

# Measuring attention using flash-lag effect

Satoshi Shioiri

Research Institute of Electrical Communication,  
Tohoku University, Sendai, Japan



Ken Yamamoto<sup>1</sup>

Hiroki Oshida

Department of Information and Image Sciences,  
Chiba University, Chiba, Japan



Kazuya Matsubara

Research Institute of Electrical Communication,  
Tohoku University, Sendai, Japan



Hirohisa Yaguchi

Department of Information and Image Sciences,  
Chiba University, Chiba, Japan



We investigated the effect of attention on the flash-lag effect (FLE) in order to determine whether the FLE can be used to estimate the effect of visual attention. The FLE is the effect that a flash aligned with a moving object is perceived to lag the moving object, and several studies have shown that attention reduces its magnitude. We measured the FLE as a function of the number or speed of moving objects. The results showed that the effect of cueing, which we attributed the effect of attention, on the FLE increased monotonically with the number or the speed of the objects. This suggests that the amount of attention can be estimated by measuring the FLE, assuming that more amount of attention is required for a larger number or faster speed of objects to attend. On the basis of this presumption, we attempted to measure the spatial spread of visual attention by FLE measurements. The estimated spatial spreads were similar to those estimated by other experimental methods.

<sup>1</sup>Ken Yamamoto passed away after his crucial contribution to the present study.

Keywords: attention, motion—2D, temporal vision, spatial vision

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## Introduction

A stimulus that is presented briefly when a moving stimulus arrives at the same location appears to spatially lag the moving stimulus (Eagleman & Sejnowski, 2007; Murakami, 2001b; Nijhawan, 1994, 2008; Whitney & Murakami, 1998). Several interpretations have been proposed to explain this phenomenon, the flash-lag effect (FLE), which include extrapolation of motion trajectory (Nijhawan, 1994), differential latencies (Murakami, 2001a; Whitney & Murakami, 1998), motion bias (Eagleman & Sejnowski, 2007), and attention (Baldo & Klein, 1995). Although the origin of the FLE is still in debate, recent studies support the theory with differential latencies (but see Eagleman & Sejnowski, 2007). Assuming a constant delay of the flashed stimulus relative to the moving stimulus can explain much of the empirical data, including the FLE for flash initiation, flash termination, and changing directions of the flash, although an additional assumption of temporal blurring or uncertainty is often required (Murakami,

2001a). It is important to note that the temporal factor, which influences the FLE, is not only the difference in processing time. Latency differences can be caused by stimulus luminance, presentation eccentricity, attention, and possibly other factors.

The focus of the present study is on the effect of attention on the FLE. Here, we use the term attention to refer to the selection mechanism that is controlled by cueing as in Posner's classical experiment (Posner, 1980). By cueing a location, the mechanism is assumed to facilitate the visual process at the location. The degree of facilitation perhaps varies dependently on conditions or tasks required and we assume that the change of the facilitation effect reflects the change in amount of attention oriented at the location. Several studies have shown that the FLE is reduced when attention is controlled or assumed to be on the location or to the timing of the flash (Baldo, Kihara, Namba, & Klein, 2002; Chappell, Hine, Acworth, & Hardwick, 2006; Sarich, Chappell, & Burgess, 2007), or simply when the location or timing of the flash presentation is predictable (Murakami, 2001a; Namba &

Baldo, 2004). These studies suggest that attention reduces the magnitude of the FLE (but see Khurana, Watanabe, & Nijhawan, 2000). The FLE may vary in magnitude as the attentional state changes, and the amount of attention is potentially estimated from the FLE. Although previous studies have suggested that attention modulates the magnitude of the FLE, it is not clear how amount of attention influences the FLE magnitude.

The first aim of this study is to investigate the relationship between the amount of attention and the magnitude of the FLE. The FLE can then be used to estimate the amount of attention if there is a monotonic relationship between them. For this purpose, we measured the FLE under several stimulus conditions, where the amount of the observers' attention oriented to the cued location was assumed to vary. In [Experiment 1](#), the number of moving stimuli changed, and their speed changed in [Experiment 2](#). These experiments showed that the magnitude of the FLE varied, depending on the number and the speed of the moving objects. The second aim of the study is to attempt to measure a spatial spread of visual attention using the FLE. [Experiment 3](#) showed that the FLE magnitude changed with the increase in the distance from the observers' attentional focus. We compared our results with data in the literature, which were obtained by more conventional methods under similar conditions.

