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An ERP study of visual change detection: effects of magnitude of spatial frequency changes on the change-related posterior positivity

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Abstract

In event-related brain potential (ERP) studies using a visual S1-S2 matching task, change stimuli elicit a posterior positivity at around 100-200 ms. In the present study, we investigated the effects of magnitude of spatial frequency changes on change-related positivity. Each trial consisted of two sequentially presented stimuli (S1-S2), where S2 was either (1) the same as S1 (i.e., NO-change, $p = .40$), (2) different from S1 in spatial frequency only (SF-change, .40), (3) different in orientation only (OR-change, .10), or (4) different in both spatial frequency and orientation (BOTH-change, .10). Further, three magnitude conditions (Large, Medium, and Small) were used to examine the effect of the magnitude of the spatial frequency change. Participant's ($N = 12$) task was to respond to S2 with a change in orientation (from vertical to horizontal, or from horizontal to vertical) regardless of the spatial frequency of the stimulus. Changes in the spatial frequency elicited change-related positivity at a latency range of about 120-180 ms, which was followed by a central negativity (N270) and a late positive component (LPC). The amplitude of the change-related positivity tends to be enhanced as the magnitude of the change is increased. These results support the notion that the change-related positivity reflects memory-based change detection in the human visual system.

Key words:

Event-related brain potential (ERP), Visual change detection, Magnitude of stimulus changes.

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1. Introduction

Involuntary processing of changes in the environment, which are irrelevant to ongoing tasks, is a fundamental ability needed for biological organisms to survive. It has been assumed that the information regarding changes processed in the pre-attentive change detection system is sent to the capacity-limited system, which enables the allocation of attentional resources to task-irrelevant changes in the environment. Such neural mechanisms of change detection processing in the human brain have been clarified through the use of event-related brain potentials (ERPs) (e.g., Näätänen, 1992). In the auditory modality, changes in several stimulus features elicit a mismatch negativity (MMN) at around 100-200 ms after stimulus onset (e.g., Näätänen et al., 1978). MMN is thought to be elicited by a mismatch process between a sensory memory trace of a previously presented stimulus and an incoming stimulus (i.e., memory-based comparison hypothesis) (e.g., Jacobsen and Schröger, 2001; Jacobsen et al., 2003, for reviews, see Näätänen, 1992; Näätänen et al., 2005). Moreover, it has been proposed that MMN reflects automatic change detection processing, since it can be observed even when the participant attends to other auditory or visual inputs (e.g., Sussman et al., 2003, for a review, see Näätänen, 1992).

Some previous studies with the oddball paradigm have reported an MMN-like negativity in the

visual modality in response to the infrequent deviant stimulus inserted into the sequence of the frequent standard stimulus (i.e., visual MMN, for a review, see Pazo-Alvarez et al., 2003). Visual MMN at around 100-300 ms can be elicited by the infrequent deviant stimuli presented at unattended locations, which suggests the existence of pre-attentive change detection in the visual modality (e.g., Alho et al., 1992; Czigler et al., 2002, 2004; Heslenfeld, 2003; Kenemans et al., 2003; Lorenzo-Lopez et al., 2004; Mazza et al., 2005; Pazo-Alvarez et al., 2004; Stagg et al., 2004; Winkler et al., 2005). For the functional significance of visual MMN, however, two contrasting hypotheses have been proposed: memory-based comparison hypothesis and different refractoriness state hypothesis. Memory-based comparison hypothesis assumes that visual MMN reflects a mismatch signal as a result of comparison between current stimulus input and the memory trace of the preceding stimulus, such as auditory MMN (e.g., Czigler et al., 2002; Heslenfeld, 2003; Winkler et al., 2005). On the other side, according to the different refractoriness state hypothesis, visual MMN reflects less refractoriness of neuronal populations specifically activated by a low-frequent stimulus in comparison with a high-frequent stimulus (e.g., Alho et al., 1992; Kenemans et al., 2003; Mazza et al., 2005). At present, it is still unclear whether or not visual MMN reflects the same cognitive function as auditory MMN.

These debates seemed to come from the use of two stimuli with different global probabilities (infrequent deviant and frequent standard stimuli). However, a change does not have to be a rare event, and any stimulus that is different from the previous one can be considered as a change (e.g., Mazza et al., 2005). Actually, although auditory MMN is typically obtained in response to the infrequent deviant stimulus presented in the oddball sequence, the low global probability of the

deviant stimulus is not necessary for the elicitation of auditory MMN (e.g., Giese-Davis et al., 1993; Sams et al., 1983, 1984). Therefore, to identify the ERP correlate of memory-based change detection processing, it seems important to control the effects of global probability. In recent studies, to identify an ERP correlate of visual change detection under the control of the possible effects of global stimulus probability, several studies have used an S1-S2 matching paradigm (e.g., Fu et al., 2003; Kimura et al., 2005, in press; Wang et al., 2003). In previous studies with a visual S1-S2 matching paradigm, ERPs elicited by two types of stimuli (i.e., S2 that is different from the preceding S1 in some attribute ("change") and S2 that is the same as S1 ("no change")) with equal probabilities were compared. In these studies, the earliest effect of a change in the visual stimulus was a posterior positivity at around 60-100 ms for orientation change (Fu et al., 2003), at around 100-180 ms for color change, shape change, and the conjunction change (Kimura et al., 2005), at around 120-240 ms for color change, motion direction change, and the conjunction change (Kimura et al., in press), and at around 60-200 ms for a change in the conjunction of color, global shape, and local shape (Wang et al., 2003). For the functional significance of the change-related positivity, however, there is no study directly testing whether this component reflects memory-based mismatch processing or different refractoriness state of neurons. Kimura et al. (2005, in press) preferred the memory-based comparison hypothesis of change-related positivity based on the results that this component had different scalp-distributions from those of the exogenous components, and that the scalp-topographies of this component differed according to changing features. In contrast, Fu et al. (2003) preferred the different refractoriness state hypothesis of change-related positivity based on the result that this component showed no

