



## Effects of subjective preference of colors on attention-related occipital theta oscillations

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### ABSTRACT

Human daily behaviors are often affected by subjective preferences. Studies have shown that physical responses are affected by unconscious preferences before conscious decision making. Accordingly, attention-related neural activities could be influenced by unconscious preferences. However, few neurological data exist on the relationship between visual attention and subjective preference. To address this issue, we focused on lateralization during visual attention and investigated the effects of subjective color preferences on visual attention-related brain activities. We recorded electroencephalograph (EEG) data during a preference judgment task that required 19 participants to choose their preferred color from 2 colors simultaneously presented to the right and left hemifields. In addition, to identify oscillatory activity during visual attention, we conducted a control experiment in which the participants focused on either the right or the left color without stating their preference. The EEG results showed enhanced theta (4–6 Hz) and decreased alpha (10–12 Hz) activities in the right and left occipital electrodes when the participants focused on the color in the opposite hemifield. Occipital theta synchronizations also increased contralaterally to the hemifield to which the preferred color was presented, whereas the alpha desynchronizations showed no lateralization. The contralateral occipital theta activity lasted longer than the ipsilateral occipital theta activity. Interestingly, theta lateralization was observed even when the preferred color was presented to the unattended side in the control experiment, revealing the strength of the preference-related theta-modulation effect irrespective of visual attention. These results indicate that subjective preferences modulate visual attention-related brain activities.

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### Introduction

Subjective preferences that affect decision making are defined not only by subjective and conscious evaluations, such as when providing answers to a questionnaire, but also by objective and unconscious evaluations, including eye movement and neural activity. For example, in one study, when participants were required to indicate their preference for one of 2 simultaneously presented attractive faces (i.e., a forced-choice paradigm), the participants gradually gazed more often at the preferred face as they made their decision (Shimojo et al., 2003). Recent functional magnetic resonance imaging (fMRI) studies have shown that the signals from the nucleus accumbens to the orbitofrontal cortex increase during decision making (Kim et al., 2007), and electroencephalograph (EEG) studies have shown that frontal theta and posterior gamma activities are related to the formation of a subjective preference (Lindsen et al., 2010). These results suggest that physical responses are affected by unconscious

preferences before conscious decision making. Accordingly, attention-related neural activities such as eye movements could also be influenced by unconscious preferences. However, few neurological data exist on the relationship between visual attention and subjective preference: the causes of subjective preference judgments such as the amount of visual processing and attention are difficult to determine by using attractive faces because they include a large number of visual features (e.g., facial contour, eye color, and hair length).

In this study, we focused on lateralization during visual attention to simple features, because the visual cortices mainly process information from the contralateral visual hemifields (Hillyard et al., 1998; Kastner et al., 1999; Luck et al., 1997); for example, the right visual areas are associated with processing of left visual hemifield information and vice versa. Human EEG studies have also shown that alpha (~10 Hz) and theta (~6 Hz) oscillatory brain activities are modulated in the posterior and occipital regions contralateral to the visual hemifield on which attention is placed, although some controversial results on enhancements or decrements of these activities exist (Kelly et al., 2006; Sauseng et al., 2005; Thut et al., 2006; Worden et al., 2000; Yamagishi et al., 2003). If subjective preferences are influenced by unconscious attention before decision

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making, contralateral activity for visual attention toward the preferred of 2 simultaneously presented stimuli would be facilitated. To clarify the neural mechanisms involved in subjective preferences during visual attention, we recorded EEG data during a preference judgment task (2-alternative, forced-choice task) that required participants to choose the preferred color from 2 colors simultaneously presented to the bilateral visual hemifields. We focused on the temporal relationship among EEG oscillations, which reflect the dynamic linking of cell assemblies through the synchronization of numerous neurons for a particular function (Kawasaki et al., 2010; Klimesch et al., 2008; Varela et al., 2001).

## Materials and methods

Nineteen healthy right-handed volunteers (8 women and 11 men; mean age,  $21.5 \pm 0.5$  years; age range, 18–27 years) with normal or corrected-to-normal visual acuity, normal hearing acuity, and normal motor performance participated in the EEG experiment. All participants provided written informed consent, and the study was approved by the Ethical Committee of the RIKEN (in accordance with the Declaration of Helsinki).

At the beginning of each trial, 2 colored squares ( $2^\circ \times 2^\circ$ ) were presented for 1 s as visual stimuli to the bilateral hemifields relative to a central white fixation point with a gray background (red ( $r$ ) = 128, green ( $g$ ) = 128, blue ( $b$ ) = 128) on a computer display (stimulus display; Fig. 1). The distance between the squares was  $2^\circ$ . Two colors were selected for each trial from the 11 highly distinctive colors (white [ $r=255, g=255, b=255$ ], black [ $r=0, g=0, b=0$ ], red [ $r=255, g=0, b=0$ ], green [ $r=0, g=255, b=0$ ], blue [ $r=0, g=0, b=255$ ], yellow [ $r=255, g=255, b=0$ ], magenta [ $r=255, g=0, b=255$ ], cyan [ $r=0, g=255, b=255$ ], olive [ $r=128, g=128, b=0$ ], purple [ $r=128, g=0, b=128$ ], and aqua [ $r=0, g=128, b=128$ ]). The participants were required to fixate on the central point throughout the trial. They were asked to choose their preferred color within 2 s of the display by pressing a button when the fixation point was red.