## Experiment 1: Effect of the number of moving objects

The number of items is a well-known factor that affects attentional states. Usually, an observer pays attention to one place or one object, although observers are sometimes asked to pay attention to multiple targets in an experiment of divided attention. It is more difficult to pay attention to more items simultaneously, as has been shown clearly in multiple object tracking (MOT) studies. The observer can track several objects in motion, while the ability depends on the number of items (Alvarez & Cavanagh, 2005; Pylyshyn, 1998). [Experiment 1](#) investigated how the number of moving objects influences the flash-lag effect (FLE).

## Methods

### Stimulus

[Figure 1A](#) shows the stimulus configuration and the sequence of a trial. The moving stimulus was a white disk with a diameter of  $1.1^\circ$  ( $51 \text{ cd/m}^2$ ) on a gray background ( $28 \text{ cd/m}^2$ ). The stimuli moved along a circular path with a radius of  $7^\circ$  while the observer fixated on the center of the circle. The flash stimuli were a pair of black disks with a diameter of  $0.7^\circ$  ( $<0.01 \text{ cd/m}^2$ ). The flash disks were

presented briefly (one frame of 6 ms) near the target disk ( $1.6^\circ$  between the centers), so that the observer was able to judge the alignment between the target and the flash stimuli. The number of moving disks was one, two, or six (disk separation was  $180^\circ$  or  $60^\circ$  for the two- or six-disk condition, respectively; see [Figure 1B](#)). All disks moved at the same speed in the same direction. The speed of the moving disks was 0.33 rps ( $15.0^\circ/\text{s}$  in terms of the linear motion in visual angle). A demonstration movie can be seen in [Figure 1C](#).

### Procedure

We used cue and no-cue conditions to manipulate the attentional state of the observer. In the cue condition, the observer was informed which disk was the target disk in the pre-trial display. The no-cue condition differed from the cue condition only in the pre-trial display that was used to indicate the target disk. In the pre-trial display, the size of the target disk (diameter of  $1.1^\circ$ , as in the trial) was larger than that of the other disks (diameter of  $0.28^\circ$ ) in the cue condition, while all disks were identical ( $1.1^\circ$ ) in the no-cue condition. The observer was instructed to track the target in the cue condition so that they could identify the flash quickly. In contrast, in the no-cue condition, the observer was instructed to distribute his attention to cover the whole stimulus field.

After showing the pre-trial display for 0.5 s, the disks started moving. The flash disks were presented at unexpected timing between 1 and 2 s after the onset of motion. The disks stopped after moving for 3.5 s in total. The target disk was indicated by the size difference after the disks stopped, and the observer checked whether the disk was indeed the disk he tracked (in the cue condition) or the disk they compared its location with the flash (in the no-cue condition). When the disk indicated as the target was not the one that the observer had tracked or compared, the observer pressed a key to cancel the trial. The observer responded by pressing one of two keys, indicating whether the flashes appeared to be ahead or behind the target disk.

We did not recode the number of the cancelled trial. The number of cancelled trials might be important information when accuracy and/or speed of processing are measured because a speed–accuracy trade-off complicates the interpretation of reaction time even when reaction time is analyzed only for trials with correct responses. However, this is not a problem at all in our measurements. The aim of this experiment was to estimate the localization bias, measuring the FLE in the condition where a given tracking task was performed successfully.

The location of the flash relative to the target was varied from trial to trial based on the observer's response in the previous trial. The flash location was shifted in the direction to cancel the difference. If, for example, the observer's response was "behind", the flash location was

