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Spatial Attention Can Enhance or Impair Visual Temporal Resolution*

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Transient attention impairs observers'temporal resolution in a cued location. This detrimental effect of attention was ascribed to inhibitory connections from parvocellular to magnocellular neurons [1]. Alternatively, the difficulty might arise because attention facilitates the temporal summation of two successive stimuli. The current study examined this hypothesis by manipulating the luminance polarity of the stimuli against a background. Attention should not modulate temporal summation of two anti-polar stimuli because these are processed in separate channels. Indeed, observers judged the temporal order of two successive stimuli better in the cued location than in the uncued location when the stimuli were opposite in polarity, but temporal resolution was worse in the cued location when the stimuli had the same polarity. Thus, attentional effects on temporal resolution may be attributed to temporal summation rather than parvocellular inhibition of magnocellular activity.

Key words : spatial attention, temporal resolution, visual attention

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The human brain is often faced with a huge array of sensory inputs, which exceeds the capacity of the visual system. It is assumed that we cannot process all the incoming stimuli, and, therefore attention is necessary to focus the mind on a subset of stimuli. A number of studies have reported that attending to a specific spatial location improves performance at the attended location attention shortens target detection time [2] and improves sensitivity for the stimuli at the attended location [3, 4].

A recent report by Yeshurun and Levy [1], however, suggested that attention degrades, rather than enhances, temporal resolution of visual processing. This counterintuitive proposal came from their observation that observers showed better performance on the stimuli at the unattended location than for those at the attended location. In their experiments, participants reported whether they saw one disk or two identical disks with a brief temporal gap. When two disks appeared, they were presented in rapid succession at the same location. In half of the trials, the peripheral cue appeared before the onset of the disk, drawing attention to one specific target location. The rate that participants correctly reported the number of the presented disks was lower in the cued trials than in the neutral trials.

Yeshurun and Levy accounted for the detrimental effect of attention in terms of parvocellular-magnocellular interaction. That is, attention facilitates the activity of parvocellular neurons at the attended location, in an attempt to facilitate spatial processing. However, because parvocellular neurons inhibit magnocellular neurons [5, 6] and stay activated for longer response duration and decay more slowly than magnocellular neurons [7, 8], parvocellular facilitation induced by attention could result in degraded temporal resolution. Parvocellular-magnocellular inhibition hypothesis explains both the enhancement in spatial resolution [9] and the impairment in temporal resolution at the attended location [1, 10].

However, there are conflicting evidences regarding the effects of attention on temporal resolution. If attention degrades temporal processing by means of inhibiting the magnocellular channel, it should impair performance on the attended moving. As opposed to this explanation, previous studies have reported that motion direction discrimination thresholds for attended motion stimuli were lower than those for unattended stimuli [11, 12]. That is, attention facilitates the processing of motion information, which is a visual property processed by magnocellular channels. Besides, research using the temporal order judgment (TOJ) task, another task requiring temporal resolution, has added evidence attentional advantage on temporal processing. One aspect of such studies concerns 'visual prior entry', which is the perception of the attended stimuli prior to the unattended stimuli[13-16]. Visual prior entry showed that attention can accelerate temporal processing for the visual stimulus so that the cued stimulus is perceived prior to the uncued one.

The studies mentioned above and that of Yeshurun and Levy showed seemingly contradictory results, and entailed opposite interpretations of the attentional effects on temporal processing. We suggest that the temporal summation induced by attention could explain the discrepancy between these studies. Yeshurun and Levy used two identical disks at the same location. This manipulation brought about the possibility of temporal summation induced by attention. When the two stimuli are presented at the same location, the overlapping of the signals from the two disks might increase attention can induce temporal summation of signals, which degrades the temporal gap detection task performance for the attended stimuli compared to those unattended. A close inspection of Yeshurun and Levy's data supports this account. The observers made two types of errors: reporting two flickering disks as a single continuous one, and reporting one continuous disk as two disks. In their data, the former of errors was more dominant than the latter. This tendency reveals that observer's performance impairment mainly occurred because the signals of two disks are perceived as one, or summated, not because one continuous disk is perceived as two disks.

