were obtained across all participants for each condition.

Statistical analyses. According to previous studies, the posterior area has been consistently associated with the extrastriate symmetry response. In addition, the anterior and central areas have been implicated in visual

processes related to perceptual and cognitive tasks [44; 82]. Therefore, we examined the effect of the number of symmetry axes on the electrophysiological responses in the anterior, central and posterior areas. In addition, the responses in the left, middle and right regions were identified to determine the presence of laterality, which has been suggested by previous symmetry studies [9; 57]. Thus, we focused our analysis on nine regions of interest (ROIs): left anterior (LA: Fp1, F3 and F7), middle anterior (MA: F3, Fz and F4), right anterior (RA: Fp2, F4 and F8), left central (LC: T7, C3 and CP5), middle central (MC: CP1, Cz and CP2), right central (RC: T8, C4 and CP6), LP (PO7, PO3 and O1), middle posterior (MP: Pz, POz and Oz), and right posterior (RP: PO8, PO4 and O2). The signal from each of the nine ROIs was measured as the mean of the signals from three adjacent electrodes. We utilized time windows commonly found in the literature [44] to capture ERP components: N1 (120–220 ms) and P2 (180–280 ms) in the posterior and central areas and N1 (150–220 ms), P2 (200–300 ms) and N2 (300–400 ms) in the anterior areas. The amplitudes and latencies of these components were statistically analyzed using repeated-measures analysis of variance (ANOVA) with symmetry level (1-axis, 2-axes, 3-axes, 4-axes, 5-axes, and 6-axes) and ROI (LA, MA, RA, LC, MC, RC, LP, MP, and RP) as within-subject factors. In addition, to test the hypotheses dictated by the two models, one-way ANOVA with symmetry level as a variable was conducted separately

for each ROI, and orthogonal polynomial contrasts (linear, quadratic, cubic, quartic, and quintic) were constructed. All statistical analyses were performed using SPSS 19 software for Windows. Greenhouse-Geisser corrections were applied with adjusted degrees of freedom, and the effect size was estimated with the partial η^2 for the ANOVAs. A p value <0.05 was considered to indicate a statistically significant difference.

5.3 Results

The grand average ERPs over 9 ROIs are shown in Figure 5.3. As in previous studies [10, 21, 22], clear differences in the amplitudes and latencies of the N1, P2 and N2 components were present from posterior to anterior. Along this spatial axis, the amplitudes were decreased and the latencies were delayed for N1 and P2. In addition, N2 components were observed in the central and anterior areas but not in the posterior areas. Regarding symmetry levels, the amplitudes of the N1 and P2 components increased with the number of symmetry axes. In addition, the latencies of these two components decreased as the number of symmetry axes increased, see Figure 5.4.