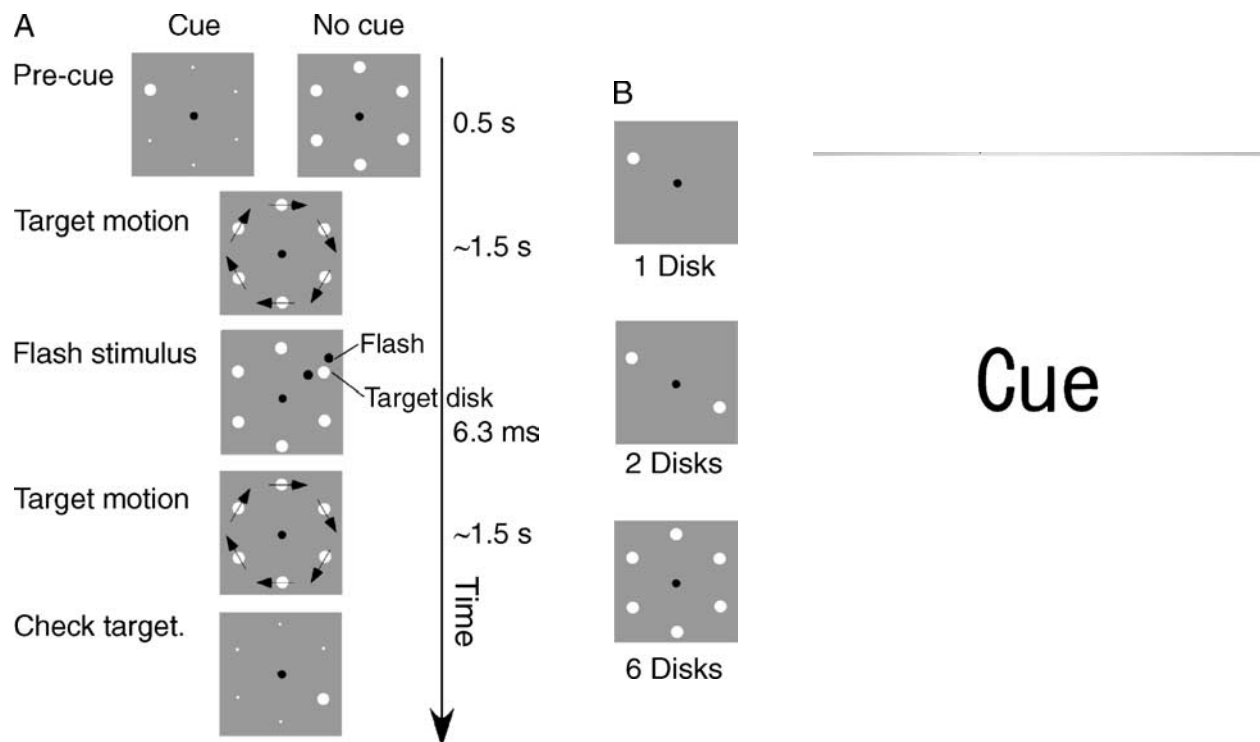


Figure 1. (A) The sequence of a trial. (B) The three conditions with differing disk number. (C) A [demonstration movie](#) (colors and scales are not the same as in actual stimuli).

shifted one step in the motion direction in the next trial. When the observer perceived that the flashes were aligned with the target, he pressed the third key to indicate the alignment, which terminated the adjustment. The direction of disk rotation was randomly chosen for each adjustment and kept constant across trials for the adjustment. The absolute location of the flash presentation varied from trial to trial randomly. Six adjustments (three repeats for each of the clockwise and counterclockwise rotations) were performed for each combination of the two cue conditions (the cue and no-cue conditions) and the three disk numbers (1, 2, or 6). These conditions were chosen in random order. One author and four naive observers participated in the experiment. All observers had normal or corrected-to-normal visual acuity.

### Apparatus

Stimuli were generated on a color display (Sony, GDM-FW500) controlled by a personal computer equipped with a graphic card (Cambridge Research Systems, VSG 2/4). The frame rate of the display was 160 Hz and the spatial resolution was  $800 \times 600$  pixels ( $27^\circ \times 20^\circ$ ). The viewing distance was 80 cm, and the observer viewed the display binocularly. A chin rest was used to stabilize the head of the observer. The experiments were carried out in a dark room. We assumed that the observers' eye fixations were stable during a trial in this setup in the basis of the report showing little effect of eye movements in an attentive

tracking experiment similar to the present one (Verstraten, Hooge, Culham, & Van Wezel, 2001).