amplitude difference between two stimulus onset asynchrony (SOA) conditions (200 versus 400 ms).

At present, there are few studies reporting this positivity, and the nature of the change-related positivity has not yet been well determined. The purpose of the present study was to determine the basic characteristics of change-related positivity. This study had three main objectives: (1) to determine whether or not task-irrelevant changes in spatial frequency could also be reflected by change-related positivity, as changes in color, shape, motion direction, and orientation, (2) to determine whether or not change-related positivity could be observed regardless of the evoking stimulus attribute, (3) to examine the effects of the magnitude of the difference between S1 and S2 on change-related positivity. It has been shown that auditory MMN is independent of the evoking stimulus attribute (e.g., Näätänen and Alho, 1997; Näätänen et al., 1989), which support the notion that this component reflects an endogenous process such as memory-based mismatch processing. Also, amplitudes of auditory MMN have been shown to be sensitive to the magnitude of the stimulus change: as the magnitude of the change is increased, the amplitude tends to be enhanced (e.g., Kujala and Näätänen; 2003; Näätänen and Alho, 1997; Näätänen et al., 1989; Novak et al., 1990; Paavilainen et al., 1989; Sams et al., 1985; Tiitinen et al., 1994). If change-related positivity is associated with a mismatch process between the representation of an incoming stimulus and a memory trace of a previously presented stimulus, as predicted by the memory-based hypothesis, change-related positivities in response to a stimulus change should be sensitive to the magnitude of the difference between S1 and S2 regardless of physical attributes of the evoking stimulus.

2. Methods

2. 1. Participants

Twelve normal students (6 women, 6 men; age range = 20-29 years, $M = 23.6$ years) participated in this experiment. All participants were right-handed and had normal or corrected-to-normal vision. Written informed consent was obtained from each participant after the nature of the study had been fully explained.

2. 2. Stimuli

Twelve circular squarewave gratings (black and white) were used as stimuli (10.5 cm × 10.5 cm, 6.0° × 6.0° of visual angle from a viewing distance of 100 cm). Each grating was defined by the spatial frequency (6.000, 4.500, 3.000, 1.500, 1.125, or 0.750 cpd) and orientation (horizontal or vertical), and presented at the center of a display against a black background. Each trial consisted of two sequentially presented stimuli (Stimulus 1-Stimulus 2; S1-S2; 100 ms each) separated by a brief blank (400 ms), where S2 was either (1) the same as S1 (i.e., NO-change, 40 %), (2) different from S1 in spatial frequency only (SF-change, 40 %), (3) different in orientation only (OR-change, 10 %), or (4) different in both spatial frequency and orientation (BOTH-change, 10 %). In addition, three magnitude conditions (Large, Medium, and Small) were used to examine the effect of the magnitude of the spatial frequency change. Further, two types of S2 with different spatial frequencies were assigned for each magnitude condition (Low and High spatial frequencies) (see

Table 1). This stimulus configuration was applied to manipulate the magnitude of spatial frequency change in three levels and the physical attribute of evoking stimulus in two levels while leaving the probability of each spatial frequency stimulus equal throughout the experimental session ($p = .083$ each). Also, to enable a reliable evaluation of the effects of a change in task-irrelevant spatial frequency, the physical attributes of the eliciting S2 were the same among four change types for each condition. The intertrial interval between the onset of S1 and the next S1 was 1500 ms.

2. 3. Procedure

This experiment consisted of 8 blocks, each of which had 240 trials in which the 24 S1-S2 pair types (4 change types \times 3 magnitude conditions \times 2 spatial frequency types, see Table 1) were presented in random order. The participant was seated in a reclining chair in a sound- and electro-shielded room. Participants were instructed to press a button with the right thumb as quickly and accurately as possible when the orientation of S2 was different from that of S1 (from horizontal to vertical, or from vertical to horizontal) regardless of the spatial frequency of the stimuli (i.e., respond to the OR-change and BOTH-change stimuli). Participants were also asked to focus on the center of display, and to minimize any eye movement during trials.

Insert Table 1 around here.

2. 4. Recordings

An electroencephalogram (EEG) was recorded using an electrocap (Quik-Cap) attached to 25 silver-silver chloride cup electrodes placed at positions, Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, PO7, PO3, POz, PO4, PO8, O1, Oz, and O2 according to the modified International 10-20 System. All electrodes were referenced to the nose tip. Blinks and eye movements were monitored with electrodes above and below the right eye (vertical electrooculogram, V-EOG) and at the right and left outer canthi of the eyes (horizontal electrooculogram, H-EOG). The impedance of the electrodes was kept less than 5 k Ω . EEG and EOG signals were amplified with a band-pass filter of 0.03-30 Hz, and digitized at 250 Hz.