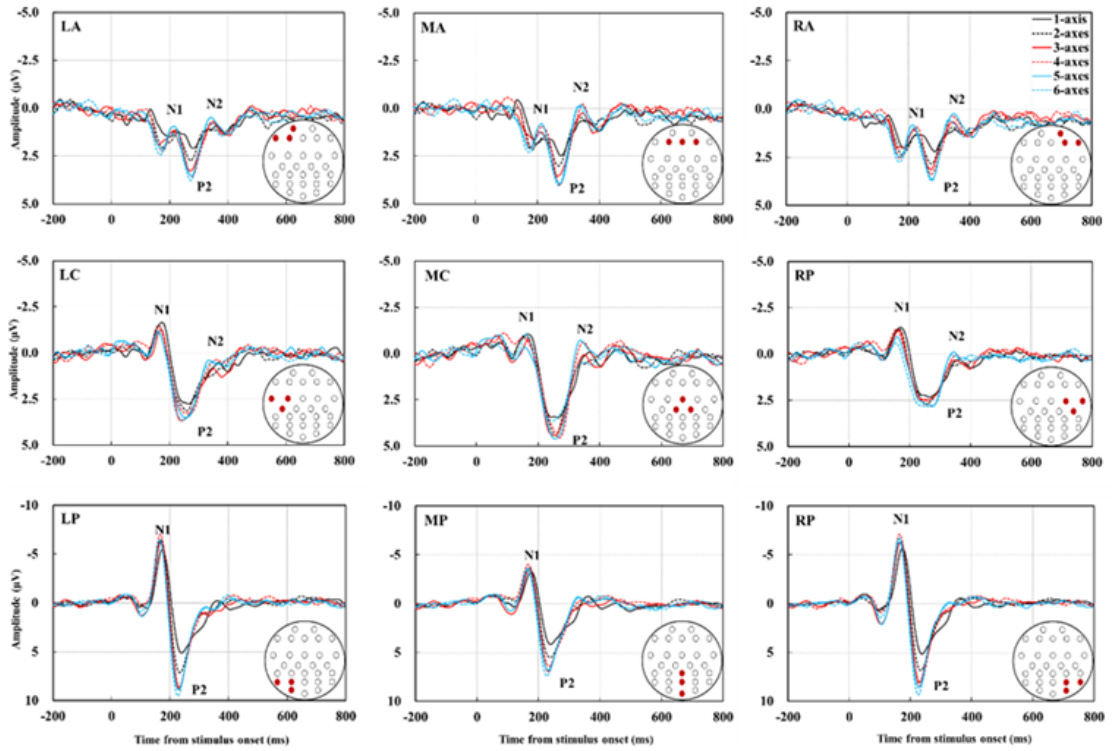
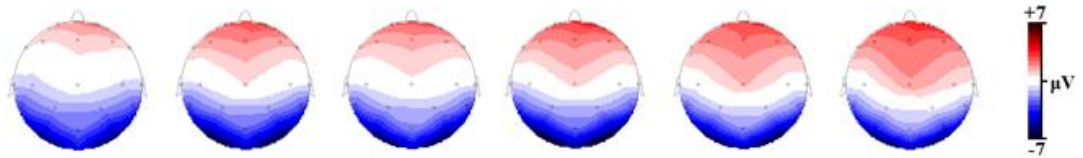


Figure 5.3 Grand average ERPs in the nine ROIs.

(A) N1 at approximately 165-175ms



(B) P2 at approximately 230-250ms



(C) N2 at approximately 340ms

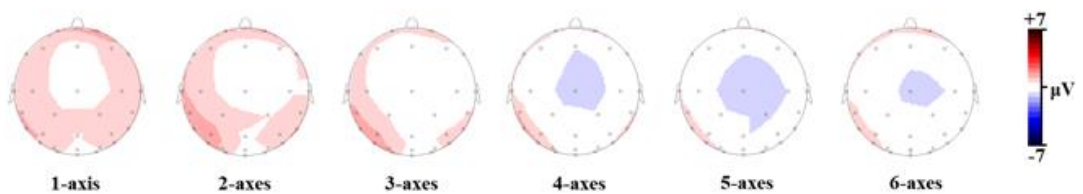


Figure 5.4 Topographic maps of ERP components: (A) N1, (B) P2 and (C) N2.

(A) Peak amplitudes

For N1 amplitude, the effect of symmetry level was significant ($F(5,95) = 3.382, p < 0.001, \eta^2 = 0.151$), with more symmetry axes leading to a higher amplitude. The effect of ROI was significant ($F(8,152) = 32.464, p < 0.001, \eta^2 = 0.631$), with N1 amplitudes increasing from anterior to posterior. The interaction between ROI and symmetry level was also significant ($F(40,760) = 37.407, p = 0.001, \eta^2 = 0.663$). Post hoc comparisons showed a higher amplitude in posterior areas for the 4-axis condition than for the 1-axis and 3-axis conditions (all $p < 0.01$). Follow-up one-way ANOVA for the ROIs revealed a main effect of symmetry level on the responses in RP ($F(5,95) = 2.507, p = 0.035, \eta^2 = 0.117$), with significant quadratic ($F(1,19) = 6.767, p = 0.018, \eta^2 = 0.263$) and quintic trends ($F(1,19) = 11.816, p = 0.003, \eta^2 = 0.383$).