### Results and discussion

Figure 2 shows the result of the flash alignment as a function of the number of items. The right vertical axis shows the spatial lag and the left vertical axis shows the temporal delay, which was calculated from the lag under the assumption that the FLE is caused by the differential latency:  $\text{delay [s]} = \text{lag [}^\circ\text{]} / \text{speed [}^\circ\text{/s]}$ . The red circles and green squares represent the data obtained from the cue and no-cue conditions. Only one condition is shown with one moving disk because there was no difference between the cue and no-cue conditions in this case (the one disk condition is shown nominally as the cue condition because the observer was able to track the target disk). Figure 2 shows that the delay is almost identical between the cue and no-cue conditions with two disks. A *t*-test showed that the difference was not statistically significant ( $t(4) = 0.05$ ,  $p = 0.96$ ). In contrast, the difference was larger in the case of six disks. The same statistical test showed that the difference was highly significant ( $t(4) = 13.9$ ,  $p < 0.001$ ).

Tracking the target reduced the FLE by a significant amount when there were many distractors. The temporal delay between the moving target and the flash stimulus was

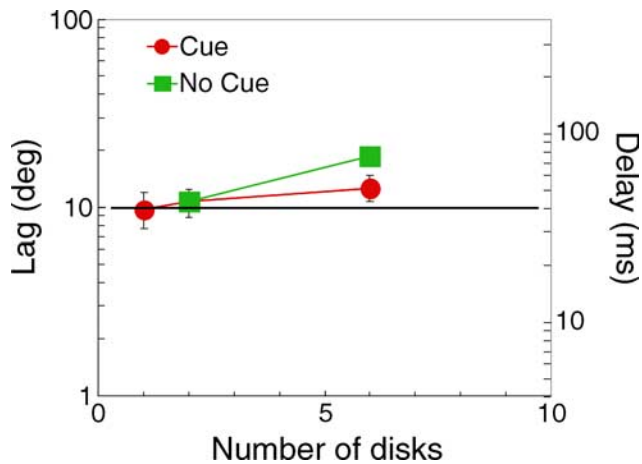


Figure 2. Flash locations relative to the target disk (lag in terms of rotation angle) for perceived alignment (left axis) as a function of disk number. Error bars indicate standard error of mean across observers. Lag is transformed to temporal delay using the relationship between space and time for a fixed speed (right axis): delay [s] = lag [°] / speed [°/s].

reduced by as much as 30 ms. Thus, it was confirmed that focusing attention on the target, or near the flash, reduces the FLE. This can possibly be attributed to attention facilitating processing of the flash stimulus so that the difference in processing time from processing of a moving stimulus is reduced (see [General discussion](#) section).

## Experiment 2: Effect of speed

Speed is also a factor that influences the attentional states for tracking moving objects. It is more difficult to track faster moving objects (Alvarez & Franconeri, 2007; Pylyshyn & Storm, 1988), and the temporal limit has been estimated for attentive tracking (Verstraten, Cavanagh, & Labianca, 2000). The speed of the objects was varied in [Experiment 2](#) to examine how speed influences the effect of attention on the flash-lag effect (FLE). It has been shown that the FLE depends on speed if evaluated in terms of the spatial lag, and this has been interpreted as a consistent differential latency (Khan & Timney, 2007; Krekelberg & Lappe, 1999; Nijhawan, 1994; Whitney, Murakami, & Cavanagh, 2000). In this experiment, we compared the differential latency between the cue and no-cue conditions while varying the speed of the moving objects. If more attention is required to track objects moving faster, the effect of attention on the FLE is expected to be larger for faster motion.

## Methods

The same method and observers were used as in [Experiment 1](#). The speed of the moving disks was varied

between 0.08 and 0.88 rps (3.7 and 40.0°/s in terms of linear motion in visual angle). Only six-disk stimulus was used for all speeds.

## Results and discussion

[Figure 3A](#) shows the spatial lag of the flash, and [Figure 3B](#) shows the temporal delay. Spatial lag increased with speed, and temporal delay decreased with speed in both the cue and no-cue conditions. The variation between different speeds in spatial lag was more drastic than the variation in delay. This is consistent with the report that the FLE in delay is approximately constant with the speed of the moving objects (the FLE in spatial lag depends on the speed). The effect of speed on spatial lag can be attributed, at least partly, to the approximately constant delay. With a constant delay, the lag increases with speed. However, the present data showed that the delay changed with speed. A two-way repeated ANOVA showed that the main effects of speed and cue conditions were statistically significant ( $F(4, 40) = 7.32, p < 0.001$ ;  $F(1, 40) = 18.7, p < 0.001$ ), while the interaction between the two factors was not significant ( $F(4, 40) = 1.43, p > 0.1$ ).