A separate average was computed for each of the 24 S1-S2 pair types (4 change types \times 3 magnitude conditions \times 2 spatial frequency types) for each electrode location¹. Averaging epochs were 800 ms, starting 100 ms before and ending 700 ms after the onset of S2. Automated artifact rejection was applied to remove data epochs that were contaminated by blinks, saccades, or excessive muscle activity over 100 μ V. Epochs with incorrect responses were also excluded. The averaged ERPs were corrected with respect to the mean amplitude baseline during the 100 ms that preceded the onset of S2.

2. 5. Data analysis

Behavioral performance was measured in terms of reaction time, percentage of correct responses (hit rate), and percentage of false alarms (false alarm rate). Responses were scored as hits if they occurred within 100-700 ms after the onset of stimuli with a change in orientation (i.e., OR-change

and BOTH-change). Responses to stimuli without a change in orientation (i.e., NO-change and SF-change) were classified as false alarms. Behavioral data were subjected to a repeated-measures analysis of variance (ANOVA) with three factors: 2 Change types (Change, No change) \times 3 Magnitude conditions (Large, Medium, Small) \times 2 Spatial frequency types (High, Low). Greenhouse-Geisser corrections were used to reduce the positive bias of the *F*-test due to violations of the sphericity assumption.

For the purpose of the present study, the ERP data in response to non-target stimuli (i.e., NO-change and SF-change stimuli) were reported here. To estimate the effects of spatial frequency changes on ERPs, the waveform elicited by the NO-change stimulus was subtracted from those elicited by the SF-change stimulus for each magnitude condition. In the difference waves, three change-related ERP components were identified: a posterior positivity at around 90-200 ms, a central negativity at around 200-350 ms, and a central late positive component (LPC) at around 350-600 ms. In addition, the posterior positivity seemed to have two peaks at around 100 ms and 160 ms.

To test whether these change-related components were independent of physical attributes of an evoking stimulus, the mean amplitudes of the averaged ERPs within latency ranges of these change-related effects were calculated: within 60-120 ms (Oz) for the early part of the posterior positivity, 120-180 ms (Oz) for the late part of the posterior positivity, 260-320 ms (Cz) for the central negativity, and 460-520 ms (Cz) for the LPC. For each magnitude condition, these amplitudes were subjected to a repeated-measures ANOVA with two factors: 2 Change types (Change, No change) \times 2 Spatial frequency types (High, Low).

To investigate the effect of the magnitude of spatial frequency changes on the amplitudes of these change-related components, the mean amplitudes of the SF-change minus NO-change difference waves within latency ranges of these change-related effects were calculated: within 60-120 ms (Oz) for the early part of the posterior positivity, 120-180 ms (Oz) for the late part of the posterior positivity, 260-320 ms (Cz) for the central negativity, and 460-520 ms (Cz) for the LPC. These amplitudes were subjected to a repeated-measures ANOVA with two factors: 3 Magnitude conditions (Large, Medium, Small) \times 2 Spatial frequency types (High, Low).

To compare the scalp-distributions of these change-related components among the three magnitude conditions, the mean amplitudes of SF-change minus NO-change difference waves were calculated for 25 electrode sites: within 120-180 ms for the posterior positivity, 260-320 ms for the central negativity, and 460-520 ms for the LPC (spatial frequency types were pooled). The mean amplitude values were subjected to a repeated-measures ANOVA with two factors: 3 Magnitude conditions (Large, Medium, Small) \times 25 Electrode sites (Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, PO7, PO3, POz, PO4, PO8, O1, Oz, O2). Firstly, the analysis was performed on the original (i.e., not normalized) data. Then, the same analysis was performed on the amplitude values that were normalized by vector length, where each amplitude value was divided by the square root of the sum of squared amplitudes over 25 electrode locations for each magnitude condition, as recommended by McCarthy and Wood (1985).

3. Results

3. 1. Behavioral performance

Table 2 shows mean reaction times, hit rates, and false alarm rates. Three-way ANOVA (2 Change types \times 3 Magnitude conditions \times 2 Spatial frequency types) for reaction times showed significant interaction of Magnitude condition \times Spatial frequency type ($F(2,22) = 20.11, p < .01, \epsilon = .91$). Post-hoc tests revealed that for S2s with high spatial frequency, the reaction time became longer as the magnitude of the spatial frequency change increased. Three-way ANOVA for hit rates showed significant interaction of Change type \times Magnitude condition \times Spatial frequency type ($F(2,22) = 5.50, p < .05, \epsilon = .65$). This interaction was due to the fact that the for the OR-change S2 with low spatial frequency, hit rate became higher as the magnitude of the spatial frequency change increased, while for the other conditions, hit rate became lower as the magnitude of spatial frequency change increased. With regard to false alarm rates, the interaction of Change type \times Magnitude condition was significant ($F(2,22) = 4.61, p < .05, \epsilon = .83$). Post-hoc tests revealed that this result stemmed from the fact that while the false alarm rates for the NO-change stimuli were consistently low among the three magnitude conditions, the false alarm rates for the SF-change stimuli increased as the magnitude of the spatial frequency change increased, regardless of the spatial frequency of S2.