In this study, we investigated whether the detrimental effect of attention on temporal resolution can be generalized to other conditions. We used two different disks presented at the same location to explore how attention affects temporal processing when two signals suffer from temporal summation (Experiment 2) compared to when the stimuli are unaffected by temporal summation (Experiment 1), and what mechanism underlies these attentional effects. Although stimuli appearing at the different locations also could avoid temporal summation of the two events, processing these stimuli might be affected by spatial resolution as well as temporal resolution. Therefore, to rule out attentional effects concerning spatial resolution, we used stimuli successively presented at the same location. In order to control the occurrence of temporal summation effectively, we manipulated whether the two disks may be processed through separated channels or through the same channel. When the two signals from the disks pass through separated channels, the visual system can avoid the temporal summation, regardless of attention. Therefore, whether the location is attended to or not, the temporal processing will not be impaired. However, when the two signals pass through the same channel, it is more likely for temporal summation of the two signals to occur, thus resulting in the observers' lower performance at the attended location than at the unattended location.

Experiment 1. TOJ between different luminance polarity disks

In Experiment 1, we explored whether attention degrades the subject's performances in a temporal order judgment task when the two successive disks are processed through different channels. In order to constrain the two stimulus signals to be processed through different channels, we used two disks with different luminance polarities. Several physiological and behavioral evidences support the existence of separate pathways in charge of the sensation of brightness and darkness [17-26]. It is known that the separation starts from the retina and exists functionally even at the early visual cortex. Thus, stimuli of different luminance polarities pass through different channels, whereas stimuli of the same luminance polarity pass through the same channel. To manipulate the luminance polarity, we employed a dark and a bright disk in the gray background. Although attention causes temporal summation of the two disks to occur more easily, attention would not degrade the performance when the successive signals are processed via two different channels, as designed in this Experiment.

Methods

Thirteen undergraduate students at Yonsei University participated in this Experiment for course credit. All had normal or corrected-to-normal vision. None of the participants were aware of the purpose of the Experiment.

The experiment was conducted on an IBM-compatible computer using MATLAB equipped with psychophysics toolbox extensions [27]. The stimuli were presented on a monitor with the 85 Hz refresh rate. Participants' viewing distance was fixed to 50 cm, by using a chinrest.

The procedure of a typical trial is illustrated in Figure 1. The participants were asked to report which of the two disks (dark or bright) came first. Each trial began with a fixation dot against a mid-gray background (50 cd/m^2), followed by a cue to direct attention. The cue remained present until the target offset, appearing 0.5° above the target location. The cue was either 'peripheral' or 'neutral' both cues were green bars (75 cd/m^2), but they differed in horizontal length. The peripheral cue was short (1° × 0.3°), appearing at one of the six possible locations (±1.5°, ±4.5°, or ±7.5°) to draw attention to one specific target location, while the neutral cue was long (16.5° × 0.3°), subtending all possible locations of a peripheral cue so that it would not draw attention to one specific target. The first disk was presented 94 ms after the cue onset. The disk of neutral cueing condition was presented at one of the six locations along the horizontal meridian, but the disk of the peripheral cueing condition always appeared at the cued location. Then the second disk was presented at the same location as the first disk. The two disks were temporally separated by varying inter-stimulus intervals (ISI) (11, 23, or 47 ms), and were present for 71 ms.

