EEG phase synchronization analysis applied to the attentional blink phenomenon

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The attentional blink (AB) phenomenon was investigated using dynamic cross-lag phase synchronization of scalp EEG. We hypothesized that long-distance phase synchronization of gamma-band scalp EEG is necessary for conscious report of two targets in RSVP. To test the hypothesis, a dynamic cross-lag phase synchronization index (dcPSI) was computed for 45 pairs of electrodes. The dcPSI is a robust index to monitor spatio-temporal patterns in EEG phase synchronization. Our results showed that the synchronization between distant electrodes increased after the onset of the first target (T1). When the second target (T2) was presented after the AB period, the synchrony also increased immediately after T2 onset. On the other hand, if T2 was presented during the AB period, the synchronization did not increase immediately after T2.

Keywords: attentional blink, scalp EEG, gamma band, phase synchronization

Introduction

The attentional blink is a well-known dynamic perceptual phenomenon - when two target stimuli are to be detected in a rapid serial visual presentation (RSVP) stream, the detection of the second target is determined by the temporal relationship between the two targets. If the second target (T2) is presented just after the first one (T1), i.e., the lag between the targets is one, T2 is likely to be detected despite the short interval between the targets (Lag 1 sparing). However, when the lag becomes 2 to 5, the second target is likely to be missed. The detection rate recovers when the lag is six or greater. Failure of detection during lags 2 to 5 is called attentional blink (AB). The AB period and Lag 1 Sparing have been reported in various visual, auditory, and cross-modal studies. Therefore, the phenomenon may reflect a fundamental aspect of target detection. (Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnel, 1992. For a review, see Shapiro, 2001).

To observe the attentional blink phenomenon, a T1 must be processed, and T2 task needs to be capacity-limited or masked (Kawahara, Di llolo, & Enns, 2001). For Lag 1 Sparing, all stimuli should be presented in the same spatial location (Visser, Bischof, & Di Lollo, 1999). These conditions suggest that T2 processing is impaired by lack of attentional resource in combination with the effect of masking.

In comparison to spatial attention, temporal characteristics of attention, in general, have not been studied extensively. The AB phenomenon is a fortunate exception; its well-documented temporal characteristics have made the AB an ideal platform to investigate *neural correlates of attentional dynamics*. To investigate the dynamics of attention in the AB paradigm, a measure of brain dynamics should have enough temporal resolution to be used in RSVP. It is also desirable to be able to monitor the spatial pattern of the brain activity. To meet these requirements, we chose the dynamic cross-lag phase synchronization index (dcPSI) as our measure of temporal attention. The dcPSI of gamma-band scalp EEG (30-70 Hz) has been used in spatial attention tasks (Rodriguez, George, Lachaux, Martinerie, Renault, & Varela, 1999). Rodriguez et al. presented a high-contrast image that contained a target object. Due to the contrast, the target was hard to find. While participants were trying to identify the target, the spatio-temporal pattern of the dcPSI was monitored. Rodriguez et al. reported that gamma-band synchronization between distant electrodes increased when the target was successfully perceived (See also Tallon-Baudry, Bertrand, Delpuech, & Permier, 1997, on closely related issues). In the current study, the dcPSI method was applied to gamma-band EEG during the AB task. We hypothesized that long-distance gamma synchronization would increase/sustain when attention is required. Thus, we expect that the dcPSI will increase when attention is needed to report two targets in RSVP.

Method

Participants. Five college students (3 men and 2 women, 18 – 22 years old) participated. All participants were right-handed, and had normal or corrected-to-normal vision.

Stimuli and Design. Stimuli were capital alphabets and digits. Twenty stimuli were shown in RSVP in each trial. SOA was 100 ms and ISI was 75 ms, i.e., each stimulus was presented for 25 ms and was followed by a 75 ms blank screen. One of the stimuli was shown in blue as the target (T1) for the first task, in which participants judged if the stimulus was a letter or a digit. Thus, T1 was an alphabet or a digit in 50/50% of the trials. T1 was presented either at the seventh or tenth position. The rest of the stimuli were alphabets presented in white color on a gray background. In a half of the trials, a letter ‘O’ was present. This letter was the target (T2) of the second task, in which presence/absence of T2 was reported. T2 was presented as either the 1st, 3rd, or 7th stimulus after T1 (Lag 1, Lag 3 and Lag 7 trials). At least three distracters (non-target white alphabets) were presented after T2.

After RSVP, participants were asked to identify the category of T1 (letter or digit) and also to report presence/absence of T2 (dual task condition). In the control condition, no task was requested for T1, yet a blue stimulus was present (single task condition). Participants were instructed to make the best guess when they were not sure about their perception. Dual and single task conditions were blocked, and the order of the blocks was counterbalanced between participants. In both task conditions, participants completed 96 trials (32 Lag 1 trials, 32 Lag 3 trials, and 32 Lag 7 trials) and the same number of no-T2 trials. The order of trials was randomized within a block.