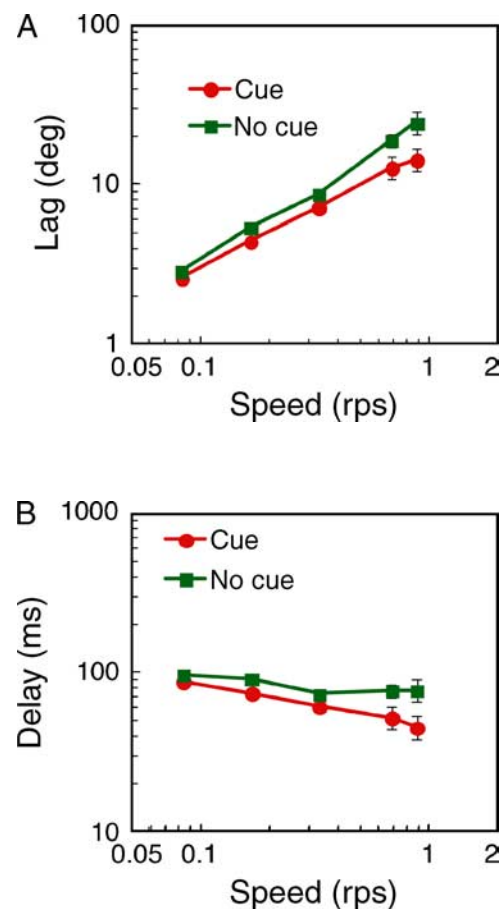


Figure 3. (A) Lag as a function of disk speed. (B) The delay corresponding to the lag. Error bars indicate standard error of mean across observers.

Cueing the target reduced the FLE in general with one exception (the FLE in the cue and no-cue conditions was approximately the same for the slowest motion). The difference in the FLE between the cue and no-cue conditions increased with speed. The correlation between speed and the difference in FLE was significantly greater than zero ( $t(4) = 5.24, p < 0.01$ ). The temporal delay that was shortened by cueing the target was less than 10 ms for the slowest motion (0.08 rps) and increased to more than 30 ms for the fastest motion (0.88 rps).

The speed of the object influenced the FLE. At slow speeds, smaller FLE was obtained. The difference between the cue and no-cue conditions increased with increasing speed. The larger cueing effect at the faster speed suggests that the observers devoted more attention to track the target moving faster. In other words, the difference in FLE among different target speeds can be explained by the difference in the amount of attention required to track the target.

Interestingly, speed itself influenced the FLE both in the cue and no-cue conditions. The temporal delay tended to decrease with speed in both conditions. This may be because more attentional resources are required to track faster moving targets in general. However, we do not discuss this issue farther because no clear statistical difference was found among conditions (Tukey–Kramer test showed significant differences between only three pairs of speed conditions in cue conditions at 5% level: the slowest and the fastest speeds, the fastest and the second slowest speeds, and the second fastest and the slowest speeds).

### Experiment 3: Spatial spread of attention

We confirmed that attention reduces the flash-lag effect (FLE) in Experiments 1 and 2. In Experiment 3, we used the FLE in order to estimate a spatial spread of visual attention. The effects of the object number and speed suggested that the FLE is monotonically related to the amount of attention oriented to the cued location. Based on this result, we assumed that the FLE can be used as an index of attention strength.

Several researchers have shown that modulation of attention on a visual task differs as a function of the distance from the center of attention (Downing & Picker, 1985; Eriksen & St James, 1986; LaBerge, 1983; Matsubara, Shioiri, & Yaguchi, 2007; Shioiri, Yamamoto, Kageyama, & Yaguchi, 2002). Among them, Matsubara et al. reported that attention is spread over a certain range along the circular path of moving stimuli, under experimental conditions similar to those used in the present study. We measured the FLE as a function of the distance from the target disk. If attention is spread over an area around the target, we expect a similar but smaller difference in FLE between the cue and no-cue conditions at the disks adjacent to the target.