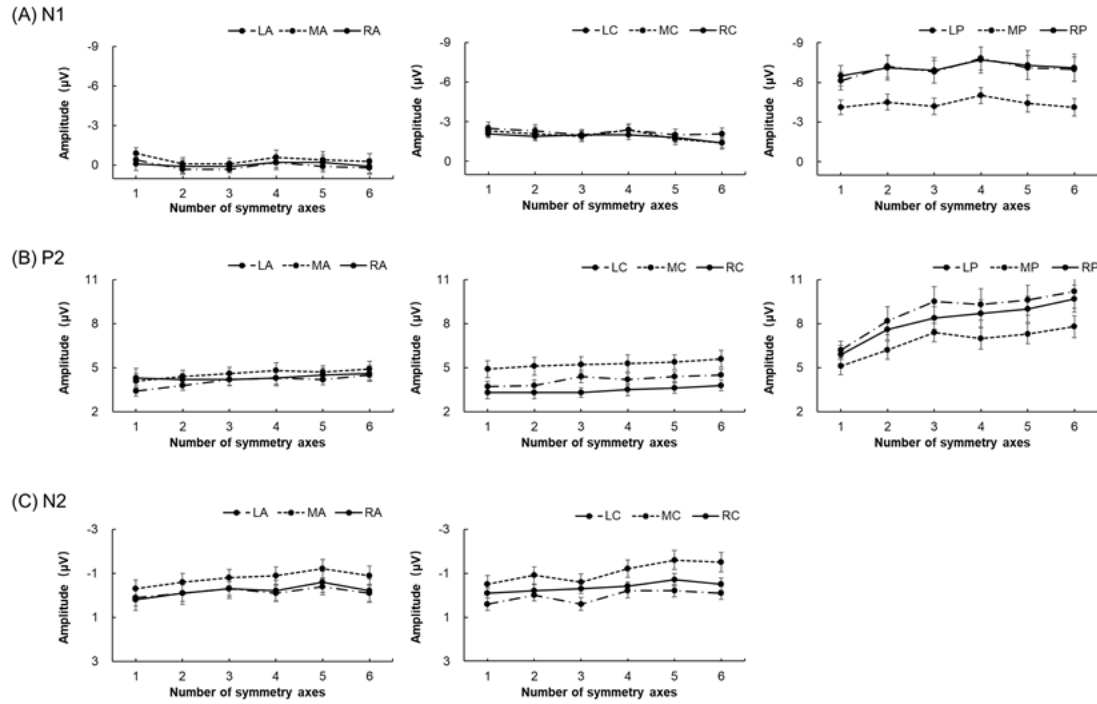


Figure 5.5 Amplitudes of (A) N1, (B) P2 and (C) N2 ERP components.

For P2 amplitude, ANOVA revealed a significant effect of ROI ($F(8,152) = 24.029$, $p < 0.001$, $\eta^2 = 0.558$). Post hoc comparisons showed that the amplitudes were larger in the posterior areas than in the anterior and central areas (all $p < 0.01$). The interaction between ROI and symmetry level was significant ($F(40,760) = 7.250$, $p < 0.001$, $\eta^2 = 0.276$), as was the effect of symmetry level ($F(5,95) = 15.060$, $p < 0.001$, $\eta^2 = 0.442$). Post hoc comparisons showed that the number of symmetry axes had an effect in the LA, LC, LP, MP and RP areas. One-way ANOVA revealed that the amplitude increased linearly in these areas as the number of symmetry axes increased (all $p < 0.05$, Figure 5.5).

For N2 amplitude, ANOVA revealed a significant effect of ROI ($F(5,95) = 5.871$, $p = 0.005$, $\eta^2 = 0.236$). Post hoc comparisons showed that the amplitudes were larger in the middle than in the corresponding bilateral areas (and $MA < MC$, all $p < 0.05$). However, there were no significant effects of symmetry level, or interaction (all $p > 0.05$).

(B) Peak latencies

For N1 latency, the effect of ROI was significant ($F(8,152) = 207.065$, $p < 0.001$, $\eta^2 = 0.916$). Post hoc analysis found that N1 peaked later in anterior areas than in central and posterior areas (all $p < 0.05$), while the peaks of the latter two regions did not differ from each other. The interaction between ROI and symmetry level was significant ($F(40,760) = 112.821$, $p = 0.001$, $\eta^2 = 0.856$). One-way ANOVA showed a significant effect of stimulus level in MP ($F(5,95) = 3.754$, $p = 0.019$, $\eta^2 = 0.165$) and RP ($F(5,95) = 9.376$, $p < 0.001$, $\eta^2 = 0.330$), with a decreasing linear trend in both areas (all $p < 0.05$)