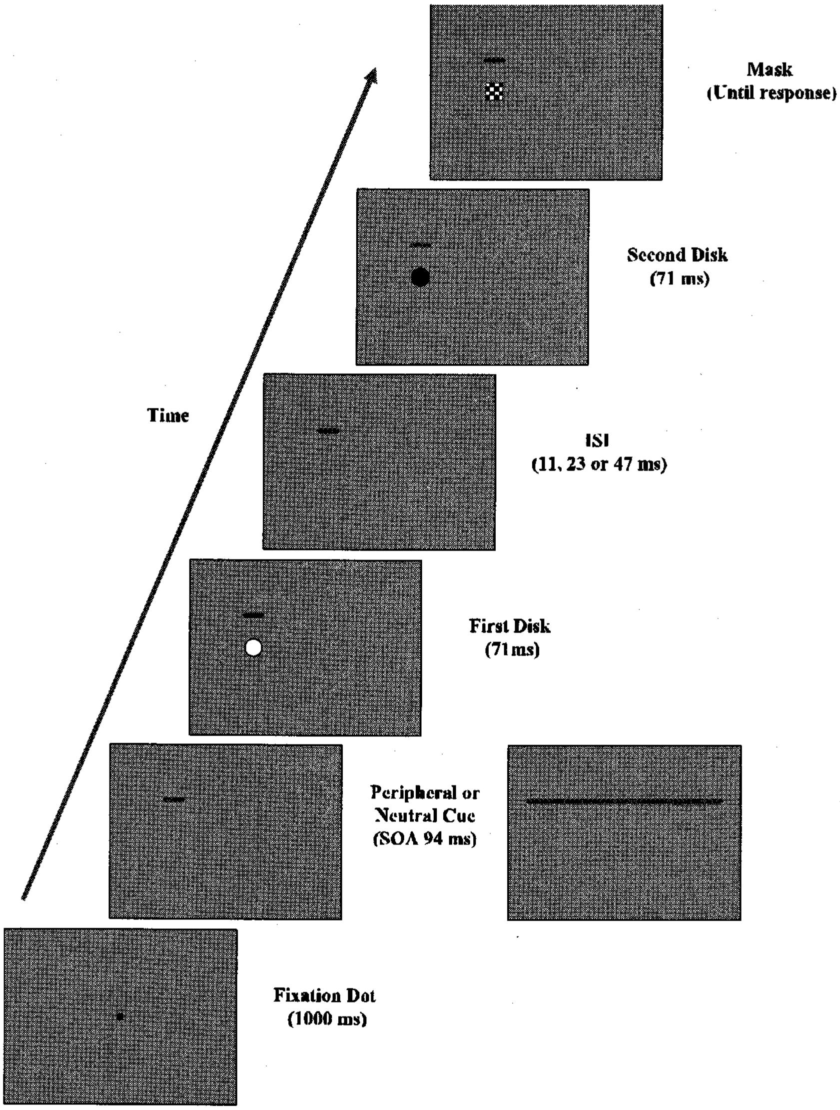

Figure 1. Schematic trial and the design of Experiment 1. On each trial, subjects judged temporal order of two disks. At the initiation of each trial, a fixation point was presented at the center of screen, followed by either peripheral cue or neutral cue. In the random order, a dark disk and a bright disk successively appeared at one of the six possible locations along the horizontal meridian with a varying ISI. After two disks disappeared, mask was presented at the target location. ISI = interstimulus interval. SOA = stimulus onset asynchrony.

The disks had a diameter of 1.5°. The surface luminance was 30cd/$m^2$for the dark disk, and 70 cd/m^2 for the bright one. Immediately following the offset of the second disk, a checkerboard mask appeared for 100 ms and remained on the screen until response. The mask was a square covering disks (1.5° × 1.5°) and consisted of 4 by 4 component squares, which had the same luminance as those of the disks (either 30 cd/m^2 or 70 cd/m^2). Half of the trials presented the dark disk first and the other half presented the bright disk first. Each observer viewed 576 trials in a randomized order.

Results and Discussion

A within-subject three-way ANOVA (Cuing × Eccentricity × ISI) on accuracy (d') indicated that the main effects for all three factors were statistically significant performance accuracy was significantly higher (1) for the peripheral cue condition compared to the neutral cue condition ($F(1, 12) = 8.362$, $p \leq .05$), (2) for the disks of the smaller eccentricity compared to the larger eccentricity ($F(2, 24) = 11.674$, $p \leq .01$), and (3) for the longer ISI than for the shorter ISI ($F(2, 24) = 8.439$, $p \leq .01$). In addition, the interaction between Cuing condition and ISI was also significant ($F(2, 24) = 4.659$, $p \leq .05$).

