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# Measurement of Object-based Attention with Steady-state Visual Evoked Potential

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**Measurement of Object-based Attention with Steady-state Visual Evoked Potential**

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The spatial extent of visual attention, which facilitates perceptual performances, has been classified into spatial and object-based attention. Object-based attention refers to a type of attention limited within an object that encloses a cued location, which contrasts with spatial attention that spreads around the attentional focus, regardless of the object shape. Whether object-based attention is enabled by the deformation of an attentional “spotlight” or by the prioritization of locations to which the attentional spotlight is directed is a matter of much debate. The present study addresses this issue by employing an EEG (electro-encephalogram) technique called steady-state visual evoked potentials (SSVEP) during a psychophysical experiment. The SSVEP amplitude is modulated by visual attention. During the EEG recording, we asked participants to perform a rapid serial visual presentation task designed to exhibit object-based attention, and a simple detection task to measure the spatial spreading/deployment of attention. The visual stimuli flickered at different frequencies at different spatial locations, which enabled us to tag stimulus locations with temporal-frequency components in the EEG data. We

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found an effect of object-based attention on SSVEP amplitudes and behavioral performances. Additionally, the absence of event related potential changes at the cued location, triggered by random and frequent presentations of detection-task stimuli throughout a trial, suggests that object-based attention may be based on a steady state mechanism, i.e., spatial spreading, rather than a dynamic one, such as prioritizing shifts of attention to locations within the cued object.

**Key words**: visual attention, object-based attention, EEG, SSVEP

**【要　約】**視知覚の能力を促進する視覚的注意の広がりは，空間的注意と物体随伴性注意の2つに分類される。注意の焦点を中心に広がる空間的注意とは対照的に，物体随伴性注意の広がりは注意の焦点を包含する物体内部に限られる。物体随伴性注意が，注意スポットライトの変形とスポットライトの定位における優先順位のどちらで実現されているかは，長く議論の対象になっている。本研究では，心理物理実験中に脳波（EEG）の一種である定常視覚誘発電位（SSVEP：振幅が注意の影響を受ける）を測定することにより，この問題にアプローチした。脳波計測中，参加者は物体随伴性注意を観測できるRVSP課題に加え単純な検出課題を行ない，注意の広がりを心理物理の手法で測定した。空間位置に依存して異なる時間周波数で視覚刺激を点滅させ，脳波成分と空間位置とのタグ付けを行なった。その結果，心理物理実験とSSVEP振幅の両方で物体随伴性注意の効果を確認した。同時に，テスト刺激以外の位置にランダムに呈示される妨害刺激により事象関連電位に変化が生じなかったことから，我々の研究で観測された物体随伴性注意は，優先順位によるスポットライトのシフトのような動的メカニズムではなく，静的なメカニズムに起因することを示唆していると考えられる。

The performance of a visual task can be improved by the presentation of a cue for the target, either as a spatiotemporal or as a semantic guide; this phenomenon is the effect of visual attention (Posner, 1980; Posner & Cohen, 1984). Visual attention has been widely investigated by using pre-cueing effects, namely the *Posner paradigm*. The Posner paradigm elucidates the presence of attentional effects on visual task performances that occurred either with or without the participant's intention; these effects are referred to as *endogenous* and *exogenous* attention, respectively.

Visual attention is often illustrated by a *moving spotlight*. The size of this visual attention spotlight varies (Eriksen & St. James, 1986); however, it is not clear whether every item in the spotlight is subject to an attentional effect or if the attentional effect is limited within the object to which the focus of visual attention is directed. In either case, the efficiency of visual attention decreases, in general, with distance from the center of the spotlight (Andersen & Kramer, 1993; Matsubara et al. 2007; Shioiri et al., 2002, 2010).

Psychophysical experiments are used to clarify this controversy by testing perceptual performances with two possible target areas that are located within the object where the cue is presented or in a different object in addition to the cued location. Egly et al. (1994) conducted a detection task by presenting a target at two locations, either within or between two larger items, at an equal distance from the cued location (See Figure 1 in Egly et al., 1994). Their study demonstrated that the reaction time for the target presented at the two cue-invalid (un-cued) positions was different: reaction time for the *target within the same object* as the cued location was shorter than the other location. They argued that the pre-cueing effect may spread within the same item, and reflects the presence of *item/object-based attention* (Duncan, 1984).

Studies on object-based attention have left the mechanisms responsible for such attention an open question. The higher attentional bias for the target in the same item/object could occur, for example, by an irregularly or anisotropically shaped attentional spotlight extended within the item (Richard et al., 2008). Conversely, the higher attentional bias may be realized by differences in the priority of search by a small attentional spotlight, if the temporal shift in the small spotlight location takes place under a higher priority for a target in the same object than another target at the same distance but in a different object (Shomstein & Yantis, 2002).

One possible approach to this issue is the use of EEG (electroencephalogram) based measurement of visual attention. EEG is able to record changes in neuronal activity in the human brain on the order of milliseconds. This temporal resolution of EEG is sufficiently high, since the temporal changes in the location of the attentional spotlight take several hundreds of milliseconds (Egeth & Yantis, 1997; Roelfsema et al., 1998; Wright & Ward, 2008). Additionally, the modulation of event-related potential (ERP) components, such as the P300, N1, N2, and N2 pc, have been shown to reflect the participant's state of visual attention (Luck & Hillyard, 1994; Kasai, 2010; Kashiwase et al., 2013; Polich, 2007). In this paper, the *state of visual attention* refers to the status of inclined/declined visual task performance due to differences in spatial spreading or deployment of visual attention.