Insert Table 2 around here.

3. 2. Event-related brain potentials

Fig. 1 shows the grand averaged ERPs elicited by the NO-change stimuli in the Large, Medium, and Small conditions, respectively. ERPs in response to all types of S2 were characterized by six components: C1 at around 95 ms, P1 at around 140 ms, N1 at around 175 ms, P2 at around 210 ms, N2 at around 250 ms, and a late positive component (LPC) at around 400-600 ms from the onset of S2. It could be observed that in comparison with ERPs to low spatial frequency S2, high spatial frequency S2 elicited enhanced C1 and P1 components at posterior electrodes for each magnitude condition.

Fig. 2 shows the grand averaged ERPs elicited by the NO-change and SF-change stimuli in the Large, Medium, and Small conditions, respectively (spatial frequency types were pooled). ERPs in response to all types of S2 were also characterized by C1, P1, N1, P2, N2, and LPC. It could be observed that ERPs elicited by the NO-change and those elicited by the SF-change stimuli differed starting at the C1 latency range. Fig. 3 shows the difference waves obtained by subtracting ERPs elicited by the NO-change stimuli from those elicited by the SF-change stimuli. Relative to the NO-change stimuli, the SF-change stimuli elicited three ERP components: a posterior positivity between 90 and 200 ms (change-related positivity) (Kimura et al., 2005, in press), a central negativity between 200 and 350 ms (N270)² (e.g., Wang et al., 2001, 2003, 2004), and a LPC between 350 and 600 ms.

To test whether these change-related components were significantly elicited by spatial

frequency changes regardless of physical attributes of an evoking stimulus, mean amplitudes of averaged ERPs were subjected to two-way ANOVAs (2 Change types \times 2 Spatial frequency types) for each magnitude condition. Upper part of Table 3 summarized the results of this analysis. For the early part of the posterior positivity (60-120 ms at Oz), two-way ANOVAs showed significant main effects of Spatial frequency type for all magnitude conditions. These effects were due to the enhanced C1 component for the high frequency S2s. In addition, although the main effect of Change type was not significant for the Large and Small conditions, there was significant interaction of Spatial frequency type \times Change type for the Medium condition. Post-hoc tests revealed that this interaction was due to the fact that compared to ERPs to the NO-change stimulus, those to the SF-change stimulus were shifted to positive polarity only for the low spatial frequency S2. In contrast, for the late part of the posterior positivity (120-180 ms at Oz), there are significant main effects of Change type and Spatial frequency type without their interactions for the Large and Medium conditions. These effects were due to the positive shift to spatial frequency changes and enhanced P1 component for the high frequency S2s. For the N270 (260-320 ms at Cz) and LPC (460-520 ms at Cz), there are significant main effects of Change types for all magnitude conditions. In addition, within LPC latency range, significant main effect of Spatial frequency type was observed for the Medium condition.

Insert Figs. 1-3 and Table 3 around here.

To test the effects of magnitude of spatial frequency changes on these change-related components, the mean amplitudes of the SF-change minus NO-change difference waves were calculated (Fig. 4). The mean amplitudes of difference waves were subjected to a two-way ANOVA (3 Magnitude conditions \times 2 Spatial frequency types). Lower part of Table 3 summarized the results of this analysis. This analysis showed significant main effects of the Magnitude condition for the late part of the posterior positivity, N270, and LPC, while there was no significant effect for the early part of the posterior positivity. Post-hoc tests revealed that for three change-related components, the amplitude was larger for the Large and Medium conditions than the Small condition.

Fig. 5 shows the topographical maps of the change-related positivity, N270, and LPC for each magnitude condition (spatial frequency types were pooled). To compare the scalp-distribution of the change-related component among the three magnitude conditions, the mean amplitudes in the SF-change minus NO-change difference waves (spatial frequency types were pooled) were subjected to two-way ANOVAs (3 Magnitude conditions \times 25 Electrode sites). The analyses performed on the original (i.e., not normalized) data showed significant interactions of Magnitude condition \times Electrode sites ($F(48,528) = 5.36, p = .01, \epsilon = .09$ for the change-related positivity, $F(48,528) = 7.68, p = .01, \epsilon = .12$ for the N270, and $F(48,528) = 2.64, p = .05, \epsilon = .08$ for the LPC). Following the analyses, the same analyses were performed on the normalized values that were scaled by vector length (McCarthy and Wood, 1985). The significant interaction was no longer revealed.

Insert Figs 4 and 5 around here.

4. Discussion

Behavioral performance in response to target stimuli was generally good. However, the reaction time for S2s with high spatial frequency became longer as the magnitude of the spatial frequency change increased for both OR-change and BOTH-change stimuli. Also, hit rate became higher as the magnitude of the spatial frequency change increased for the OR-change S2 with low spatial frequency, while hit rate became lower as the magnitude of spatial frequency change increased for the other conditions. These results indicate that it becomes more difficult to discriminate the orientation of the grating as the spatial frequency of the grating becomes higher. While the false alarm rates for the NO-change stimuli were consistently low among the three magnitude conditions, those for the SF-change stimuli increased as the magnitude of the spatial frequency change increased. These results indicate that changes in a spatial frequency tend to trigger the participant's orienting responses.