In addition, we investigated whether the spatial spread of attention is constant or changes depending on experimental conditions. A model of limited attentional resources (Norman & Bobrow, 1975) predicts that paying attention to a wider area reduces the amount of attention at each location. The limit of attentional resources is an idea that the visual system has some resources that can be used to facilitate processing visual information where attention is oriented. Because the amount of the resources is limited, there is also limitation in total amount of facilitation effect over the visual field. Matsubara et al. reported such a correlation between the spatial spread and the effect of attention from threshold measurements of flash detection (Matsubara et al., 2007). They showed that attending to a larger area broadens the attentional spread while it reduces the sensitivity. We investigated such a size–strength correlation of attention using the FLE technique in this experiment. If the amount of attention oriented at a location varies with the spread size of attention, the FLE at the target location is expected to be smaller when the participant’s attention is spread over a larger area.

### Methods

The method was similar to that used in Experiments 1 and 2. The most important difference was the locations of the flash presentation. The flashes were presented not only at the target but also at one of the other disks. The location for one session was chosen from several possible locations, depending on the conditions: one-, three- and five-location (1-L, 3-L, and 5-L) conditions (Figure 4). In the 5-L condition, the flash location was selected randomly from five locations (all disks except the one on the opposite side of the target). There were two 3-L conditions. The separation between the locations was either 60° or 120° (Figure 4). In the 60° 3-L condition, the flash was presented at the target or either of the two disks adjacent to the target. In the 120° 3-L condition, the flash was presented at the target or at either of the two disks that were 120° from the target. The 1-L condition was the same as the cue condition in Experiment 1, where the flash was presented only at the target disk. The flash location was determined relative to the target disk in all cases, and the actual locations were varied randomly from trial to trial. Three rotation rates were used: 0.33, 0.67, and 0.83 rps. All three speeds were used in the 5-L condition while only 0.67 rps was used in the other conditions. Four new participants performed the experiment. In each condition, we used the no-cue condition as a comparison. We defined the difference in FLE magnitude between the cue and no-cue conditions as the effect of attention.

The method of constant stimuli was used in this experiment. For each disk, the flashes were presented at one of six locations near the point of the perceptual alignment that was roughly estimated in a pilot experi-

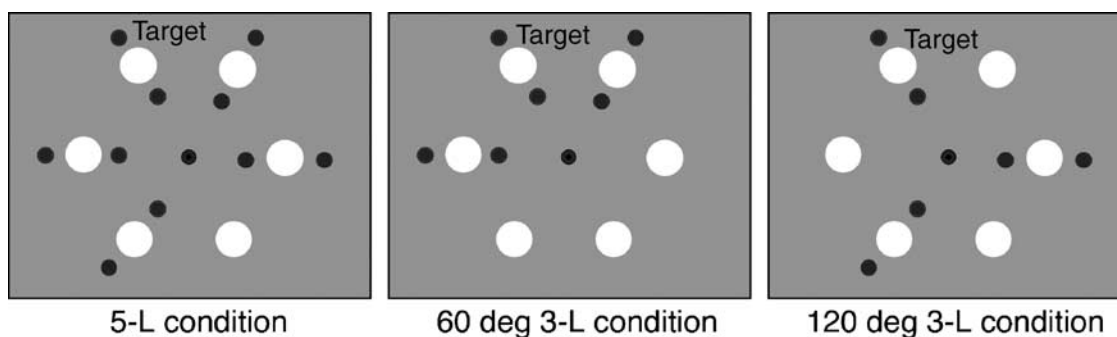


Figure 4. Stimulus configuration for each of the three flash presentation conditions. The flash stimulus consists of two black dots. Relative location of the flash stimulus is shown for each condition.

ment. Each flash location consisted of ten presentations of the flash (five for each rotation direction) in a session and each observer repeated four sessions for each condition. The rotation direction was varied from trial to trial and the results in the two directions were combined in analysis. The alignment point was determined as the flash location with 50% “ahead” responses from the psychometric function, using probit analysis.