We also conducted a control task to identify the neural oscillations involved in the lateralization effects of visual perception. In this task, a white arrow was presented below the white fixation point during the presentation of the 2 colored squares. The participants were required to focus on the colored square indicated by the arrow without

choosing their preference. Thereafter, they pressed the button corresponding to the indicated direction.

In both the tasks, the intertrial interval (ITI) was 2 s. Each participant completed 110 trials. All possible color combinations were presented twice with reshuffling of the right and left positions. All the participants could indicate their preference for the right or left color by pressing the button with their right index finger.

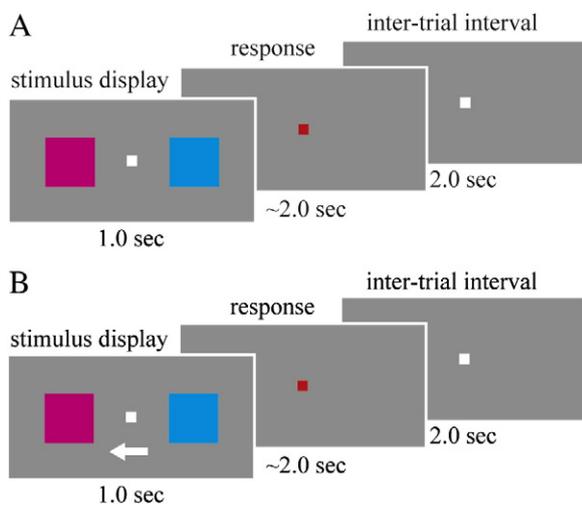
For the EEG recordings, 60 scalp electrodes were embedded in an electro cap and amplified by using Neuroscan (Compumedics, Charlotte, NC) equipment (sampling rate = 500 Hz) in an electrical and magnetic shield room. Reference electrodes were placed on the right and left ears. Electrooculography (EOG) was performed by using electrodes above and below the left eye for monitoring blinking and vertical eye movements. Electrodes placed 1 cm from the right and left eyes were used to monitor horizontal eye movements. To reduce or eliminate artifacts, we rejected trials in which the EOG data were above or below  $80 \mu\text{V}$  during the stimulus presentation and conducted infomax independent component analysis (ICA) for the EEG data from the successful trials. The ICA components significantly correlated with the vertical or horizontal EOG data were rejected and the ICA-corrected data were recalculated by using regression of the remaining components. The mean (S.E.M.) number of removed trials was 4.63 (2.55); we removed 3.73 (0.84) (range = 0–13) components from the preference judgment task and 8.11 (1.99) (range = 0–26) components from the control task. Further, to elucidate the cortical activity recorded by the scalp EEG electrodes without volume conduction errors, we conducted current source density analysis by applying the spherical Laplace operator to the voltage distribution on the scalp surface.

To identify time–frequency (TF) amplitudes during the stimulus presentation, we applied wavelet transformation by using Morlet wavelets with a Gaussian shape in the time domain ( $\text{SD } \sigma_t$ ) and frequency domain ( $\text{SD } \sigma_f$ ) around the central frequency ( $f$ ) (Tallon-Baudry et al., 1997). The TF amplitude at each time point of each trial was the squared norm of the results of the convolution of the original EEG signals with complex Morlet wavelet function ( $f/\sigma_f = 7$ ). The TF amplitudes were averaged across single trials in each condition. The event-related TF amplitude was calculated by subtracting the baseline data measured in the ITI at each frequency band and then averaged across the participants. For all statistical analyses, nonparametric Wilcoxon signed-rank test was used across the events or conditions because the TF amplitude population distributions were far from Gaussian. The statistical analyses included the theta amplitudes (frequency range = 4–6 Hz) during 0–500 ms and alpha amplitudes (frequency range = 10–12 Hz) during 500–1000 ms from the stimulus onset. Topographic color plots were used to compare the multiplication values of the theta amplitudes and durations in the same electrodes between the attended and the preferred contralateral and ipsilateral colors.

We next conducted event-related brain potential (ERP) analysis. To create mean ERP waveforms, the EEG data obtained between  $-200$  and  $1000$  ms from the stimulus onset were corrected by subtracting the average baseline potential ( $-500$  ms to  $0$  ms from the stimulus onset) and then averaged in each condition. To compare the ERP values between different events or conditions, we applied nonparametric Wilcoxon signed-rank tests for the maximum ERP components within the specific time periods from the stimulus onset according to predetermined findings (N2pc: 200–350 ms) because the ERP population distributions were far from Gaussian.