ANOVA on P2 revealed significant effects of ROI ($F(8,152) = 3.812$, $p = 0.038$, $\eta^2 = 0.167$) and of the interaction between ROI and symmetry level ($F(40,760) = 2.172$, $p = 0.034$, $\eta^2 = 0.103$). One-way ANOVA showed a significant effect of symmetry level in posterior areas (LP: $F(5,95) = 4.553$, $p = 0.011$, $\eta^2 = 0.193$; MP: $F(5,95) = 4.291$, $p = 0.007$, $\eta^2 = 0.184$; RP $F(5,95) = 8.699$, $p = 0.001$, $\eta^2 = 0.314$), and latency

exhibited a decreasing linear trend in these areas (all $p < 0.05$). For N2 latency, there were no significant effects of symmetry level, ROI, or interaction (all $p > 0.05$, Figure 5.6).

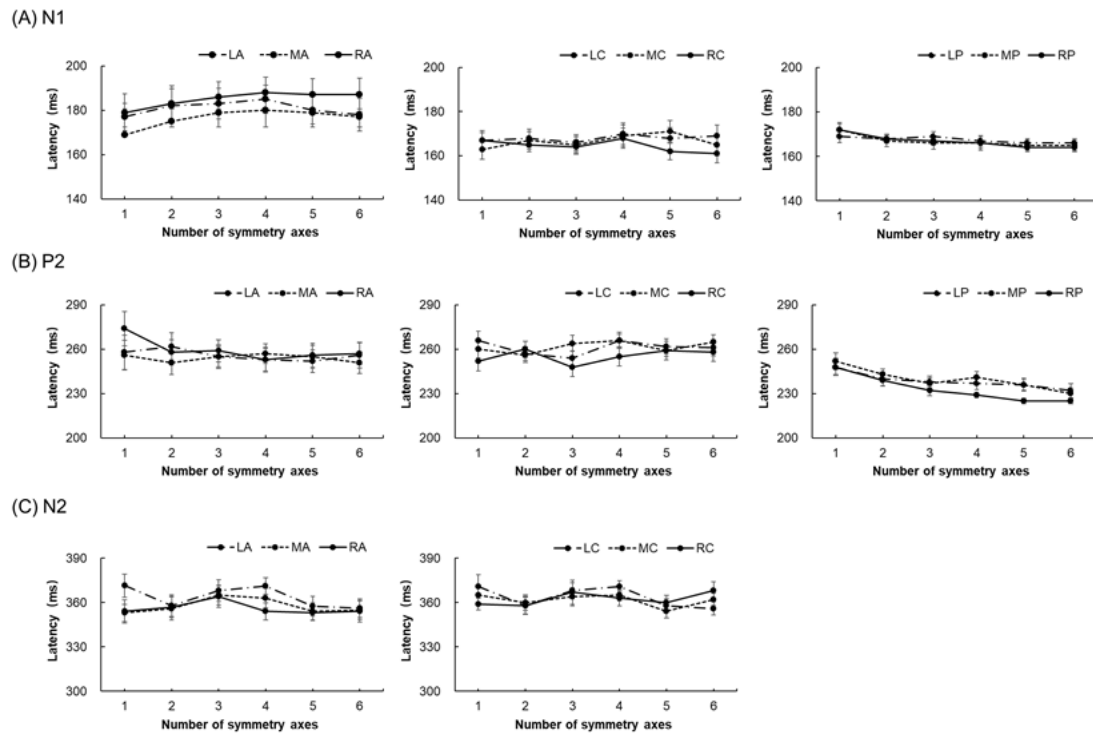


Figure 5.6 Latencies of (A) N1, (B) P2 and (C) N2 ERP components.

5.4 Discussion

In the present study, we investigated brain activity in response to different numbers of visual symmetry axes by conducting a high-temporal-resolution ERP experiment. Our results demonstrated that not only the bilateral posterior areas but also the anterior and central areas responded differentially to different numbers of symmetry axes. In addition, the number of symmetry axes affected both the amplitude and the latency of

ERPs, with an increase in the former and a decrease in the latter as the number of symmetry axes increased.