### Results and discussion

Speed varied only with 5-L condition and the results of different speeds are shown in Figure 5. The different flash conditions were performed only with the speed of 0.67 rps and the results are shown in Figure 6. Figure 5 shows the

FLE in the 5-L conditions for three speeds. The vertical axis shows the delay relative to that of the no-cue condition as a function of the distance from the target disk and the horizontal axis shows the distance of flash from the target in the direction of disk motion (positive indicates ahead of the target). The FLE in the no-cue condition was similar among the three speed conditions and was 80.1 ms on average, which was approximately the same as the average FLE of the three fast motion conditions in Experiment 1 (74.0 ms). The positive value indicates longer delay in the cue condition. The shortest FLE, which corresponds to the largest effect of attention, was seen at the target location (zero on the horizontal axis) and the FLE increased with increasing distance from the target location. These results suggest that attention spreads spatially around the target.

The FLE profile across space differs between speed conditions. The variation between flash locations was smallest at the slowest speed (0.33 rps). This is consistent with the results of Experiment 1, where the effect of

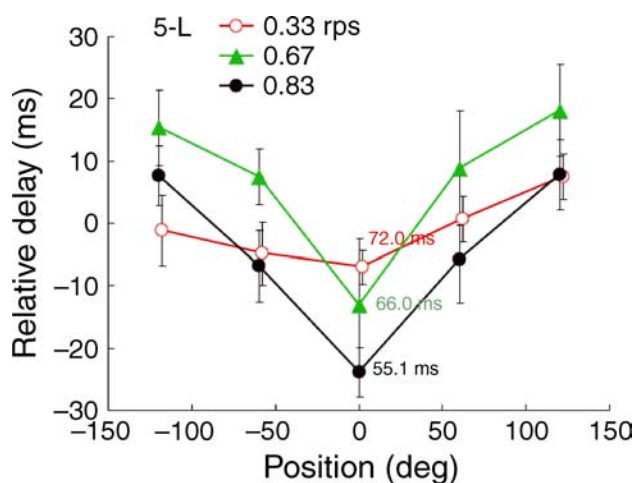


Figure 5. Relative delay as a function of flash location for three speed conditions. Vertical axis shows the difference in the delay between the cue condition and the no-cue condition. Horizontal axis shows the distance between the flash and the target disk (positive value indicates the direction of disk motion). The absolute value of the FLE is shown near the point at 0° for each speed condition. Error bars indicate standard error of mean across observers.

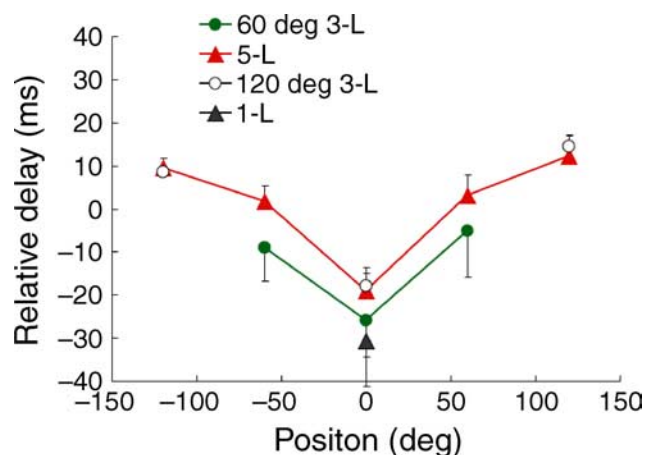


Figure 6. Relative delay as a function of flash location for four different flash-location conditions. The vertical axis shows the difference in the delay between the cue condition and the no-cue condition. Horizontal axis shows the distance between the flash and the target disk. Error bars indicate standard error of mean across observers.

cueing increased with the speed of the stimulus motion. The effect of cueing was larger when the observer tracks objects moving faster. Note that the effect of cueing itself was also found in this experiment. The value near the point at  $0^\circ$  indicates the absolute value of the FLE in millisecond, which show the larger cueing effects (more reduction of the FLE) with faster motion conditions.

Figure 6 shows the FLE for conditions with different flash-location sets. Our interest is in the effect of possible flash locations on the FLE. If there is no such effect, the FLE should be decided solely by the distance from the target. In order to examine this issue, we first compare the FLE at the target location between the conditions, across which the spatial spread of the observer's attention was assumed to vary. Since the trial with the flash at the target was identical for all conditions, the difference can be attributed to the difference in the observers' attentional states. The shortest FLE was found in the 1-L condition, the second shortest in the  $60^\circ$  3-L condition, and the longest in the 5-L condition. These results are consistent with the model of limited attentional resources. When the observer pays attention to a wider range, as in the 5-L condition, less attention can be paid to the target location if attentional resources are limited.