Steady-state visual evoked potentials (SSVEP) have been shown to exhibit reliable modulation related to visual attention bias (Kashiwase et al., 2012; Kim et al., 2007; Müller et al., 1998; Störmer et al., 2014). ERP components are evoked by an *instantaneous event* and SSVEP is more suited to monitoring *temporal changes* in the state of attention, which occurs, for example, while sustained endogenous attention is deployed. Another advantage of using SSVEP is the ability to monitor the state of attention at multiple locations by the use of multiple stimulus frequencies. It is possible that SSVEP is able to measure the deployment of visual attention across/within objects while participants maintain attention at a corner of the stimulus. However, the capability of SSVEP to observe object-based attention is yet to be established. We measured the effect of object-based attention on SSVEP during the steady state attentional tasks, as an attempt to dissociate the underlying mechanisms.

The primary purpose of the present study was to confirm whether SSVEP could be used to measure the status of visual attention, specifically in relation to object-based attention. We found an effect of object-based attention on SSVEP amplitudes: the amplitude was significantly larger for the un-cued target within the object compared to the un-cued target outside of the object.

## Methods

### Overview of the experimental design

To measure object-based attention, we modified the stimulus design of Egly et al. (1994) such that it would accommodate SSVEP measurements during the behavioral tasks. The main task was to detect a target letter "H" in a *rapid serial visual presentation* (RSVP) stream at the target location. The second task was presented at all possible locations to measure the state of visual attention psychophysically, as a "ground truth"; the second task was to detect 30% luminance reductions of letter elements at the four locations, which occurred at random timing with equal possibility at all locations aside the RSVP task. The SSVEP amplitudes were measured at the four locations for the target. The details are provided in the following subsections.

### Apparatus

All visual stimuli were generated with a visual stimulus generator ViSaGe (Cambridge Research Systems, U.K.), controlled by MATLAB 7.5.0 (Mathworks, U.S.A.) on a Dell PC. Visual stimuli were presented on a CRT screen (SONY GDM-G520); spatial resolution was 1,024 × 768 and the screen refresh rate was 160 Hz. EEGs were recorded with a sampling rate of 1,000 Hz using a clinical EEG amplifier and a D/A converter system Neurofax EEG9100 (Nihonkoden, Japan), using an electrode cap with international 10–20 electrode arrangement. EEG data were recorded and digitized at a sampling rate of 1,000 Hz, and a temporal band-pass filter of 0.5–120 Hz was applied. The reference electrode was connected to the earlobe, and data from the occipital, parietal, and temporal electrodes (O1, O2, P3, P4, T5, and T6) were primarily used for the analysis of SSVEP. Electrooculograms (EOG) were recorded with other electrode pairs to monitor eye movements during the EEG recording. EEG data of trials with an excessive EOG magnitude (>40 μV) were discarded from further analysis. All analyses of visual evoked potentials (VEP) and the following statistical analyses were conducted off line, using an in-house software and Statistics Toolbox in the MATLAB.

**Participants**

Nine students were recruited from the Graduate School of Information Sciences, Tohoku University, and participated in the experiment on a volunteer basis (all male; average age = 23.2, *SD* = 0.83 years). All subjects were right handed and had normal or corrected to normal visual acuity. Data from three participants were discarded due to frequent eye movements, and the data from one participant was discarded because of a low signal-to-noise ratio (SNR; details on the SNR is provided in the Analysis subsection). The experiment was conducted in accordance with the Declaration of Helsinki, and was approved by the Internal Review Board (ethics committee for experiments using human participants) of the Research Institute of Electrical Communication, Tohoku University. All participants gave written informed consent before starting the experiment.

**Stimuli**

The stimuli arrangements were modified from those in the study by Egly et al. (1994) on object-based attention. Four squares of target/distractor areas, subtending 7 deg × 7 deg in visual angle centered at the eccentricity of 10 deg in the periphery, were used as locations for the attention tasks. Each of the two large rectangles (each subtended 11 deg × 24 deg) surrounded a pair of target areas in a top/bottom or a left/right arrangement (see inset of Figure 1). These