## Results

The behavioral results showed a significant difference in reaction times between the preference judgment and the control conditions (preference,  $0.84 \pm 0.05$  s vs. control,  $0.70 \pm 0.03$  s;  $t(18) = 2.74$ ,  $P < 0.01$ ). However, no significant difference in reaction times was



**Fig. 1.** Schematic of trial sequences in the preference judgment task (A) and control task (B). The preference judgment task required the participants to choose the preferred color from 2 simultaneously presented color on the right and left displays; the control task required the participants to focus on the colored square indicated by the white arrow without choosing their preference.

noted between the right and the left color choices in either condition (preference,  $t(18) = 0.30$ ,  $P = 0.77$ ; control,  $t(18) = 0.20$ ,  $P = 0.83$ ).

To identify the oscillatory activities involved in the neural mechanisms of visual attention, the TF amplitudes from the EEG data were analyzed in the control condition. The averaged TF amplitudes showed increased theta activities (frequency range = 4–6 Hz) in the occipital electrodes during the stimulus display period (from the stimulus onset to 500 ms thereafter) compared with the ITI baseline (e.g., left occipital [O1],  $Z = 2.82$ ,  $P < 0.01$ ; right occipital [O2],  $Z = 2.84$ ,  $P < 0.01$ ). Specifically, the occipital theta synchronizations showed lateralization effects during visual attention (Fig. 2A): that is, the right occipital theta synchronizations were significantly enhanced compared with the left occipital theta synchronizations when the participants focused on the left hemifield (Fig. 3A; O1 vs. O2,  $Z = 2.37$ ,  $P < 0.02$ ) and vice versa when they focused on the right hemifield (O1 vs. O2,  $Z = -4.26$ ,  $P < 0.01$ ). Furthermore, the contralateral theta synchronizations were significantly enhanced compared with the ipsilateral ones (left vs. right attended: O1,  $Z = 2.10$ ,  $P < 0.04$ ; O2,  $Z = -2.59$ ,  $P < 0.01$ ). The theta lateralization effects were mainly found in the occipital regions shown in Fig. 4. For example, no significant differences were noted between the right and the left frontal amplitudes when the participants focused on either the right or the left hemifield (e.g., AF3 vs. AF4: left hemifield,  $Z = 0.44$ ,  $P = 0.66$ ; right hemifield,  $Z = -0.76$ ,  $P = 0.44$ ).

Theta synchronizations were also found in the occipital electrodes during the preference judgment task (O1,  $Z = 3.51$ ,  $P < 0.01$ ; O2,  $Z = 3.28$ ,  $P < 0.01$ ). Attention-related theta lateralization in the occipital electrodes was observed in the hemifield in which the preferred color was presented in the preference judgment task (Fig. 2B). The contralateral occipital theta synchronizations were significantly enhanced compared with the ipsilateral ones for the preferred color (Fig. 3B; O1 vs. O2: left hemifield,  $Z = 3.27$ ,  $P < 0.01$ ; right hemifield,  $Z = -2.78$ ,  $P < 0.01$ ). Interestingly, the durations of the increased contralateral theta synchronizations beyond 1  $\mu$ V were significantly longer than those of the ipsilateral synchronizations (Fig. 3C; O1 vs. O2: left hemifield,  $Z = 2.76$ ,  $P < 0.01$ ; right hemifield,  $Z = -2.40$ ,  $P < 0.01$ ). The durations of the contralateral occipital theta synchronizations were not significantly correlated with the response times for preference decision making (O1:  $r(19) = 0.31$ ,  $P = 0.18$ ; O2:

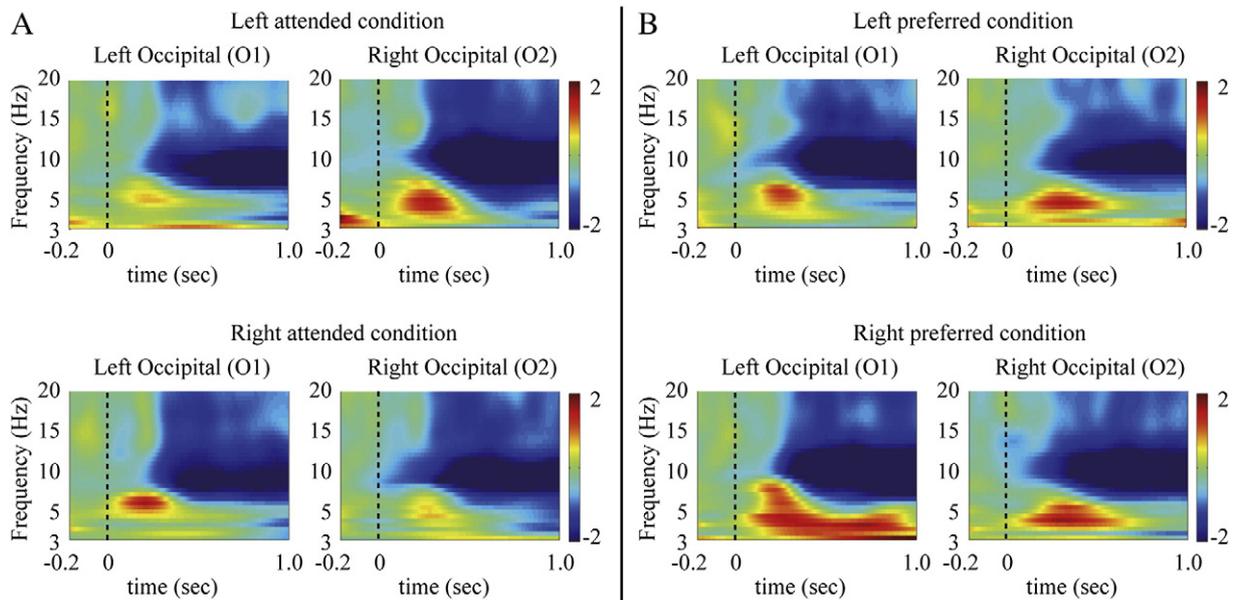
$r(19) = 0.29$ ,  $P = 0.21$ ). Therefore, the observed theta activities were not caused by the reaction times. These results indicated that visual attention-related neural activities in the occipital regions are affected by subjective preferences such as focusing on the location of the preferred item.

The theta synchronizations showed no significant differences between the contralateral and the ipsilateral color choices in the right occipital electrodes, although lateralization was observed in the left occipital electrodes (left vs. right attended: O1,  $Z = 4.37$ ,  $P < 0.01$ ; O2,  $Z = -0.88$ ,  $P = 0.39$ ). This finding is attributable to the different durations of the theta synchronizations. Therefore, the multiplication values of the theta amplitudes and durations revealed significant differences between the contralateral and the ipsilateral color choices in the right occipital electrodes (left vs. right attended: O2,  $Z = 2.20$ ,  $P < 0.02$ ). The theta lateralization effects were mainly observed in the occipital regions shown in Fig. 4.

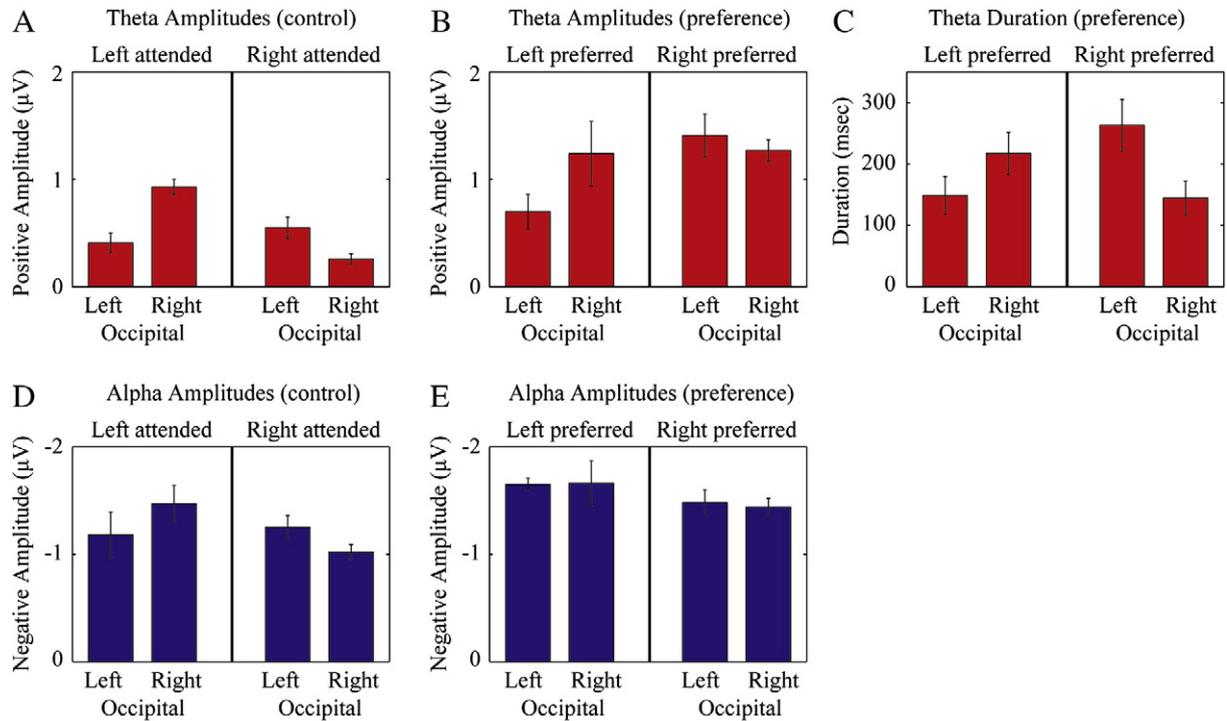
Under both the experimental conditions, the alpha amplitudes (10–12 Hz) decreased in almost all the electrodes. Desynchronizations were observed after the occipital theta amplitude increases disappeared (500–1000 ms from the stimulus onset). Similar to the theta amplitudes, the negative alpha amplitude values showed lateralization: that is, significant differences were noted between the contralateral and the ipsilateral electrodes in the control condition (Fig. 3D; O1 vs. O2: left hemifield,  $Z = -3.92$ ,  $P < 0.01$ ; right hemifield,  $Z = 2.04$ ,  $P < 0.05$ ). However, these differences were not found in the preference judgment condition (Fig. 3E; O1 vs. O2: left hemifield,  $Z = -1.24$ ,  $P = 0.21$ ; right hemifield,  $Z = 0.80$ ,  $P = 0.42$ ).