Increased amplitude with increasing numbers of symmetry axes. Our results showed that the amplitude of N1 increased along with the number of symmetry axes, showing quadratic and quintic trends, which suggests that the effect of symmetry axes on component is predicted by the holographic model [71]. Only a few studies have explored the effect of symmetry on N1[56; 59]. Makin et al. (2012) used white and black patterns to investigate the effect of reflection symmetry on visual perception [59]. They found a larger N1 over the bilateral posterior areas in response to reflection symmetry than in response to random designs. Markin et al. (2013) further manipulated stimuli with different regularity (reflection, rotation, translation, and random) to clarify their neural correlates [56]. Their results revealed that regularity altered N1, with greater N1 amplitude observed for reflection and rotational symmetry than for translational symmetry or random designs. This finding, together with prior evidence, suggests that the effect of symmetry axes begins at N1 and originates in the posterior areas, where the representations of symmetry are linked to the amplitude of the neural response.

Note that the effect of symmetry axis modulation was demonstrated as a monotonically increasing pattern for P2 (Figure 5.5B), as predicted by the transformational model [71]. These results were in agreement with

previous fMRI studies [8] showing that brain activation in the extrastriate cortex was related to the number of symmetry axes, with the weakest response to stimuli with 1-axis and the strongest to stimuli with 6-axes. In addition, P2 is considered to play a role in symmetry processing, and the amplitude of P2 was positively correlated with symmetry salience [6; 38; 59]. Therefore, the effect of symmetry axes is also linked to the P2 amplitude; the more symmetry axes within the stimulus, the stronger the symmetry perception is.

Reduced latency with an increasing number of symmetry axes. Importantly, the number of symmetry axes affects latency. To our knowledge, this is the first report of the temporal characteristics of symmetry processing. Our results showed that the latencies of N1 and P2 within posterior areas decreased linearly as the number of symmetry axes increased. These results suggest that the modulating effect of symmetry axes on latency can be predicted by the transformational model. This may relate to the theory of multiple orientation channels in symmetry processing [62]. On the one hand, symmetry processing can be performed independently in each channel. Horizontal symmetry is processed more slowly than vertical symmetry but more quickly than diagonal symmetry. On the other hand, these channels can also be processed in a temporally overlapping, parallel system of limited capacity, which leads to a faster response. Indeed, Wenderoth et al. reported that the response time was

related to the number of axes (1-axis > 2-axes = 3-axes > 4-axes) [76]. Therefore, we speculate that when the number of symmetry axes within the stimulus is increased, the number of channels in use also increases, which increases the processing speed.

In addition, the temporal effect of symmetry axis modulation was lateralized to the right hemisphere. The right hemisphere plays an important role in visual cognitive processing, including visual structure processing and visuospatial attention [43; 68]. Some studies have reported ERP results similar to those of our study [9; 28; 54]. Makin et al. investigated the influence of symmetry processing by contrasting the SPN for reflected stimuli with that for translated stimuli [54]. Their results revealed that the SPN occurred in the bilateral posterior regions, but it was stronger in the RP than in the LP. They also measured alpha power, i.e., event-related desynchronization, and found consistent right laterization [9; 57; 58]. In addition, psychophysical studies have shown that symmetrical stimuli can be detected slightly faster when presented in the left hemifield than in the right hemifield [41]. Thus, our results build on previous findings by establishing that right-hemisphere laterization is present not only in response amplitude but also in response latency.

Comparing our results with fMRI findings showed that the number of symmetry axes modulated activity not only in posterior areas but also in frontal and central areas. In the current study, symmetric activity occurred

at 230-250 ms for posterior areas, 255 ms for central areas and 272 ms for frontal areas. These results suggested that the effect of symmetry might be projected from posterior areas across corresponding central areas to frontal areas in the ventral visual processing pathway [50]. The P2 in the frontal area is generally correlated with high-level sensory processing, which occurs before decisional processes leading up to action execution [63]. Indeed, we found that the modulatory effect of symmetry axes disappeared at N2. There were some differences between the present study and previous ERP studies [59; 81]; these differences may be related to the experimental task. Previous studies used a delayed response paradigm, which required participants to retain symmetry information until they responded. In contrast, the present study used an oddball paradigm; participants needed only to detect whether white circle was presented. This view is supported by Oka et al. (2001), who investigated the characteristics of visual evoked potentials with different symmetry saliences using a passive paradigm [6]. Their results showed that symmetry-dependent activity persisted in P2. Therefore, we believe that the effect of symmetry axes at the intermediate stage of visual processing was generated in the bilateral posterior areas and extended to the central and frontal areas.