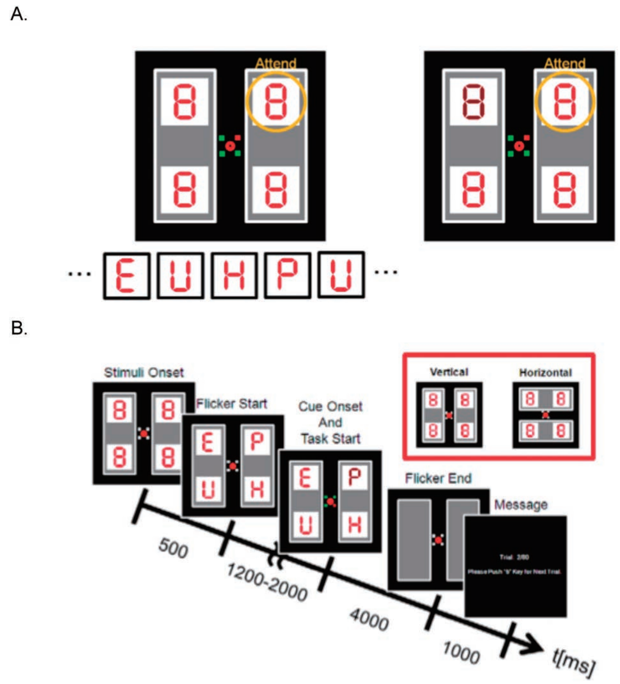


Figure 1.　Stimuli and procedure. A. *Left panel*: an example image of the visual stimulus in the vertical arrangement. A red small square on the top right near the fixation point (a bull's-eye at the center of the display) is the attentional cue. A seven-segment letter on the top right location, marked with a yellow circle, is the position to which the participant was asked to direct attention. The cued location was randomly assigned among the four areas. Alphabets at the bottom show example letters that are used for the rapid serial visual presentation (RSVP) task. *Right panel*: an example image of luminance change, shown in the top-left location. The participants had to detect luminance changes while conducting an RSVP task at the cued location. B. The time course of stimulus presentation. EEG data for each trial were sampled between −1,200 ms and +4,000 ms with respect to the cue onset. Inset shows vertical and horizontal arrangements of the object.

rectangles were arranged either horizontally or vertically; hereafter referred to as *horizontal* and *vertical arrangement* conditions, respectively. The horizontal ("H") and vertical ("V") arrangements were tested to reject any possibility of anatomical bias from hemisphere-based processing. Details of the analysis are provided at length below.

The immediate surrounds of the four target/distractor areas (white squares) flickered at different temporal frequencies: 16, 17.8, 20.0, and 26.7 Hz. They were presented as a square-wave flicker at a duty cycle of 50% with a 100% luminance contrast (white to black). There were two patterns for the spatial arrangement in terms of the temporal frequency assignment to the four locations, and they were counterbalanced across trials to avoid any artifacts from the combination of stimulus location and temporal frequency.

In each flickering area, an alphabet letter was presented in a seven-segment array (2.1 deg×4.2 deg). Letters were alternately presented at a rapid sequence (200 ms per letter) for the RSVP task. The letters were "P," "E," "U," or "H" ; "H" was the target letter and was presented at only one location within each time bin (=200 ms). The presentation of "H" at the same location was temporally separated by at least three time bins (i.e., inter-stimulus interval: ISI= 600 ms). The presentation of "H" at the target location ranged 1–7 times per trial, (4.25 times per trial, on average). The width of the line segment was optimized for each participant to equate the difficulty of the task across participants.

A red fixation circle (a small bull's-eye) was presented at the center of the display and one square dot was placed in the direction of each target/distractor stimuli (four total). One of the surrounding dots changed its color (red in the example of Figure 1) to identify a cued location in the trial. EEG data for each trial were sampled between −1,200 ms and +4,000 ms with respect to the cue onset (i.e., cue-onset latency or latency), and the EEG data recorded between −500 ms and +3,500 ms of the onset latency were used for analysis.

**Participant's task and procedure**

Participants were asked to conduct two tasks: 1) to detect a target letter "H" *at the cued location* and respond as soon as possible, 2) to detect a luminance decrement of the letter (see example at top-left corner in the top-right panel of Figure 1) *at all locations* and respond as soon as possible. They were also told to keep their eyes on the fixation point during a trial. The first task (RSVP) was used to measure object-based attention. The second task (luminance-change detection) was used to measure the spatial deployment of attention to the four letter positions during each trial. This behavioral response was compared with the SSVEP amplitude data, since the RSVP task was conducted only at the cued location in a trial. In the second task, the luminance of the letter was intermittently dropped by 30% only once in a trial at a latency larger than 800 ms after the cue presentation.

The time of cue presentation varied with latencies ranging from 1,200 to 2,000 ms (200 ms steps) after the start of flicker. Each participant completed eight sessions of 80 trials (640 trials in total): they were four cue locations×two object positions (horizontal or vertical)×two temporal frequency arrangements×five cue-lead time×four luminance-change locations×two trials. All participants served one session for training, before serving for the formal recording sessions.

**Analysis**

**Behavioral data**. Behavioral data were obtained by preparing a time window for the button press reaction time after presentation of the target stimuli. First, a reaction time histogram was generated for each participant. The histogram was fitted with a Gaussian distribution function $N(\mu, \sigma)$ and the time window was determined by assuming that the button press occurred during the window of $\mu \pm 3\sigma$. It ranged from 293.4 to 785.4 ms on average across all participants. If a button press occurred within this time window after the stimulus onset, it was counted as 'Hit' and other button presses were counted as 'False Alarms' (FA). The rates of Hit and FA were calculated by dividing the sum of Hit or FA within a time bin (width= 200 ms) by the number of the targets or distractors, respectively.

**SSVEP data.** SSVEP amplitudes were derived for comparisons between locations. A detailed definition is described in a previous study from the authors' group (Kashiwase et al., 2012). The summary is as follows: four frequency components of the EEG data, each of which corresponded to the flicker frequency of a particular location, were derived by applying the *fast Fourier transformation* (FFT) to the time-series data of EEG in MATLAB. The amplitude of each frequency component was derived by applying a 500 ms moving window. Since the absolute amplitude of the SSVEP components varied among both the participants and flicker frequencies, the amplitudes were first normalized to Z-scores within each participant and flicker frequency, before calculating the averages across participants at each stimulus location.