We compared the oscillatory amplitudes between the preference judgment and the control conditions to evaluate the effects of the subjective preferences on the attention-related theta synchronizations and alpha desynchronizations in the occipital electrodes. The theta synchronizations were significantly enhanced in the preference judgment condition compared with the control condition (O1,  $Z = 4.21$ ,  $P < 0.01$ ; O2,  $Z = 4.44$ ,  $P < 0.01$ ), whereas the alpha desynchronizations were not significantly different between the conditions (O1,  $Z = 0.85$ ,  $P = 0.40$ ; O2,  $Z = 1.21$ ,  $P = 0.23$ ).

Next, we examined whether the preference-related theta synchronizations are detectable even when the preferred color is presented to the unattended hemifield in the control condition,



**Fig. 2.** Subject-averaged ( $N = 19$ ) TF amplitudes on the O1 (left) and O2 (right) electrodes while attending to the left (top) and right (bottom) stimuli during the display periods in the control (A) and preference judgment (B) conditions. The upper and lower panels show the results obtained while attending to and selecting the preferred left and right stimuli, respectively. These values, normalized with respect to the intertrial interval baseline, were averaged across successful trials for all the participants. The dotted vertical lines indicate the stimulus onset.



**Fig. 3.** Subject-averaged positive theta amplitudes on the O1 (left) and O2 (right) electrodes when the right or left color was attended in the control condition (A) and when the right or left color was preferred in the preference judgment condition (B). The averaged durations of theta synchronizations on the O1 and O2 electrodes in the preference judgment condition (C). Subject-averaged negative alpha amplitudes on the O1 and O2 electrodes in the control condition (D) and preference judgment condition (E). The error bars denote the S.E.M.

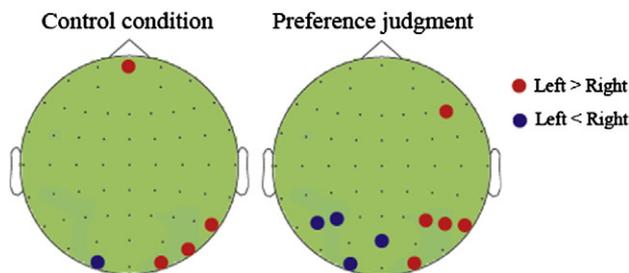
which is not directly related to the preference judgment. First, by using the individual behavioral data of the preference judgment task, we decided which of the 2 colors was preferred. Next, we divided the control task trials into 4 conditions: (1) attention to the left color when the right color is preferred, (2) attention to the right color when the right color is preferred, (3) attention to the left color when the left color is preferred, and (4) attention to the right color when the left color is preferred. Under conditions (1) and (4), the preferred colors were presented on the unattended sides. Finally, we compared the theta amplitudes among these conditions. TF analyses showed that the contralateral theta activities were enhanced when either a preferred or a non-preferred color was presented on the attended side (Figs. 5A(2), B(1), A(4), and B(3)). Interestingly, contralateral theta activities were observed even when the preferred color was presented on the unattended side (Figs. 5A(1) and B(4)). These results revealed the strength of the preference-related modulation effect irrespective of visual attention.

Finally, we conducted ERP analyses of the EEG data because numerous studies using similar experimental paradigms have shown ERP components related to attentional processes. In particular, N2pc components are enhanced at 200–350 ms latencies after the onset of a visual cue in the posterior electrodes contralateral to the target locations in spatial attention and visual search tasks (Luck and Hillyard, 1994; Eimer, 1996; Woodman and Luck, 2003; Kiss et al., 2008). Similar to the earlier findings, we found lateralization of the N2pc potentials (200–350 ms from the stimulus onset; Fig. 6). The N2pc potentials for the attended or preferred contralateral colors were significantly larger than those for the attended or preferred ipsilateral colors in the control condition (O1,  $Z=2.45$ ,  $P<0.02$ ; O2,  $Z=3.59$ ,  $P<0.01$ ) and preference judgment condition (O1,  $Z=2.58$ ,  $P<0.01$ ; O2,  $Z=3.39$ ,  $P<0.01$ ). The N2pc-lateralization results suggested that attention-related N2pc components are also influenced by subjective preferences.