Apparatus and EEG recording. The experiment was controlled by a Neuroscan STIM 4.2 package on a PC. Stimuli were presented by a CRT based projection system (Marquee 9500LC by Electrohome). EEG was recorded using a commercial EEG recording system (Neuroscan) using a cap with 64 Ag/AgCl electrodes. Linked ears were used as reference. Sampling rate was 1000 Hz. Eye movements were monitored by vertical and horizontal EOGs. In order to minimize phase distortion, no notch filter was used. Instead, lines between the electrodes and the preamplifier were electrically shielded. This method effectively eliminated AC noise.

Results

Behavioral data. In Figure 1, percentages of correct T2 report in dual task condition and single task condition were summarized. The pattern of results was quite similar to that reported in previous AB studies including ones using EEG measurement (e.g., Experiment 1 in Vogel, Luck, & Shapiro, 1996). T2 detection rate was slightly worse in the dual task condition than in the single task condition, $F(1, 4) = 5.10$, $p < .1$ for the main effect of task in a 2 (tasks) by 3 (lags) ANOVA. The difference among lags was highly significant, $F(2, 8) = 10.74$, $p < .01$, and so was the interaction between task and lags, $F(2, 8) = 8.90$, $p < .01$. The difference between the dual and single task conditions was significant in the Lag 3 condition, $t(4) = 2.86$, $p < .05$, but not in the Lag 1 condition, $t(4) = 1.84$, $p > .1$, and in Lag 7 condition $t < 1$. Thus, the attentional blink phenomenon was replicated in the behavioral data.

In the dual task condition, the average correct T2 report in the Lag 1 condition was better than in Lag 3 condition, $t(4) = 3.30$, $p < .05$. The average correct T2 report rate in the Lag 1 condition was about 15 % better than that in the Lag 3 condition. This result meets the criterion for Lag 1 sparing, which is “the level of performance at Lag 1 exceeded the lowest level of performance by more than 5% in absolute terms” proposed by Visser, et al. (p. 460, 1999). Thus, Lag 1 sparing was replicated in the behavioral data as well. The behavioral data allow us to conclude that the attentional blink phenomena, including Lag 1 sparing, were replicated in the present experiment.

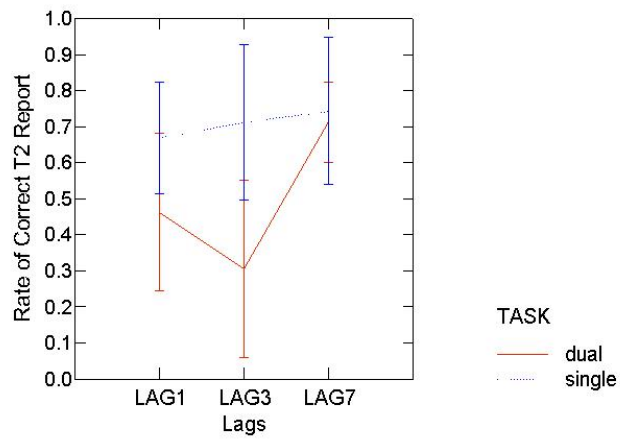

Figure 1. Average percent correct T2 report in dual task and single task conditions.

Dynamic Cross-lag Phase Synchronization Index (dcPSI). The dcPSI was computed from EEG in single trials. In each trial, Time 0 was set at T1 onset. EEG data from –700 ms to +1000 ms were submitted to analyses. In this time segment, a stimulus was presented every 100 ms, but eye movements and blinks seldom occurred[1]. Discrete Fourier transformation (DFT) was applied to the EEG data. Next, Hilbert transform was applied to 38-43 Hz components to estimate their instantaneous phase (Pikovsky, Rosenblum, & Kurths, 2001). The bandwidth was set to ensure accuracy of phase estimation. The central frequency (40 Hz) was arbitrarily chosen within the gamma band.

The dcPSI is an index of phase synchronization between a pair of electrodes. In this experiment, the dcPSIs were computed from 45 pairs. Out of 62 EEG channels, 10 electrodes (Fp1, Fp2, F3, F4, C3, C4, P3, P4 O1 and O2) were selected. The 10 electrodes are chosen to reduce overlapping of signals. Exhaustive pairing of the 10 electrodes made the 45 pairs. The synchronization index is 1 when the instantaneous phases are in-phase, and 0 if they are in counter phase. The dcPSI takes into account of constant time lags. When phases of two distant brain areas are synchronized, the phases may show a constant lag due to the traveling time of the signal between the electrodes. To evaluate the constant phase lag, a window was set to ±100 ms from a given data point. Phase synchrony with a constant time lag was considered as synchronized, thus termed ‘cross-lag’ (Gong, Nokolaev & van Leeuwen, 2003).

The dcPSI was examined, first, individually. Next, its spatio-temporal patterns were compared across participants. For each participant, average dcPSIs in the dual task and single task conditions were computed. Differences between the averages were tested at each time point by a bootstrap hypothesis test that computed a ‘t’ distribution for H_0: $\mu_{\text{dual task}} = \mu_{\text{single task}}$. To generate the distribution, the bootstrap procedure was repeated for 1000 times. The test provided *when* and *what electrode pair* showed a significant difference between the task conditions. H_0 rejection level was set less than 5%. A positive ‘t’ value indicates that the average dcPSI is higher in the dual task condition than in the single task condition, while a negative ‘t’ indicates the opposite.