These results showed that covert attention did not impair but improved temporal order judgment (See Figure 2). Whereas performance for the task that requires temporal resolution is impaired when the same disks are presented at the same location [1], performance is enhanced when two different disks that are registered at different channels are presented at the same location. Attention induced overlapping of signals impairs the performance when two signals are at the same channel and location.

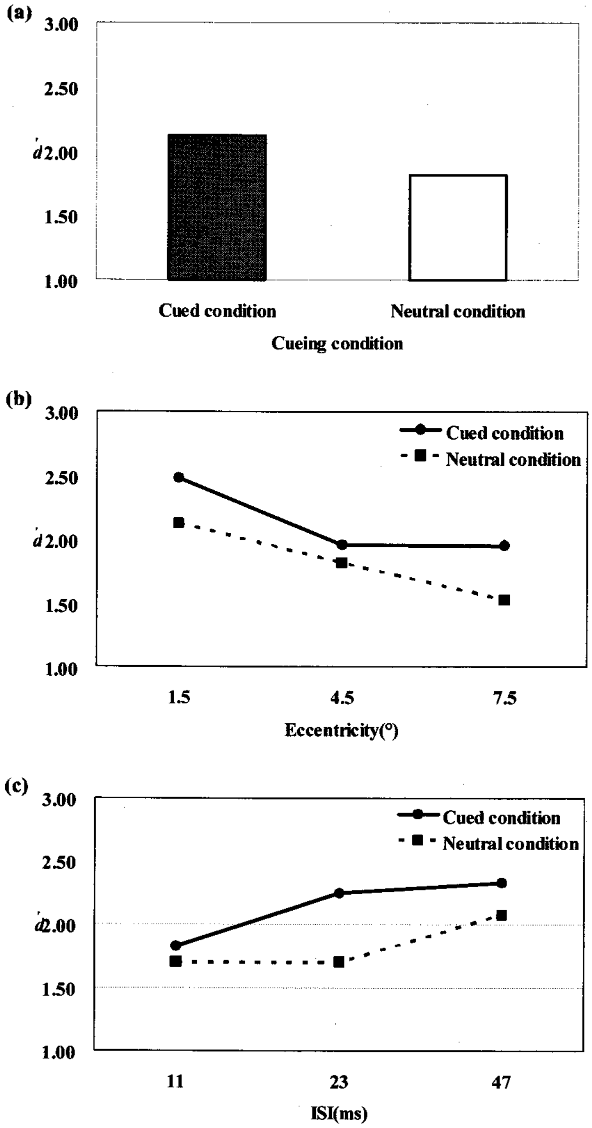

Figure 2. Results of Experiment 1Observers' accuracy for TOJ task was better at the cued condition than at the uncued location. Observers' accuracy(d') was plotted as a function of (a) cueing condition (b) cueing condition and ISI, (c) cueing condition and target eccentricity. In panel (b) and (c), solid circles indicate performance for cued location, and hollow squares for uncued location. Error bars represent standard error of the mean (SEM).

Experiment 2. TOJ between the same luminance polarity disks

In Experiment 1, we found that, covert attention enhanced, rather than degraded, observers' temporal processing for two successive signals with different polarities. However, if attention causes temporal summation of stimuli at the same location, attention to a certain location would impair the performance when the successive signals are processed through same channel. In Experiment 2, in order for two disks to pass through the same channel, we employed a dark disk and a bright disk appeared in the black background this background color was darker than that of the dark disk so that the two disks had the same luminance polarity.

Methods

Fifteen undergraduate students of Yonsei University participated in Experiment 2. They had not participated in the previous experiment, and were naive to the purpose and expected results of this experiment. As in Experiment 1, the participants had to judge the temporal order of two disks, which were successively presented at the same location. All the apparatus, stimulus, and procedure were the same as those of Experiment 1 except that the background was darker than the dark disk (10 cd/m^2, the disk luminance was not changed).