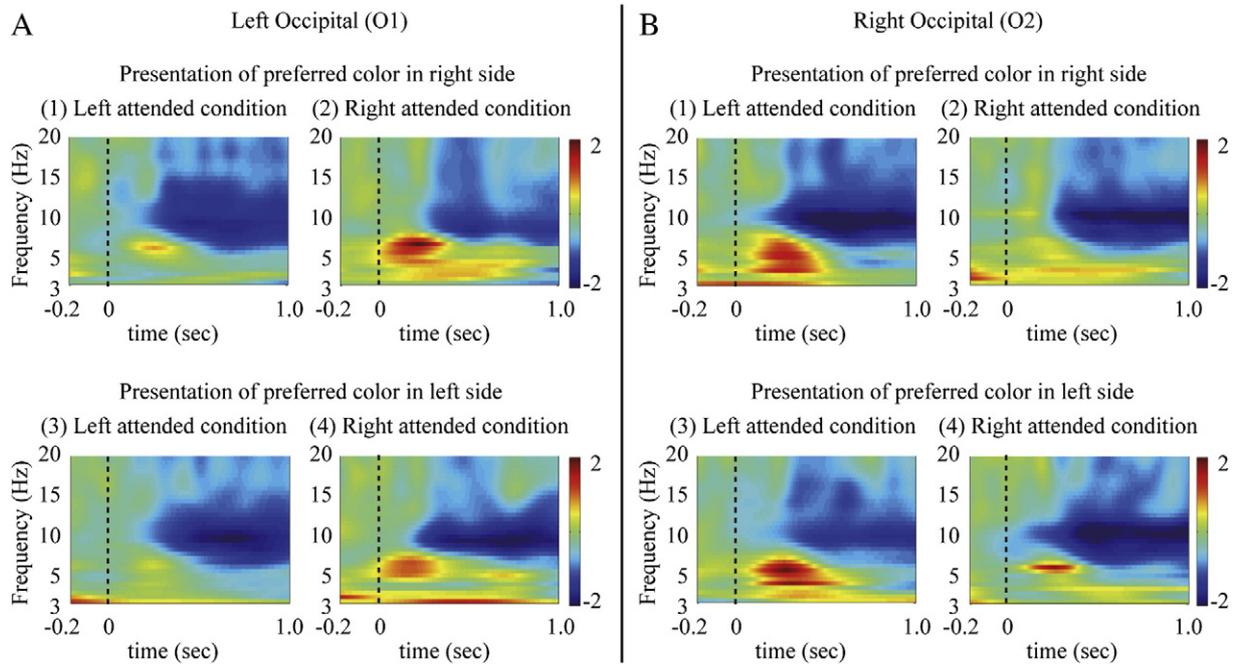
Moreover, the lateralization effects were observed during the late stage of the stimulus presentation (700–1000 ms from the stimulus onset) in only the preference judgment condition. These ERP components would be included in the sustained posterior contralateral negativity (SPCN), reflecting maintenance of the relevant stimulus in the visual working memory (Jolicoeur et al., 2006; McCollough et al., 2007). On the other hand, other attention-related ERP components such as the P1 (positive peaked amplitudes at about 100 ms from the stimulus onset) and N1 (negative peaked amplitudes at about 150 ms from the stimulus onset) components were not observed and showed no lateralization.

## Discussion

The current study demonstrates the effects of subjective color preferences on the neural mechanisms involved in visual attention via changes in EEG oscillations. In the control task, which required visual attention toward a color in the right or left hemifield without selection of the preferred color, we found that the positive theta and



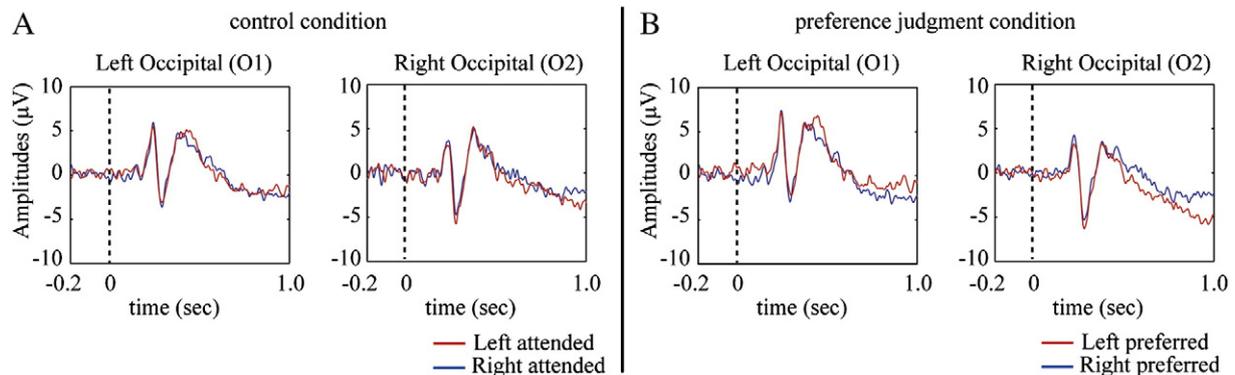
**Fig. 4.** Topographic colored scalp maps of the electrodes showing significant  $P$  values for the different theta amplitudes while attending to the right and left colors (left panel) and choosing the preferred color from the right and left choices (right panel) ( $P<0.05$ ). The red and blue circles indicate the electrodes for which the multiplication values of the theta amplitudes and durations while attending and preferring the left and right colors were significantly higher than those for the opposite colors, respectively.