As mentioned above, data from one participant was discarded due to low SNR, while those from three others were discarded due to frequent eye movements. SNRs were derived for each frequency of SSVEP flicker by dividing the amplitude of the frequency component of the SSVEP flicker with the averaged amplitude within a nearby frequency range (background noise); this nearby frequency range was chosen from the higher and lower end of each flicker frequency within a range of $\pm 1.11$ Hz (equal to 10 bins on the frequency axis after SSVEP). The lowest SNR value among the data from the five participants that passed the above-mentioned criteria was 1.06 (equivalent to 0.53 in dB); the grand average and standard deviation of the SNR values of the data used to derive results in the present study were $1.23 \pm 0.08$ (equivalent to $1.75 \pm 0.58$ in dB).

The primary purpose of the present study was to determine whether object-based attention could be observed with the SSVEP technique. Therefore, we paid attention to the sustained state while participants conducted the luminance-change-detection task (1,000–3,500 ms in latency, referred to as *integrating period*, hereafter), during which the attentional effect on the SSVEP amplitude can be robustly recorded (Kashiwase et al., 2012) for comparisons with behavioral performance. Therefore, all data shown in the present study are the average of the results during this integrating period.

**Laterality effect.** Information processing in the human visual cortex is partially separated between the left and right halves of the visual field; left and right halves of the visual field are processed in the right and left hemispheres (Wandell et al., 2007), respectively. Visual cortices in the right and left hemispheres are connected by neuron-fiber bundles straddling the posterior part of the *corpus callosum*, and they integrate information from both the left and right visual fields. Since the fiber length for the intra-hemisphere connection is obviously shorter than the inter-hemisphere connections, it is possible that the difference in the visual attention effect for both behavioral and SSVEP data could arise from the difference between the inter- and intra-hemispheric distances; such a bias in the results cannot be ascribed solely to the effect of object-based attention. In addition, the advantage of visual processing of two stimuli presented in the left and right visual fields over those presented in the same visual field can be explained by assuming separate attention resources for the left and right hemispheres (Alvarez & Cavanagh, 2005; Harasawa & Shioiri, 2011; Störmer et al., 2014). This difference should become more obvious in the vertical arrangement, if it exists. Therefore, the effects of laterality and object-based attention were examined by indices, defined as follows.

The index for object-based attention was defined by calculating the SSVEP amplitudes for the two *un-cued* locations, within or between the objects, at the same distance from the cued target stimulus in the following way:

$$I_{\mathrm{OB}} = \{(W_{\mathrm{H}} - B_{\mathrm{H}}) + (W_{\mathrm{V}} - B_{\mathrm{V}})\}/2, \qquad (1)$$

in which $W$ and $B$ represent SSVEP amplitudes for two un-cued locations *within* and *between* objects, respectively, and subscripts $H$ and $V$ represent horizontal and vertical arrangements, respectively.

It is also possible to evaluate the effect of hemispherical differences in relation to the target location in the following way:

$$I_{\mathrm{HS}} = \{(W_{\mathrm{H}} - W_{\mathrm{V}}) + (B_{\mathrm{V}} - B_{\mathrm{H}})\}/2, \quad (2)$$

in which the notations of the variables are the same as in the Formula (1).

## Results

### Behavioral results

Results of the behavioral responses to the RSVP task, in which participants detected the target letter at the cued location, are shown in Figure 2A as the rate of hit and false alarm by collapsing flicker frequency, target location conditions, and participants ($N=5$). The hit rate for detecting the target letter at the cued location increased with time, reaching a maximum of 60% approximately 500 ms after cue onset and stayed around 40–50%. These levels were sufficiently higher than the false-alarm level, which was always less than 5%.

The results of the luminance-change detection task are shown in Figure 2B as the hit and false-alarm rates. Note that the luminance changes were presented at the cue-onset latency of 800 ms and later. The hit rate was about 80% and false-alarm rate was much smaller than 5%.

Figure 2C shows the response time for the luminance change at the four locations that differed in attentional and object-related status; cued location, un-cued within object, un-cued between object, and