Results and discussion

A within-subject three-way ANOVA (Cuing × Eccentricity × ISI) was performed on accuracy (d'). The difference of accuracy between two cueing conditions was statistically significant ($F(1, 14) = 7.396$, $p < .05$). Attentional benefit for the attended location, however, was reversed. That is, contrary to Experiment 1,

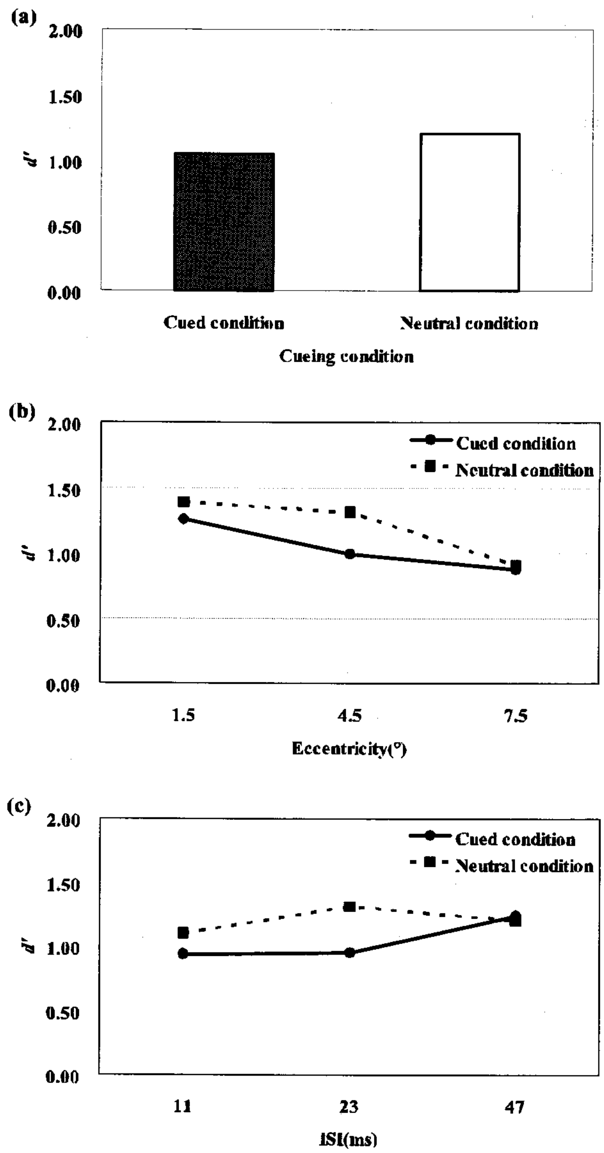

Figure 3. Results of Experiment 2 Observers'accuracy for TOJ task was worse at the cued condition than at the uncued location. Observers'accuracy as a function of (a) cueing condition (b) cueing condition and ISI, (c) cueing condition and target eccentricity. In panel (b) and (c), solid circles indicate performance for cued location, and hollow squares for uncued location. Error bars represent SEM.

performance accuracy was significantly higher for the neutral cue condition compared to the peripheral cue condition. The main effects for both eccentricity ($F(2, 28) = 12.734$, $p < .001$), and ISI ($F(2, 28) = 3.403$, $p < .05$) were also significant. The interaction between the cueing condition and ISI was significant ($F(2,28) = 7.625$, $p < .01$). The data for each condition is plotted in Figure 3.

These results demonstrate that if two signals of the different disks at the same location are processed through the same channel, attention reduces the performance accuracy in a temporal order judgment task. This finding is in accordance with Yeshurun and Levy's finding [1] that attention decreases participants' sensitivity in a temporal gap detection task, in which the same disks were employed as the successive stimuli. Contrary to Experiment 1, the results in Experiment 2 show that if two signals are processed through the same channel, attention decreases the performance accuracy in temporal order judgment task.