**Fig. 5.** Subject-averaged TF amplitudes on the O1 (left; A) and O2 (right; B) electrodes during the stimulus display periods in the control condition while attending to the left (1) and right (2) colors when the right color was preferred and attending to the left (3) and right (4) colors when the left color was preferred. These values, normalized with respect to the intertrial interval baseline, were averaged across successful trials for all the participants. The dotted vertical lines indicate the stimulus onset.

negative alpha amplitudes in the occipital regions were representative of visual lateralization, corresponding to earlier findings that the contralateral visual cortex processes information from the visual hemifield containing the visual point of interest (Hillyard et al., 1998; Kastner et al., 1999; Luck et al., 1997). The contralateral positive theta amplitudes were significantly higher than the ipsilateral ones in the early stages of visual presentation (from the stimulus onset to 500 ms thereafter), and the negative alpha amplitudes were more strongly suppressed in the contralateral electrodes than in the ipsilateral electrodes during the late stages of visual presentation (500–1000 ms from the stimulus onset). EEG studies have shown contralateral alpha suppression in the occipital regions during attention-shift tasks (Kelly et al., 2006; Sauseng et al., 2005; Thut et al., 2006; Worden et al., 2000; Yamagishi et al., 2003). Moreover, theta activities and interactions between distinct brain regions are thought to play an important role in attention (O'Connor et al., 2002; Raizada and Grossberg, 2003), although little is known about theta lateralization in such tasks. Therefore, theta synchronizations and alpha desynchronizations are likely to be associated with attention-related processes.

The attention-related theta synchronizations in the occipital regions were modulated by subjective preferences. In this study, when the preferred color was presented, the occipital theta amplitudes increased in the contralateral hemifield rather than the ipsilateral hemifield during the preference judgment task, although this condition did not require the participant to focus on a particular hemifield as in the control condition. Occipital theta synchronizations were additionally enhanced during the preference judgment condition, unlike in the control condition. Neuroimaging studies have shown that responses in the visual cortex are elicited by spatial selective attention (Kanwisher and Wojciulik, 2000; Kastner and Ungerleider, 2000; Poghosyan and Ioannides, 2008) and correlate with the attention-related loads during multiple object-tracking tasks (Culham et al., 2001; Jovicich et al., 2001). Therefore, subjective preferences increase the number of attention-related changes in the visual brain areas. In addition, the durations of the contralateral theta amplitudes were greater than those of the ipsilateral amplitudes. This difference is not attributable to the task difficulty because the theta amplitude durations were not correlated with the reaction times.



**Fig. 6.** Subject-averaged ERPs on the O1 (left) and O2 (right) electrodes while attending or preferring the left (red) and right (blue) stimuli during the display periods in the control (A) and preference judgment (B) conditions. These values, normalized with respect to the baseline (−500 to 0 s from the stimulus onset), were averaged across successful trials for all the participants. The dotted vertical lines indicate the stimulus onset.

Theta changes would be related to unconscious attention-related changes induced by subjective preferences. In the control condition, which is not directly related to the preference judgment task, theta lateralization was observed when the preferred color was presented on the unattended side (Figs. 5A(1) and B(4); “preference and non-attention” condition), as well as when it was presented on the attended side (Figs. 5A(2) and B(1); “preference and attention” condition) and when the non-preferred color was presented on the unattended side (Figs. 5A(4) and B(3); “non-preference and attention” condition). Therefore, preference-related theta synchronizations are detectable independently of the direct attention requirements. The slight ipsilateral theta synchronizations in the control condition in Fig. 2 are attributable to the “preference and non-attention” condition.