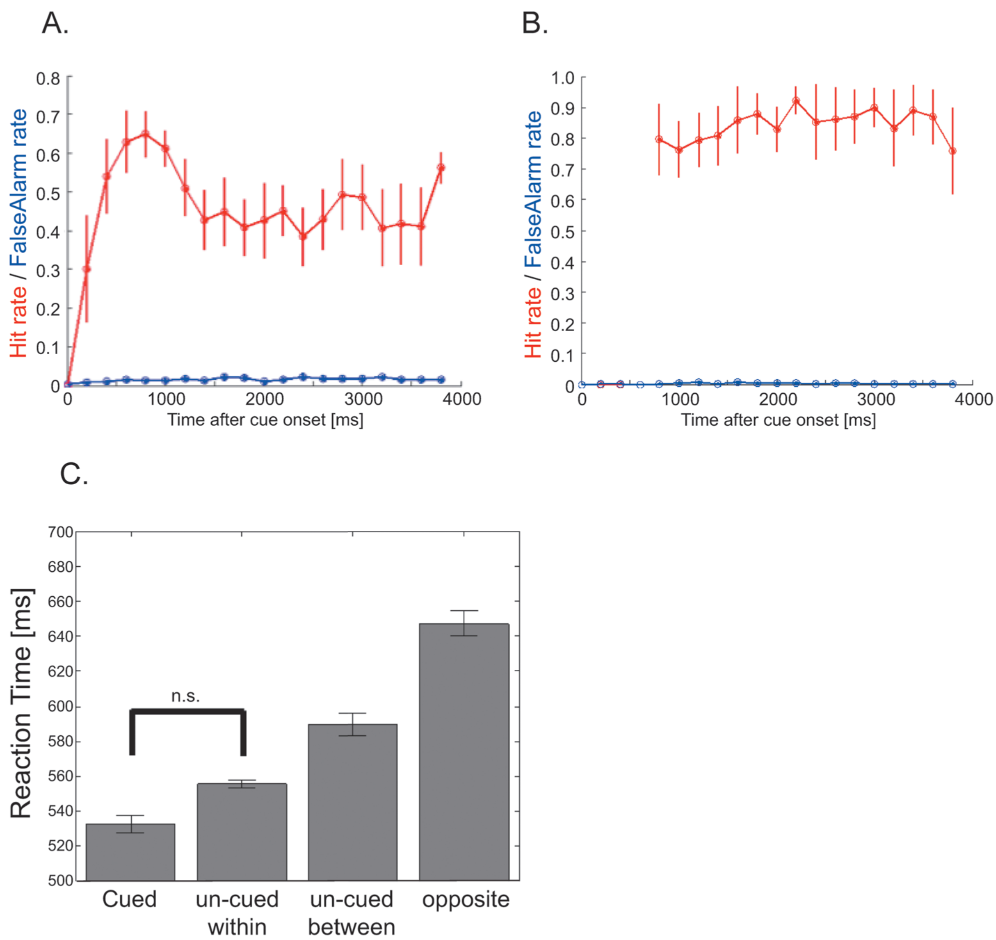


Figure 2. Behavioral performances. A and B. The hit and false-alarm rate of rapid serial visual presentation (A) and luminance-change detection (B) tasks. Red and blue lines indicate hit and false-alarm rates, respectively. C. Reaction times. Differences between locations un-cued within object and cued location were not statistically significant, but other differences were all significant ($p<.05$).

opposite location to the cue. The results are averaged across all horizontal/vertical arrangements, frequency-location conditions, cue locations, and participants. The average response increased progressively in the order of cued, un-cued within, un-cued between, and opposite locations. According to the analysis of variance, the location effect was statistically significant ($F(4, 20) = 45.1$, $p < .001$)). The *post-hoc* analysis for the multiple comparisons between conditions (*t*-test with a Bonferroni's correction for multiple comparisons) detected statistical significance for all conditions ($ts(4) > 5.28$, $ps < .00833$) except between the *cued* and *un-cued within* locations ($t(4) = 3.64$, $p = .0129$, n.s.). This result confirmed the phenomenon of object-based attention, which was consistent with the previous psychophysical study (Egly et al., 1994).

**SSVEP results**

Figure 3 illustrates the averaged spectrum of EEG recordings during the integration period. It is clear that the SSVEP amplitude becomes highest when the participant paid attention to the object flickering at the target frequency.

We next confirmed whether it is possible to measure the effect of object-based attention with SSVEP, by assessing whether the amplitude increase had a positive correlation with the behavioral result. The SSVEP amplitude was calculated by averaging the amplitude of each flicker frequency component during the integrating period, i.e., cue-onset latency of 1,000–3,500 ms. Figure 4 shows the results of the averaged SSVEP amplitudes. The amplitudes differed significantly by attentional condition, decreasing in order of *cued* location, *un-cued within*-object location, *un-cued between*-object location, and the *opposite* of the cued location.

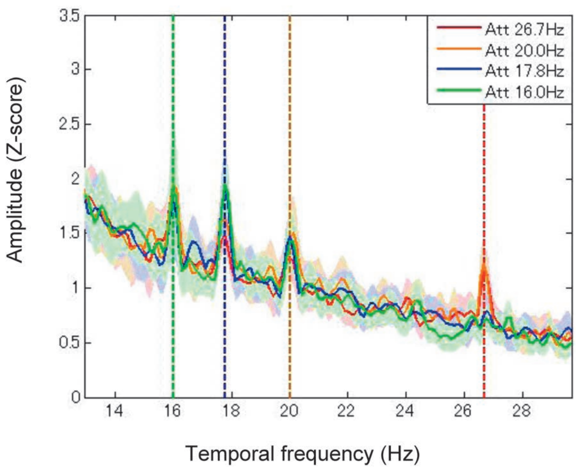


Figure 3. Typical steady-state visual evoked potentials (SSVEP) spectrum. SSVEP amplitude measured between 1,000–4,000 ms latency is shown. Colored lines indicate the differences in the attended stimulus, tagged with a temporal frequency. The colored lines become the highest at the temporal frequency of the attended stimulus.