Discussion

The only difference in the stimuli between Experiment 1 and Experiment 2 was that the luminance polarities of the two disks were either the same or different. When two disks of different luminance polarities were processed in different channels, performance for the TOJ task was not impaired, but improved by the attention (Experiment 1). Contrarily, when the two disks had the same luminance polarity and were analyzed in one same channel, attention degraded the participants' performance (Experiment 2). In short, the benefit on temporal processing by paying attention to a certain location depends on the occurrence of temporal summation; whether stimuli are processed through the same channel or through different ones.

The Parvocellular - Magnocellular Inhibition Hypothesis

Parvocellular-magnocellular inhibition hypothesis well explains the impaired performance on attended location in the temporal gap detection. The results of Experiment 1, however, are not compatible with the parvocellular-magnocellular inhibition hypothesis. This hypothesis predicts that performance will be worse at the attended location than at the unattended location even when two disks with different luminance polarities are presented at the same location. Experiment 1, however, disproves the parvocellular-magnocellular inhibition hypothesis.

To directly test the parvocellular-magnocellular inhibition hypothesis, Yeshurun [10] investigated the attentional impairment with isoluminant stimuli in a temporal gap detection task. Because the parvocellular channel is known to be more sensitive to color than the magnocellular channel, it would be the dominant system that processes isoluminant stimuli. Therefore, they reasoned that if the attentional impairment is due to the parvocellular-magnocellular inhibition process, it would be minor for the isoluminant stimuli. As a result, the impairment by attention in temporal resolution was significantly attenuated. These results seem to consistently support their supposition that the parvocellular-magnocellular inhibition is the determining factor of the attentional impairment in temporal processing. It could be that, however, the signals did not overlap because the stimuli had different colors, despite their identical luminance. Therefore, it is not evident from their results whether parvocellular-magnocellular inhibition causes attentional effects on temporal processing.

The Signal Enhancement Hypothesis

What, then, mechanism causes attentional benefits or impairments on temporal processing that we found in the current study? In this article, we propose an alternative mechanism to the parvocellular-magnocellular inhibition hypothesis which was shown to be incompatible with our observation. The signals of the attended