Theta activity is thought to be indicative of connections between different task-relevant brain areas through long-distance synchronizations, as shown during several cognitive tasks (Kawasaki et al., 2010; Kawasaki and Yamaguchi, submitted for publication; Klimesch et al., 2008; Mizuhara and Yamaguchi, 2007; Sauseng et al., 2005; Varela et al., 2001). Theta enhancements are also reported to be involved in positive emotional changes; these synchronizations are mainly found in the frontal regions (Aftanas and Golocheikine, 2001; Sammler et al., 2007). Together with the earlier findings, our results suggest a close relationship between attention and preference: that is, the preferred color is subconsciously given more attention for a longer time period than the non-preferred color before conscious decision making, including eye gazing (Shimojo et al., 2003).

The theta lateralization effects of visual attention were mainly found in the occipital region. Frontal lateralization would be absent because of our ICA eliminating the theta components of the frontal electrodes, considering that the frontal theta activities are reportedly related to the ocular activities. However, the participants were firmly instructed to maintain their focus throughout the stimulus presentations. Furthermore, the attention-related occipital activities in the current study are not directly associated with ocular activities, so our main results would not be affected by these issues.

In contrast to theta synchronizations, the occipital alpha desynchronizations showed no significant difference between the contralateral and the ipsilateral hemifields in the preference judgment task: that is, the alpha desynchronizations were unaffected by the attention associated with subjective preferences; they occurred after the theta synchronizations had diminished. Therefore, theta and alpha activities likely play different roles in attention-related processes, including visual perception, comparison, motor preparation, and decision making. In fact, alpha suppressions can be interpreted as active inhibitory processes, because some studies have shown alpha desynchronizations when a subject deliberately ignored a feature of interest (Kelly et al., 2006; Worden et al., 2000; Yamagishi et al., 2003). Our preference judgment task required the participant to choose the preferred color but not to ignore it or to select the non-preferred color, which may have caused the lack of lateralization of the alpha desynchronizations. Further studies are required to explore the sources of the observed alpha and theta oscillations by combining our techniques with other methods such as fMRI and magnetoencephalography.

Our TF results are consistent with those of ERP studies using similar attention-related task paradigms. Our ERP results showed prominent lateralization of the N2pc components in both the control and the preference judgment conditions. The N2pc is well known to be associated with attention-related processes (Luck and Hillyard, 1994; Eimer, 1996; Woodman and Luck, 2003; Kiss et al., 2008). According to the N2pc lateralization results, attention-related occipital activities would also be affected by preferences. Similar to the N2pc components, subsequent negative potentials were sustainably enhanced on the contralateral occipital electrodes to the preferred colors during the late stage of the stimulus presentations in only the preference judgment condition. In earlier studies (Jolicoeur et al.,

2006; McCollough et al., 2007), the SPCN reflected maintenance of the relevant stimulus in the visual working memory. Therefore, our preference judgment task required maintenance of the preferred stimulus, whereas the control condition did not.

On the other hand, P1 and N1 components were not observed and showed no lateralization. The P1 and N1 components on the occipital electrodes were believed to reflect spatial attention because these ERPs were enhanced in the contralateral locations during the stimulus presentations irrespective of whether these stimuli were targets or not (Mangun and Hillyard, 1987; Eimer, 1994). Therefore, P1 and N1 might not be directly associated with attention to the visual stimulus contents unlike the subsequent N2pc, which is related to the selective feature attention. The P1 and N1 components would be absent because of feature attention even in the control condition. Therefore, the attention-related theta amplitudes were also influenced by subjective preferences in the control condition (Fig. 5).

In our preference judgment task, the participants had possibly already decided their color choice and the observed theta effect would be attributable to increased attention to confirm their selection because they looked at the screen for 1 s before the response. However, we focused on the early responses of theta synchronization (0–500 ms from the stimulus onset), which would be less affected by such confirmation effects. Even in that time range, the contralateral theta amplitudes of the preferred colors were significantly higher than the ipsilateral ones. These results suggest that the confirmation effects have a small impact on the preference-related theta activities.

We used colors as information for preference decision making to decrease the number of visual features. Although these simple stimuli have advantages over natural scenes or attractive faces, both of which have many features, the other systematic components of color (e.g., brightness, RGB dimensions, and fixation colors) can influence the preference judgments and EEG differences. In fact, the averaged blue values of the RGB codes were significantly different between the preferred and the non-preferred colors (red,  $Z = 1.21$ ,  $P = 0.23$ ; green,  $Z = 0.92$ ,  $P = 0.35$ ; blue,  $Z = 2.98$ ,  $P < 0.01$ ). Such bottom-up sensory processing might be attributable to our attention and preference judgment results, although most of the participants did not prefer blue and the lateralization effects were observed even when colors other than blue were presented. These effects of the color components on preference judgments and EEG activities should be clarified in a future study.

In conclusion, we have demonstrated that subjective preferences modulate attention-related brain oscillatory activities. We found that the contralateral theta amplitudes increased and their durations were extended in the occipital regions when the preferred color was selected and attended, whereas the occipital alpha desynchronizations showed such lateralization effects only in the control condition. Our results suggest a dynamic interaction between preference and attention for theta synchronizations.

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