In our ERP data, task-irrelevant spatial frequency changes were reflected by the late part of the posterior positivity, central negativity, and central LPC. For the posterior positivity, in previous studies with a visual S1-S2 matching paradigm, similar posterior positivities were observed in

response to changes in several visual stimulus features, such as orientation (Fu et al., 2003), color, shape, and their conjunction (Kimura et al., 2005), color, motion direction, and their conjunction (Kimura et al., in press), and the conjunction among color, global shape, and local shape (Wang et al., 2003). The onset and the posterior distribution are also consistent with the properties of change-related positivities reported in the previous studies. Thus, it is evident that processing of a change in spatial frequency, as well as orientation, color, shape (local and global), and motion direction can be reflected by the change-related positivity. For the central negativity, we interpreted this negativity as N270. N270 has been observed as a robust ERP component in response to change stimuli in several studies with a visual S1-S2 matching paradigm (e.g., Kong et al., 2000; Wang et al., 2001, 2003, 2004; Yang and Wang, 2002), and is thought to reflect a modality-non-specific conflict processing system (Wang et al., 2002). For the central LPC, there are at least two possible interpretations: P3a and no-go P300. P3a has been reported to be a frontal/central positivity elicited by several types of infrequent non-target stimuli (e.g., Courchesne et al., 1975; Katayama and Polich, 1998; Squires et al., 1975), and is considered to reflect the attentional shift produced by the mismatch. On the other hand, it has been reported that infrequent non-target stimuli that are easily recognized as “typical” (i.e., not novel) could elicit another types of LPC with maximum amplitudes over the central/parietal area (e.g., Courchesne, 1978; Courchesne et al., 1978; Katayama and Polich, 1996), which is sometimes referred to as no-go P300. No-go P300 has been associated with response inhibition (e.g., Schupp et al., 1994; Strik et al., 1998).

Change-related positivity could be observed in response to task-irrelevant changes in spatial

frequency of a visual stimulus. This is consistent with the previous studies reporting that change-related positivity could be observed regardless of the participant's feature attention condition (e.g., Wang et al., 2003). This result supports the notion that change-related positivity reflects pre-attentive processing of visual changes. However, this is not sufficient to conclude that change-related positivity is completely free from participant's attention condition. Both of our behavioral data (false alarm rates) and ERP data (elicitation of a P3a-like LPC) indicated that changes in a spatial frequency tend to trigger the participant's orienting responses. Therefore, further studies testing the elicitation of change-related positivity to visual changes at unattended spatial locations are necessary before any conclusion.

High spatial frequency stimuli elicited enhanced C1 and P1 components. This is consistent with previous studies addressing effects of spatial frequency on evoked potentials (e.g., Di Russo et al., 2001; Heslenfeld, 2003; Kenemans et al., 2000; Spekreijse et al., 1973). For the effects of physical attributes of evoking stimulus on the posterior positivity, the early part of the posterior positivity was observed only for the Low spatial frequency S2 for the Medium condition. This indicates that the early part of the positivity might be contaminated by modulation of the exogenous component (C1 component). In the present study, although global probability of each spatial frequency stimulus was equal throughout the experimental session, there remains the problem of differences in local probability. Also, It has been known that lower spatial frequency stimuli are processed through transient visual channels (i.e., magno-cellular pathways), and the higher spatial frequency stimuli are processed through sustained visual channels (parvo-cellular pathways). Sustained channels are thought to be have longer recovery times than transient channels (e.g., Breitmeyer

and Ganz, 1976; Hughes et al., 1996). The present result might be due to the different temporal characteristics of transient and sustained visual channels. In contrast, the late part of the posterior positivity was not affected by the physical attributes of evoking stimulus. This result suggests that this component reflects endogenous processing such as memory-based mismatch processing. Also, the N270 and LPC were not affected by the physical attributes of evoking stimulus. Within the LPC latency range, ERPs to high spatial frequency stimulus were shifted to positive polarity only for the Medium condition. At present, the functional significance of this effect is unclear.

The amplitudes of the late part of the posterior positivity were sensitive to the magnitude of the spatial frequency change: as the magnitude of the stimulus change in spatial frequency increased, the amplitude of the positivity tends to increase. This was also supported by results of comparison of the scalp-distribution. This comparison shows that the magnitude of the spatial frequency change affects the amplitude of the positivity but does not affect the scalp-distribution of the positivity. The sensitivity of the positivity to the magnitude of the change is consistent with the notion that this component is elicited by a mismatch process between a sensory memory trace of a previously presented stimulus and an incoming stimulus.

However, although the amplitude of the late part of the posterior positivity in the Large condition was larger than that in the Medium condition, the difference was not statistically supported. This suggests that the amplitude of the change-related positivity, at least for the spatial frequency change, may reach a plateau when the magnitude of stimulus changes is increased. Similar results were also observed for the auditory MMN amplitudes, especially for stimulus changes in the tonal frequency (e.g., Novak et al., 1990; Sams et al., 1985). In addition, the

elicitation of the change-related positivity did not reach significance in the Small condition, while N270 and LPC were also observed for the Small condition. This suggests that the change-related positivity may have relatively high threshold for the elicitation.