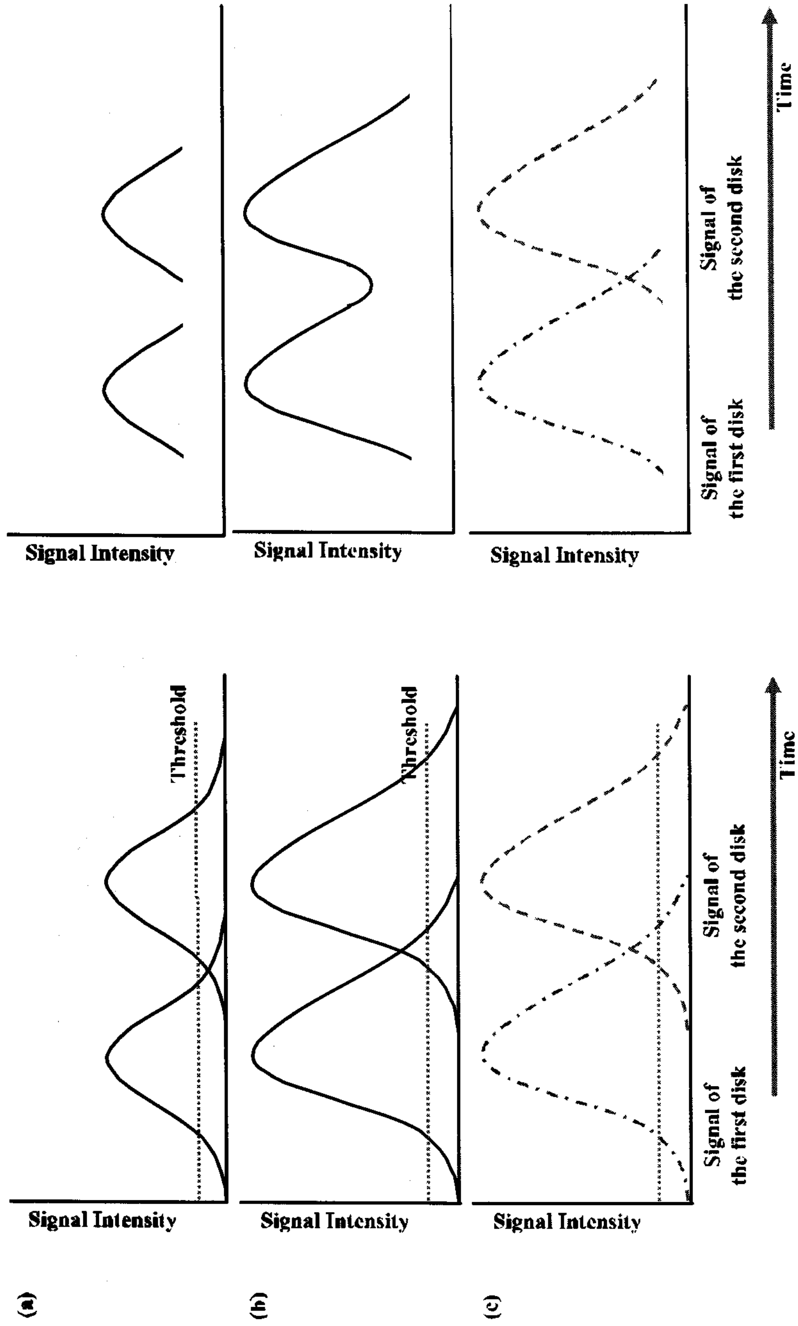

Figure 4. Schematic time-course of the signals of stimuli. Panel A illustrates the activation for the signals at the unattended location. Even though onsets of two disks are sufficiently close together in time, the combined signal of two stimuli over threshold could be perceived as two (B). However, if these disks are attended, and these signals pass through the same channel (C), two signals over threshold could be summated so that they are perceived as one (D). On the other hand, if these disks are attended, but these signals pass through separate channels(E), two signals over threshold should not be summated, so that each intensified signal is perceived as separate one and makes more fine and clear representation for each disk than at the unattended (F).

stimuli may be intensified, and this intensification causes impairment of the accuracy in the gap detection task and in the temporal order judgment task. It has been reported that attention enhances the signals of stimuli, consequently improving the quality of the stimulus representation [3, 4, 28-30]

Figure 4 illustrates the temporal aspect of signal enhancement. A sequence of two disk onsets would produce respective time-courses of the two transient signals, independently of the other disk presented (left column), and observers perceive the sum of individual signals above their threshold (right column). When the two disks that are presented at the same location are sufficiently close together in temporal sense, the sum of the individual signals is continuous (Figure 4A). Nevertheless, because what observers can perceive is above threshold, the signal would seem discontinuous so that it causes observer to perceive the separation of two stimuli (Figure 4B). On the other hand, when attention is available and intensifies the magnitude of signals (Figure 4C), signals above the threshold become temporally continuous and have more overlapped area of signals. Thus, observers are more likely to perceive the two stimuli as one (Figure 4D). However, even if attention intensifies the magnitude of signals, there is no possibility that signals of two stimuli could be summated (Figure 4F), when two stimuli presented at the same location are processed in different channels or when they are presented at different locations (Figure 4E). Therefore, observers can perceive the stimuli as separated ones. Moreover, in this case, the signal of attended stimulus has the enhanced amplitude than that of unattended stimulus, resulting in clear representation of the attended one.