5.5 Conclusions

Based on the temporal and spatial distribution of modulatory effects of

symmetry axes on brain activity, we found that the number of symmetry axes influences the intermediate stage of visual processing, arising after the initial visual response in the primary visual cortex and continuing throughout the ventral visual streams. Specifically, in the bilateral posterior areas, the perceptual benefits of symmetry were linked to the amplitude and latency of ERPs. This finding improves the present understanding of the coding of symmetry axes in the human brain. It should be mentioned here that the present results are limited only to the effect of the difference between conditions as the number of axes varies for symmetric stimuli, not showing a unique symmetry-specific activation because of including the effect of the number of stimulus elements (1-axis-6-axes).

Chapter 6 General conclusion and future projections

Summary

This thesis has investigated the whether the magnitude of eccentricity will affect the processing of visual symmetry. An ERP method was used to evaluate temporal characteristic of different visual symmetry figures. an electrophysiological method was used to examine brain activity with different symmetry axes. Additionally, the influence of the number of symmetry axes on brain activity using event-related potentials (ERPs). In this chapter, our findings are summarized below. Further, some future projections are included.

6.1 General conclusions

The current thesis includes four experiment studies. The first experiment is the basis of the thesis, an ERP method was used to evaluate temporal characteristic of different visual symmetry figures. The second experiment, we measured the processing of symmetrical stimulus (diagonal) and asymmetrical stimulus (control) with two levels of intensity by measured event-related potentials (ERPs). The third experiment investigated the how does the number of symmetry axes modulate the brain response. In the fourth experiment, we investigated the influence of the number of symmetry axes on brain activity using event-related potentials.

Chapter 2 describes the first experiment, previous studies have showed a special symmetry processing in human visual system. However, where and how visual symmetry processing is not clear at all. Furthermore, the temporal characteristic of visual symmetry processing is also unclear. In the present study, visual discrimination task was used to measure the relationship between psychical index of symmetry and perceived symmetry. An ERP method was used to evaluate temporal characteristic of different visual symmetry figures.

Chapter 3 describes the effect of visual eccentricity on symmetry perception. Although symmetry is known to be an important determinant of visual processing and an appreciation of visual symmetry has been

studied in several electroencephalography (EEG) experiments, it remains not well clear the mechanism of visual symmetry processing. To investigate this, we measured the processing of symmetrical stimulus (diagonal) and asymmetrical stimulus (control) with two levels of intensity by measured visual evoked potential (VEP). Our results showed significant difference in P8, P4 and O2, the right hemisphere for symmetry processing. In addition, the activity of visual related cortex for diagonal was weaker than that for control during the period of (160-190 ms), whereas the relationship was inverse during the period of (220-280 ms) in all intensity. This work provides a new account of neural mechanisms involved in visual symmetry perception.

Chapter 4 Describes the direction of the symmetry axis affect the recognition of symmetry. In the study, we are concerned with the neural mechanism of visual symmetry processing with different symmetry axes. We asked three questions. First, how does the number of symmetry axes modulate the brain response? Second, whether the difference of visual field will also affect the recognition of symmetry. Third, does the direction of the symmetry axis affect the recognition of symmetry? To investigate these three questions, an electrophysiological method was used to examine brain activity with different symmetry axes. By two experiments, the influence of the direction of the symmetry axis on the recognition of symmetry is in component P2, and the late component SPN has an influence.

Chapter 5 Describes the direction the influence of the number of symmetry axes on brain activity. The symmetry axes of a stimulus are a critical determinant of visual perception. Although much is known about the effects of a single symmetry axis on perception, the effects of multiple symmetry axes are still poorly understood. Here, we investigated the influence of the number of symmetry axes on brain activity using event-related potentials (ERPs). Our results showed that altering the number of symmetry axes affects both the amplitude and the latency of ERPs. Specifically, the amplitude of ERP components increased as the number of symmetry axes increased, starting at the N1 (165-175 ms) component and lasting until the P2 (230-250 ms) component in the bilateral posterior areas and until the N2 (340 ms) component in the frontal-central areas. Importantly, the latency of ERP components was reduced when the number of symmetry axes increased, starting at the N1 in the right posterior area and lasting until the P2 component in the bilateral posterior areas. The temporal and spatial differences in these effects imply that activity related to symmetry axes gradually changes throughout the ventral visual streams in the human brain.