To evaluate the statistical difference among the conditions, a comparison was conducted on SSVEP amplitudes (Figure 4C), which were averaged within the integrating period for the un-cued within and un-cued between object locations as a *pre-planned* paired comparison by *t*-test. The results showed a significant difference ($t(4) = 2.97$, $p < .05$); the statistical significance of this difference was also confirmed with non-parametric analysis ($p = .0079$, Wilcoxon's rank sum test). The trend of larger SSVEP amplitudes, shown as scattered points connected with dashed lines in Figure 4C, shows a consistent difference between the un-cued within and between conditions across all participants.

The laterality index and object-based attention index were compared to confirm that the difference between the two un-cued positions was not just due to the anatomical difference between and within visual/cortical hemisphere processing (Figure 4D). The result showed that the indices calculated from the SSVEP amplitudes (normalized with Z-scores) were significantly different; the laterality index was not significantly different from zero ($t(4) = 0.661$, $p = .27$), while the object-based attention index was significantly different from zero ($t(4) = 3.31$, $p < .05$). Lastly, the two indices were significantly different from one another ($t(4) = 2.35$, $p < .05$). Therefore, the apparent bias of higher SSVEP amplitude at the un-cued location within the same object compared to the un-cued location in the different object (Figure 4C) is

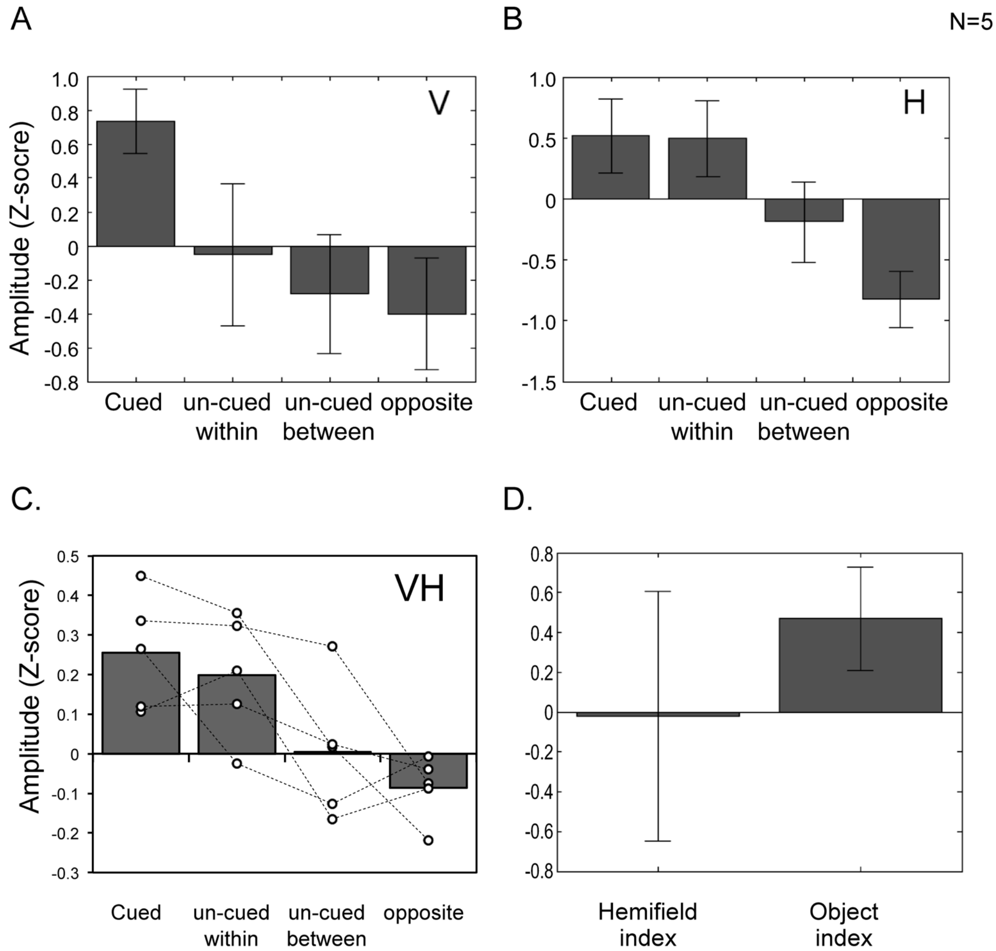


Figure 4. Steady-state visual evoked potentials (SSVEP) amplitude. SSVEP amplitudes converted to Z-scores, averaged across five participants and time (1,000–4,000 ms in latency). Panels A to D are the results for the vertical arrangement, horizontal arrangement, averages of vertical and horizontal arrangement, and hemifield/object effects (from top left to bottom right), respectively. Bars represent different locations with respect to the cued location and object shapes, shown on the horizontal axis. Error bars in panels indicate standard error of means (except VH) (SEM). C. Mean SSVEP amplitude of V and H conditions are shown with gray bars. Open symbols indicate individual participant results, connected to one another by a dotted line. All participants showed differences between *within-* and *between-object* conditions. D. Object effect showed a statistically significant difference, while the hemifield effect was not statistically significant.

not just the consequence of hemispherical correspondence.

According to the comparison of SSVEP amplitude and response times to the luminance change for each participant (Figure 5), the correlation coefficient was significantly high to reject the null-hypothesis of *zero-correlation* ($\rho = -0.90$, $t(18) = 8.76$, $p < .001$). This result indicates that the difference in the SSVEP amplitudes was consistent with those in the response time data, and that the modulation in SSVEP amplitudes reflected the effect of the participant's visual attention.