Signal enhancement by virtue of attention can account for the degraded performance in temporal gap detection. When amplified by attention (Figure 4C), signals for successive disks at the same location could overlap more than otherwise (Figure 4A). Consequently, disks at the cued location can be perceived as one fused disk. Signal enhancement hypothesis can also explain attentional advantage in temporal order judgment task shown in Experiment 1. The temporal summation of signals itself does not explain the performance enhancement by attention; it merely predicts that the performance will not be impaired at the cued location. The comparison between Figure 4B and Figure 4F, however, shows how the attentional benefit occurs. Because intensified signals without temporal summation give observers clearer and finer representation, it might be easier for observers to judge the temporal order for the attended disks than unattended. Additionally, our account can explain the enhancement in spatial resolution [9] as well as the impairment and enhancement in temporal resolution. Yeshurun and Carrasco[9]suggested that transient attention enhances spatial resolution, resulting in signal enhancement, Then, the enhanced signal makes a better temporal resolution in some cases and a worse one in other cases, as shown in this study.

Masking Effects

In this study, the mask following the disks was used to prevent observers from accessing to stimuli over the given time. Stimuli in our design have different offsets in time course. Therefore, without mask, observers could have responded depending on the iconic memory for the second coming disk rather than TOJ of two disks.

One might argue, however, that the masks caused the performance difference between attended and unattended stimuli, which was founded in Experiment 1. Enns and Di Lollo [31, 32] found that attention has influence on the masking effect; masking effect was weak when attention was given to the target, whereas strong masking occurred for the unattended target. According to their finding, the mask at the attended location little affects disks, resulting in good performance. On the contrary, at the unattended location, the mask effectively interrupts the task, making performances worse at the unattended location. If masking effects were crucial in the results of Experiment 1, those effects in Experiment 2 should have shown attentional benefit on temporal resolution. Different from the expectation, the detrimental effect of attention was founded in Experiment 2. In short, the masking effect was not the critical factor in this study.

Ecological Importance of Attention in Temporal Resolution

In summary, attention does not always degrades temporal resolution; attention enhances facilitates temporal processing when signal overlapping is not possible. In contrast, it impairs the performances when temporal summation of signal is possible. Why, then, does the human cognitive system adopt this mechanism, which is rather unfavorable? In the real world, we seldom encounter an object flickering at the same location. Usually we need temporal processing of objects that occupy varying locations (e.g. moving objects) or that gradually change at the same location. In both of these common perceptual situations, there is low possibility of signal overlapping. Therefore, it is hard to apply the detrimental effect of attention found in temporal gap detection task to other conditions. Rather, in most cases, one can find signal enhancement caused by attention brings about beneficial effects on temporal resolution.

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(요 약)

공간 주의가 시각적 시간 해상도에 미치는 영향

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특정 위치에 주의를 주게 되면, 그 위치에 있는 사물을 시각적으로 처리할 때에 시간 해상도가 저하되며, 이러한 저하는 큰세포(parvocellular)와 작은 세포(magnocellular)의 상호 억제적 연결에 기인하는 것이라고 주장이 제기되었다[1]. 이와는 다르게, 시각 주의가 같은 위치에 연속적으로 제시되는 자극들간의 시간적 겹침을 유발하기 때문에, 주의에 의한 시간 해상도 저하가 관찰되었을 가능성이 있다. 본 연구에서는, 이 가설을 검증하기 위해, 배경 대비 밝기의 극성이 다른 두개의 자극들을 사용해 자극 제시 순서를 판단하는 과제를 실시했다. 밝기 극성이 다른 자극들은 초기 시각 처리과정에서 서로 다른 경로를 통해 처리되기 때문에, 주의가 주어진다고 하더라도 시간적 중복이 촉진되지 않을 것이다. 실험 결과, 실험 참가자들은 시각 단서가 주어지지 않은 위치에서보다 주어진 위치에 나타난 자극들의 제시순서를 더 정확하게 판단했다. 반면, 같은 밝기 극성을 가진 두 개의 자극에 대한 제시 순서를 판단해야 했을 때에는, 시각 단서가 주어진 위치보다 주어지지 않은 위치에 나타난 자극들에 대해서 더 정확하게 제시순서를 보고했다. 이러한 결과는, 시각적 주의가 자극 신호의 시간적 중복을 유도함을 통해 시각적 시간해상도에 영향을 미친다는 것을 의미한다.

주요어 : 공간주의, 시간해상도, 시각적 주의