There were large individual differences in the spatio-temporal a of synchrony. Thus, we set a criterion to identify the pattern that is common across participants. In each electrode pair, segments where 3 out of 5 participants showed a significant difference in synchrony with the same direction within 100 ms were marked.

The results are summarized in Figure 2. The spatial pattern of synchrony was represented in a ‘head view’ and the views were aligned along time as a row. The top to bottom rows corresponds to the Lag 1, Lag 3 and Lag 7 conditions, respectively. Vertical lines indicate T1 and T2 onsets. In each head view, a red line connects a pair of electrodes where three or more participants showed a higher dcPSI in dual task condition than in single task condition. Blue lines indicate the opposite direction of cross-participant effect.

In all lag conditions, dcPSI was higher in the dual task condition than in the single task condition 100 to 300 ms before T1 onset. The high dcPSI may indicate that the participants anticipated T1 in the dual task condition. All lags taken together, the spatial extent of the synchronization seem to increase as T1 onset approaches. After T1 onset, patterns were different among the lag conditions. In the Lag 1 condition, there was no cross-subject pattern observed among the participants until 700 ms. The direction of the dcPSI difference was negative, i.e., the dcPSI in the single task condition was higher than that in the dual task condition. We do not have a good explanation for this. In the Lag 3 condition, the dcPSI after T1 onset was higher in the dual task condition than in the single task condition. Spatial distribution of the effect somewhat increased. But, the pattern broke around 270 ms where the dcPSI in the dual task condition became lower than those in the single task condition. Given that the T2 was presented at 300 ms, the change of pattern may relate to the failure of T2 report. Around 500 ms, the synchrony in the dual task condition became higher again, but the function of the synchrony is not clear. In the Lag 7 condition, the pattern is in accordance with our expectation – after T1 onset, the dcPSI was higher in the dual task condition than in the single task condition. The spatial extent of the synchrony increased, then ends around 350 ms. Another positive synchrony appeared around 800 ms, which was 100 ms after T2 onset.

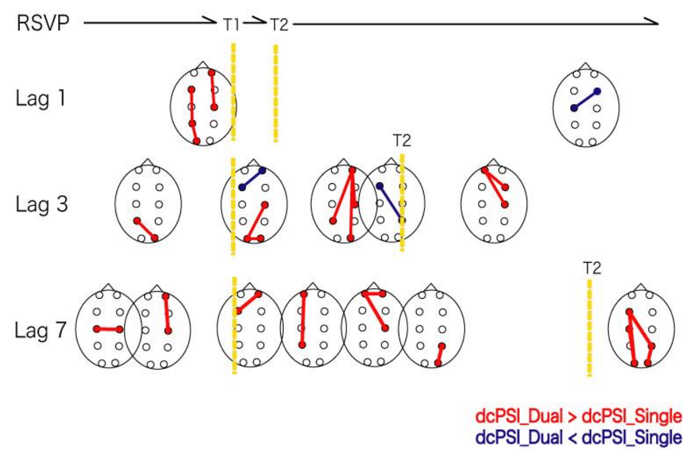

Figure 2. Spatio-temporal pattern of dcPSI in Lag 1, Lag 3 and Lag 7 conditions. Each red line indicates a pair of electrode where dcPSI was higher in the dual task condition than in the single task condition for three or more subjects. Blue lines illustrate pairs showed the opposite direction of difference.

Discussion

We hypothesized that the spatio-temporal synchronization of the gamma-band EEG would increase/sustain when attention is required. This hypothesis was supported given that the dcPSI was higher in the dual task condition than in the single task condition. The spatial-temporal pattern of the synchrony varied depending on T1-T2 lags. In the Lag 7 condition, the synchrony in the dual task condition was high up to 350 ms, and reappeared after T2 onset. Given that both targets were likely to be detected in this condition, the result suggests that the synchronization was needed for 350 ms or so for T1 processing. Then another large-scale synchronization was needed to process T2 in addition to maintain T1 information for a report. In the Lag 3 condition, however, the synchrony ended around T2 onset. In other words, the synchrony was not available when T2 information arrived. This lack of synchronization affected only to T2 report, thus the re-appearance of the synchronization around 500 ms might indicate resumed T1 process over the interruption caused by T2 presentation. The synchrony pattern in Lag 1 condition was not clear. At this stage of data analyses, we have no good explanation for this result.

Conclusion

The current study indicated *a close relationship between temporal attention and gamma-band EEG synchrony;* when attention was needed, the synchrony increased. The dcPSI method is relatively new technique and some aspects of the index are still not known. Nevertheless, the potential of the method was apparent; the method allows us to examine the dynamics of attention closely.

Footnotes

[1] The effect of EOG artifact is negligible to the current study. Eye blinks seldom occur during the RSVP period. Also, the bandwidth of the artifact (< 8 Hz) is much slower than the gamma band activity.

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