6.2 Future Projections

According to the current situation, future studies will focus on improving experiment method (e.g. functional magnetic resonance imaging (fMRI)) to uncover the cerebral cortex mechanism of visual symmetry processing and to provide further important basis for our event-related potentials (ERPs) experiment here.

Appendix

Simple introduction of EEG and B++apparatus. The BrainAmp MR plus was manufactured by BrainProduct Inc., Germany. This amplifier is a compact solution for neurophysiology research that can be combined with other units within the same product family to cover a vast range of possible application areas. This fully portable solution can be used for standard EEG/ERP recordings and can also be placed inside of the MRI bore for simultaneous EEG/fMRI acquisitions, *Figure AI-1*.

Thanks to its 5 kHz sampling rate per channel, the BrainAmp can be used to record EEG, EOG, and EMG signals as well as evoked potentials with a frequency up to 1 kHz. The 16-bit TTL trigger input allows the detection of a large number of markers from visual, acoustic, electrical, magnetic or other stimulation modalities. The BrainAmp can be used both with passive and active electrodes offering a great degree of flexibility.

The 32 channel units can be stacked to expand the number of channels up to 256 and combined with the BrainAmp ExG to record EEG, EOG, EMG, ECG, GSR (Galvanic Skin Response) and many other types of bipolar and auxiliary signals.

BRAINVISION
professional **BRAINAMP MR PLUS**



Figure AI-1 EEG amplifier of BrainAmp MR plus

Table AI-1 Technical specifications of BrainAmp MR plus

Number of Channels per unit	32
Max. Number of channels	128
Reference Type	unipolar
MR-compatibility	Yes (for scanners up to 4 Tesla)
Bandwidth [Hz]	DC - 1000
High Pass Filter [Hz]	0.016 / 10 s AC or DC switchable
Low Pass Filter [Hz]	1000 / 250 switchable
Input Noise [μ Vpp]	≤ 1
Input Impedance [$M\Omega$]	10 / 10000
Input Measurement Ground / eference	Yes
A/D-C [bit]	16
A/D-Rate [Hz]	5000
Max. Sampling Frequency [Hz]	5000
Offset Compatibility [mV]	± 300
Operating Range [mV]	selectable: ± 3.2768 ; ± 16.384 ; ± 327.68
Resolution [μ V]	selectable: 0.1; 0.5; 10.0
CMRR [dB]	≥ 110
TTL Trigger Input [bit]	16
Synchronized Digital Trigger Input [bit]	up to 16
Max. Power Consumption [mA]	160
Power Supply	rechargeable Battery
Signal Transmission	optical
PC Interface	PCI, USB 2.0
Deblocking Function	Yes
Blocking of Unused Channels	Yes
Safety	Twin Fiber optical Transmission Protection Class II, Type BF IEC EN 60601 EMC tested, electrically safe
Classification to MDD 93/42/EEC	Class IIa
Dimensions H x W x D [mm]	68 x 160 x 187
Weight [kg]	1.1

Publications

1. Journal Paper

- [1]. Meng Wang, Fengxia Wu, Gert van Tonder, Qiong Wu, Yang Feng, Yiyang Yu, Jiajia Yang, Satoshi Takahashi, Yoshimichi Ejima, Jinglong Wu. Electrophysiological response to visual symmetry: Effects of the number of symmetry axes. *Neuroscience Letters*, Volume 770, 23 January 2022, 136393.

2. International conference paper

- [1] Meng Wang, Qiong Wu, Yoshimichi Ejima, Jinglong Wu. The effect of symmetry on visual perception: an event-related potential study. *International Conference on Complex Medical Engineering (ICME)*, pp.50-51, (2017).
- [2] Meng Wang, Qiong Wu, Fengxia Wu, Jiajia Yang, Satoshi Takahashi, Yoshimichi Ejima, Jinglong Wu. The time course of symmetry effect on shape perception: an event-related potential study. *International Conference on Mechatronics and Automation (ICMA)*, pp. 210-214, (2018).

3. Japan conference paper

- [1] 王萌, 吳瓊, 高橋 智, 江島義道, 吳景龍. 発表題目：対称性知覚の心理学的・VEP分析. 第19回ヒト脳機能マッピング学会.

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