The present results support the notion that the change-related positivity reflects memory-based mismatch processing. However, the memory-based interpretation of change-related positivity must be treated with caution at least for two reasons. First, several studies reported that memory-based change detection in the visual modality was reflected by a posterior negativity (i.e., visual MMN) (e.g., Czigler et al., 2002; Heslenfeld, 2003; Winkler et al., 2005). Although the change-related positivity and the visual MMN have a similar latency and scalp-distribution, further study is necessary to systematize the relationship of the two components with inversed polarity. Second, the change-related positivity has been just reported recently, and large part of the functional significance of this component is still unknown. Therefore, for more precise conclusion, further experiments regarding the cognitive function reflected by the change-related positivity must be accumulated.

5. Conclusions

In summary, change-related positivities at around 120-180 ms with posterior scalp-distributions, which were followed by N270 and LPC, were observed in response to a task-irrelevant change in the spatial frequency of a visual stimulus. Furthermore, the amplitude of the change-related positivity was sensitive to the magnitude of the stimulus change, regardless of the physical

attributes of the evoking stimulus. The results support the notion that the change-related positivity reflects memory-based change detection in the human visual system.

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Footnotes

¹ It has been reported that in comparison with horizontal gratings, vertical gratings elicited enhanced positivity at around the C1 latency range (e.g., Kenemans et al., 2000). However, it has been also reported that this orientation effect is independent of the spatial frequency dimension. Therefore, considering the purpose of the present study, we collapsed two orientations of grating stimulus (vertical and horizontal) for each condition.

² In previous studies using the oddball paradigm, it has been reported that relative to frequent standard stimuli, infrequent stimuli elicited a central negativity, which was called N2b. N2b was considered to reflect the template mismatch (e.g., Näätänen, 1992; Sams et al., 1985), and its characteristics seem similar to those of N270 obtained using the S1-S2 matching paradigm, in terms of their possible cognitive functions, scalp-distributions, and latencies. For simplicity in this paper, negativities at around 270 ms that were elicited by a spatial frequency change between S1 and S2 were referred to as N270.

Table 1

24 S1-S2 pairs defined by 4 change types (NO-change, SF-change, OR-change, BOTH-change)
 × 3 magnitude conditions (Large, Medium, Small) × 2 spatial frequency types (Low, High) used in
 the present study

Magnitude	Spatial frequency	Change type			
		NO-change (.40)	SF-change (.40)	OR-change (.10)	BOTH-change (.10)
Large	Low	0.750 – 0.750	6.000 – 0.750	0.750 – 0.750	6.000 – 0.750
	High	6.000 – 6.000	0.750 – 6.000	6.000 – 6.000	0.750 – 6.000
Medium	Low	1.125 – 1.125	4.500 – 1.125	1.125 – 1.125	4.500 – 1.125
	High	4.500 – 4.500	1.125 – 4.500	4.500 – 4.500	1.125 – 4.500
Small	Low	1.500 – 1.500	3.000 – 1.500	1.500 – 1.500	3.000 – 1.500
	High	3.000 – 3.000	1.500 – 3.000	3.000 – 3.000	1.500 – 3.000 (cpd)

Note: This stimulus configuration was applied to manipulate the magnitude of the spatial frequency change in three levels and the physical attribute of the evoking stimulus in two levels with leaving the probability of each spatial frequency stimulus was equal. To enable a reliable evaluation of the effects of a change in task-irrelevant spatial frequency, the eliciting S2 in each condition was the same among four change types.

Table 2*Behavioral performance*

Magnitude	Spatial frequency	Reaction time (ms)		Hit rate (%)		False alarm rate (%)	
		OR-change	BOTH-change	OR-change	BOTH-change	NO-change	SF-change
Large	Low	438 ± 57	449 ± 68	96.6 ± 4.5	85.9 ± 11.2	0.1 ± 0.3	1.3 ± 1.0
	High	495 ± 66	490 ± 85	69.3 ± 23.0	81.8 ± 12.6	0.1 ± 0.3	1.4 ± 1.5
Medium	Low	444 ± 67	444 ± 68	94.5 ± 7.6	88.0 ± 12.3	0.3 ± 0.5	0.6 ± 0.6
	High	485 ± 63	454 ± 65	81.5 ± 17.4	85.4 ± 12.2	0.3 ± 0.5	0.8 ± 1.0
Small	Low	451 ± 65	450 ± 67	88.0 ± 11.9	91.7 ± 8.2	0.1 ± 0.2	0.1 ± 0.2
	High	466 ± 60	444 ± 55	87.2 ± 14.7	89.1 ± 11.0	0.2 ± 0.4	0.4 ± 0.6

Table 3

Results of two-way ANOVAs (2 Change types × 2 Spatial frequency types) performed on mean amplitudes of averaged ERPs and a two-way ANOVA (3 Magnitude conditions × 2 Spatial frequency types) performed on mean amplitudes of SF-change minus NO-change difference waves within early part of posterior positivity (60-120 ms at Oz), late part of posterior positivity (120-180 ms at Oz), N270 (260-320 ms at Cz), and LPC (460-520 ms at Cz) latency ranges