**Analysis of the effect of luminance-change stimuli on SSVEP**

The results thus far have demonstrated that SSVEP amplitudes appear to reflect the participant's object-based attention. If the SSVEP amplitude corresponds to the attentional status of the participant, no significant difference in SSVEP amplitude modulation is expected at the cued location during the flash-detection task.

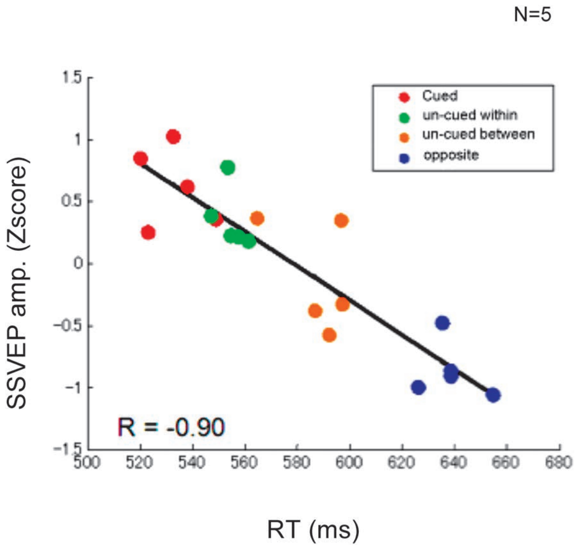


Figure 5. Correlations between behavioral and steady-state visual evoked potentials (SSVEP) results. The horizontal and vertical axes represent the response time (RT) and SSVEP amplitudes, respectively. Different colors represent different locations. Each symbol represents a different participant. The correlation coefficient between the two measures is −0.90 and was statistically significant.

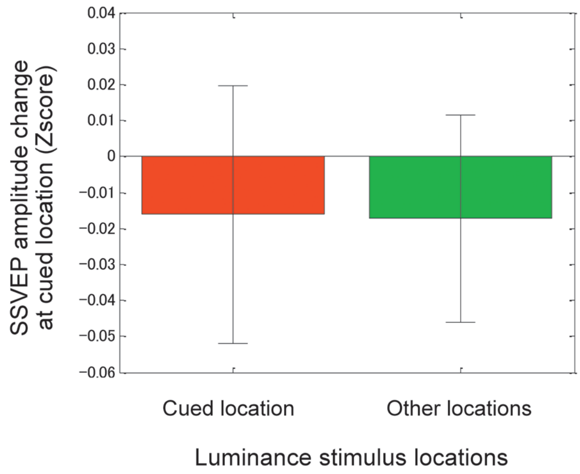


Figure 6. Effect of luminance changes at other locations on steady-state visual evoked potentials (SSVEP) at the cued location. Bars indicate changes in SSVEP amplitude (Z-score) at the instance of luminance change at cued or opposite location with +/−1 SEM. The results showed no statistically significant difference.

This is because the RSVP is the primary task at the cued location in our experiment and the performance of the RSVP task was relatively constant on average during the integrating period (Figure 2A). Furthermore, this implies that no attentional shift occurred, and spatially anisotropic attention could have caused the object-based attention. In an attempt to confirm this hypothesis, we analyzed changes in the SSVEP amplitudes at the cued location in relation to luminance changes at the cued and other locations, when the participant was conducting the RVSP and luminance-change detection tasks. Changes in the SSVEP amplitudes were evaluated at 0–600 ms after the onset of luminance-change stimulus. This latency of the analysis window was determined from the average onset latency for the SSVEP amplitude according to the effect of exogenous attention (Kashiwase et al., 2012).

The bar on the left in Figure 6 shows changes in the normalized (Z-score) SSVEP amplitudes for the cued location, averaged during the 0–600 ms latency from the onset of luminance change at the *cued location*. The bar on the right shows SSVEP-amplitude changes at the cued location immediately after (i.e., 0–600 ms) the onset of luminance changes at the *three other locations*. The averages across five participants were taken, and the standard errors of the mean (SEM) are shown as the error bars. Statistical analysis using the paired *t*-test showed that the results were not significantly different ($t(4)=0.0212$, $p=.984$, n.s.), with power ($1-\beta$) equal to 0.0268 under $\alpha=0.05$. Therefore, the side effect of the luminance change presentation, which was detected at a hit rate of 80% in the behavioral task (Figure 2B), may be said to be very small or negligible in terms of the SSVEP amplitude measurement at the cued location.

## Discussions

We conducted an experiment on object-based attention using a modified paradigm of Egly et al. (1994) while combining psychophysical and EEG measurement techniques. The results clearly exhibited the effect of object-based attention on the psychophysical response time data. Additionally, the effect of object-based attention on the SSVEP amplitude was observed; the amplitude for the un-cued location within the same object as cued-location target was significantly higher than the un-cued location at the same distance but outside the cued object (Figure 4C). We confirmed a significant correlation between the response time and SSVEP-amplitude differences (Figure 5), which supports the successful observation of object-based attention by SSVEP-amplitude modulation.

**Supporting evidence for the contribution of steady-state mechanism**

The results of the present study suggest that object-based attention is based on a steady state mechanism, i.e., spatial spreading or deformation, rather than a dynamic mechanism that prioritizes to shift attention to the location within an object. Quick shifts of attention among different locations could also explain the results, assuming that probabilities of attending at the four possible locations vary as the results showed: the highest at cued, second and third highest at within and between object locations, respectively, and the lowest at the opposite location. Although we cannot entirely rule out this possibility with our results alone, this is unlikely due to the following reasons.