Source (df)	60 - 120 ms (Oz)			120 - 180 ms (Oz)			260-320 ms (Cz)			460-520 ms (Cz)		
	F	p	ε	F	p	ε	F	p	ε	F	p	ε
<i>Large condition</i>												
Change (1,11)	—	—	—	10.86	.01	—	13.30	.01	—	45.46	.01	—
Spatial frequency (1,11)	11.40	.01	—	10.76	.01	—	—	—	—	—	—	—
C × S (1,11)	—	—	—	—	—	—	—	—	—	—	—	—
<i>Medium condition</i>												
C (1,11)	—	—	—	12.85	.01	—	19.17	.01	—	70.87	.01	—
S (1,11)	8.30	.05	—	7.84	.05	—	—	—	—	4.96	.05	—
C × S (1,11)	7.43	.05	—	—	—	—	—	—	—	—	—	—
<i>Small condition</i>												
C (1,11)	—	—	—	—	—	—	26.41	.01	—	6.43	.05	—
S (1,11)	18.62	.01	—	—	—	—	—	—	—	—	—	—
C × S (1,11)	—	—	—	—	—	—	—	—	—	—	—	—
<hr/>												
Magnitude (2,22)	—	—	—	4.02	.05	.84	8.65	.01	.72	17.82	.01	.79
Spatial frequency (1,11)	—	—	—	—	—	—	—	—	—	—	—	—
M × S (2,22)	—	—	—	—	—	—	—	—	—	—	—	—

Note: Only significant effects are presented.

Figure Captions

- Fig. 1.** Grand averaged ERPs elicited by NO-change S2 in each magnitude condition.
- Fig. 2.** Grand averaged ERPs elicited by NO-change and SF-change stimuli in each magnitude condition (spatial frequency types were collapsed).
- Fig. 3.** Difference waves obtained by subtracting ERPs elicited by the NO-change stimuli from those elicited by the SF-change stimuli in each magnitude condition (spatial frequency types were collapsed).
- Fig. 4.** Mean amplitudes of the SF-change minus NO-change difference waves within early part of posterior positivity (60-120 ms at Oz), late part of posterior positivity (120-180 ms at Oz), N270 (260-320 ms at Cz), and LPC (460-520 ms at Cz) latency ranges in each magnitude condition. L = Large condition, M = Medium condition, S = Small condition.
- Fig. 5.** Topographical maps of the SF-change minus NO-change difference waves in each magnitude condition: mean amplitude within 120-180 ms for the change-related positivity, within 260-320 ms for the N270, and within 460-520 ms for the LPC.

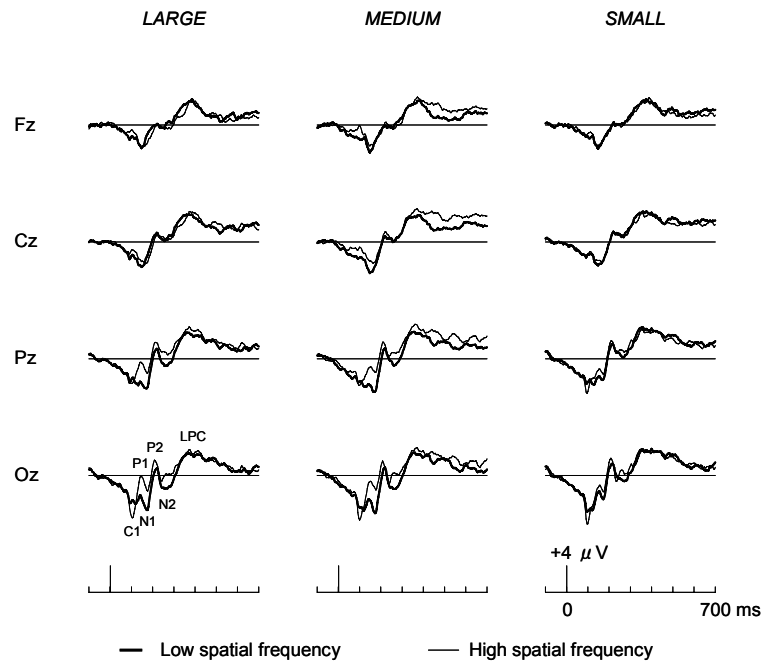


Fig. 1

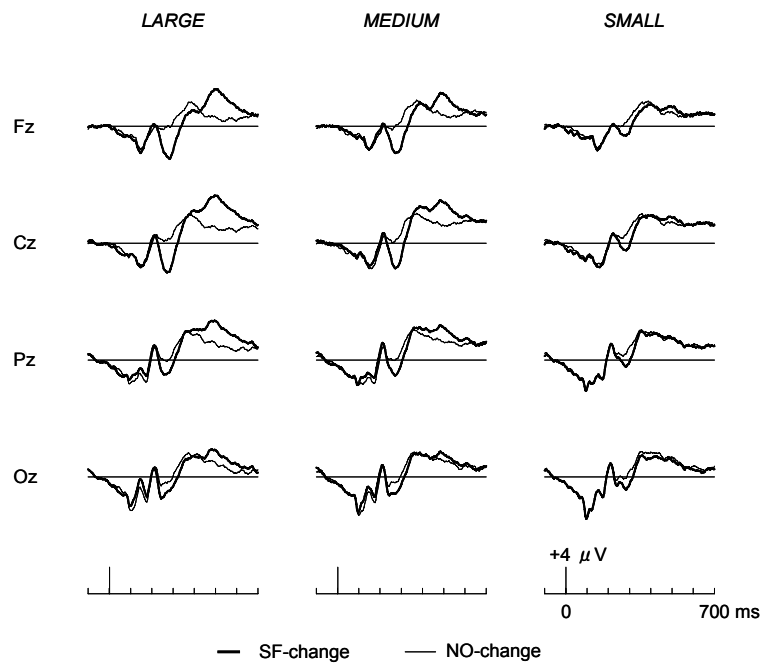


Fig. 2

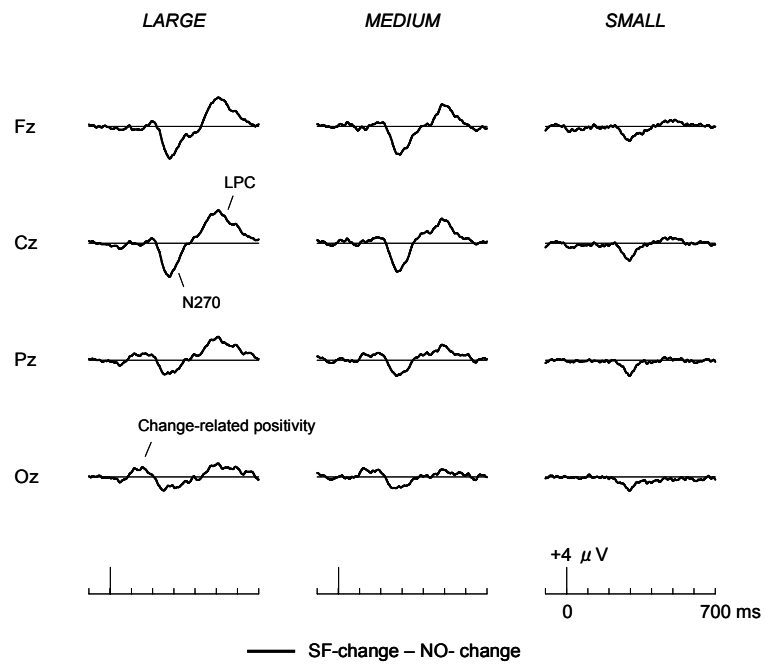


Fig. 3

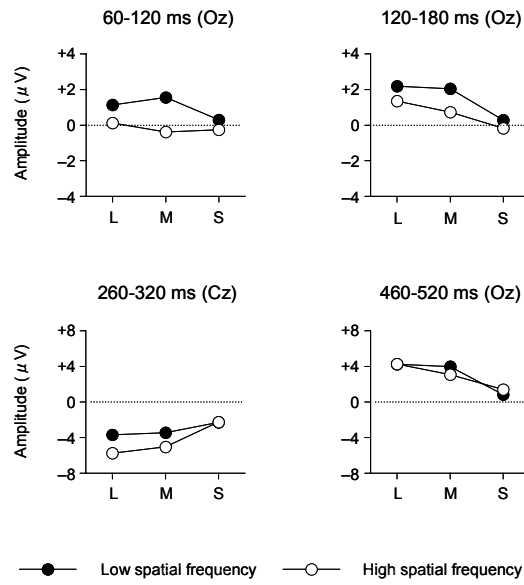


Fig. 4

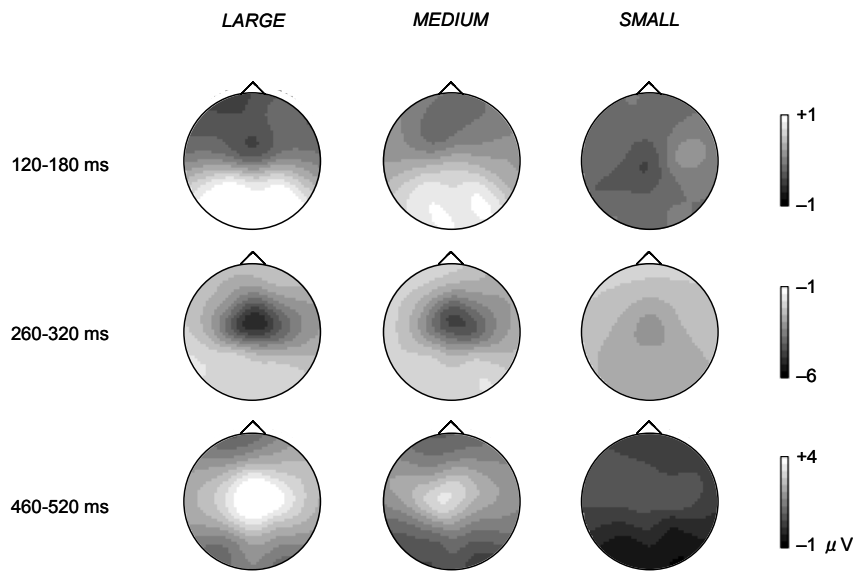


Fig. 5