First, a side effect of the luminance change was not observed in the present study; SSVEP amplitudes at the cued location did not change with the presentation of luminance changes at other locations (Figure 6). This result implies that the focus of attention was not moving across the four possible locations and was staying primarily at the cued location. Even under such a circumstance, we observed the effect of object-based attention on both behavioral performance and SSVEP amplitudes.

Secondly, according to previous psychophysical studies, the speed of a temporal shift in attention takes place on the order of several hundreds of milliseconds (Egeth & Yantis, 1997; Wright & Ward, 2008). Additionally, an electrophysiological study in monkey V1 has demonstrated that the modulation of neural responses in relation to object-based attention occurred as early as 200 ms in terms of the cue-onset latency (Roelfsema et al., 1998). Regarding the movement of spatial focus of attention from a fixation point to a target location within the parafoveal region (approx. 5.5 deg), our previous study using SSVEP reported a cue-onset latency of around 500 ms (Figures 1 and 8 in Kashiwase et al., 2012). The distribution of response times for the RSVP task in the present study (see *Analysis* subsection above) showed that response time had a variability of approximately ±240 ms in terms of 3 $\sigma$ (see also Figure 4A in Kashiwase et al., 2012). Furthermore, there are some limitations in attention shifts when a person tracks a moving object attentively; it has been reported that it is difficult to track an object changing position at 4 Hz or higher (Verstraten et al., 2000). In addition, attention seems to move with a gradual change in position when an object jumps from one location to another at 120 ms intervals (Shioiri et al., 2000). According to this behavioral and physiological evidence, it is unlikely that the attention shift occurred at a faster speed than the SSVEP time course is able to record.

Together, with our result showing the absence of side effects from luminance stimulus on the SSVEP amplitudes (Figure 6), it is unlikely that attentional focus made shifts away from the cued location during a trial.

**Comparisons with previous studies**

Our SSVEP results suggest the possibility that attention shifts (prioritization) did not seem to take place during our stimulus. Let us consider the possible reason for this by comparing two related studies that was accounted for by the prioritization hypothesis. Shomstein and Yantis (2002) reported that the letter discrimination performance fit well with a *priority setting*, and that attention reshaping did not account for their results. Their experiments used a very small sized stimulus (<0.69 deg) and the "object" was the background of a target letter, presented at the center of the screen. The flanking letters were placed at a very close distance (0.18 deg gap for a letter size of 0.38 deg), and it is possible that this paradigm measured the effect of suppression from the flanking letters. Therefore, it is crucial to compare their results directly with single-letter detection tasks, as in Egly et al. (1994) and our study.

Another recent study using conjunction/pop-out visual search tasks also used objects presented behind the fixation point, a parallel search condition in that it may resemble the conditions in Egly et al. (1994) (the target presentation in Egly et al.'s (1994) experiment can be considered a *pop out* target). Therefore, it is possible that the *object effect* in the stimulus design of Shomstein and Yantis (2002) was too small to be detected. Another recent study by Richard et al. (2008) demonstrated that the association of visual task and object shape is a key between the presence and absence of the object-shape effect. Their results indicate that the inhibition effect due to object-based attention may be reduced by the effect of "narrowly focused attention" (Shomstein & Yantis, 2002), but may still be effective under some appropriate conditions.

One possibility for our SSVEP results not showing attention shifts is that the tasks conducted around the parafoveal region require or disabled shifts in attentional focus (prioritization), while the luminance-change detection task conducted in the letter elements may be better performed with a reshaping of attentional focus (probably because it was more efficient than the other). It is also possible that our primary task (RSVP) did not give the participant a chance to shift attention, while previous studies accounted for this issue by presenting the stimuli until the participant responded. Although the present study succeeded in recording the object-shape effect in visual attention with another physiological measure (SSVEP amplitudes), it may not be suitable to argue the possible difference in mechanisms from our experiment alone. Future EEG studies designed to dissociate these points may be effective in clarifying the controversy over the mechanisms of attentional spreading or prioritization.

**Number of subjects and rejection criteria**

A possible argument against the present study is the relatively small number of participants ($N=5$). This is a consequence of the qualification by thresholding with eye movements (EOG amplitude) and SNR in the results of SSVEP recordings; only five among nine participants could pass the qualification. A possible reason for frequent eye movements and lowered SNR was the large number of trials for the SSVEP recording, which took two hours on average excluding approximately an hour of inter-trial rests, while the participants underwent attention-demanding tasks in every trial. Designing a more compact and efficient experiment may solve these eye-movement issues and SNR problems and increase the number of participants. Regardless, the present study has clearly demonstrated that object-based attention can be observed by SSVEP measurements when the criteria for minimal eye movements and high SNRs are satisfied.

## Conclusions

We have observed SSVEP amplitude differences correlated with the object-based attention effect, confirmed by the behavioral response-time results. The results of SSVEP-amplitude analysis suggest that the object-based attention is based on a steady state mechanism, i.e., spatial spreading, rather than a dynamic mechanism that prioritizes and shifts attention toward locations within an object.

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