The possible effect of the attentional resource limit is also supported by the fact that the FLEs at the target and at the  $\pm 120^\circ$  positions are virtually identical to those at the 5-L and the  $120^\circ$  3-L conditions, respectively. This indicates that the spatial range of possible flash locations, independent of the number of flash locations, is critical for attention spread. We suggest that attention cannot be divided equally between the possible flash locations and attention is spread instead to cover the locations, at least in the present condition.

Figure 6 shows that the effect of cueing does not always reduce the FLE. The difference from the no-cue condition was negative for flashes near the target, whereas it was positive for the flashes presented far from the target. This may suggest that the spatial modulation of attention includes facilitation and inhibition. When attention is paid to a location, it facilitates visual processes around the location while it may also inhibit processes at places far from the attention center. The distance is a factor to decide whether spatial modulation facilitates or inhibits. Alternatively, facilitation effect alone may be able to explain the results. If, for example, attending to the whole stimulus field decreases the FLE in the no-cue condition, the relative FLE can be positive at a location far from the target, where little facilitation due to cueing is expected in the cue-condition. The present results cannot distinguish the two interpretations and this issue is remained for future studies.

The FLE measured is based on a number of trials. The differences in FLE among conditions may be caused by statistical variation of the two distinct states: focusing on the disk or not. This provides an alternative interpretation of the present results. The statistical variation causes variability of the FLE among different conditions. If the

participants attentional state fluctuates statistically between the two states (on and off) and the probability of selecting each state varies among conditions, the FLE estimated from the psychometric function varies between the two extreme cases (100% on and 100% off). The statistical variation may change from one state to the other gradually as the distance of flash from the target increases. Since the psychometric function is assumed to be determined by a mixed distribution of the two probability distribution functions in this interpretation, slope of the psychometric function (or variance of the underlying probability function) should be larger than that determined by either distribution function corresponding to the two cases.

We examined whether the slope of the psychometric function varied as predicted from the statistical variation theory. The slope was defined as the standard deviation of the normal distribution function fitted to the data using probit analysis. Figure 7 shows the slope for each flash location in the 5-L condition. Slope is expressed by the delay in milliseconds. The figure shows that slope increases with the distance from the target location. To apply the model of statistical variation, we estimated the probability (or relative weight for selection frequency) of selecting either of the two states. We assumed that a normal distribution function determines the psychometric function in two extreme situations (100% on and 100% off) and a mixed distribution of the two distributions determines the psychometric function in other conditions. When a mixed distribution of the two states determines the point of subjective equality (PSE) in condition  $i$ , the  $PSE_i$  can be expressed as follows:

$$PSE_i = k_i \cdot m_A + (1 - k_i) \cdot m_B, \quad (1)$$

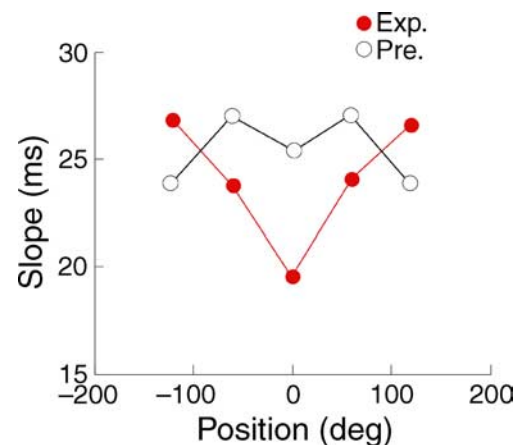


Figure 7. Slope of psychometric function for the 5-L condition with 0.67 rps in Experiment 3. Red circles represent the slope obtained from experimental results and white circles represent predictions from statistical variation model of probability distribution functions underlying the psychometric functions.

where  $m_A$  and  $m_B$  are the means of the two normal distribution functions and  $k_i$  is the relative weights of the two functions in condition  $i$ , which varies between 0 and 1. Similarly, the standard deviation of a mixed function, which we call the slope ( $SL_i$ ) of the psychometric function, is expressed as follows:

$$SL_i = k_i \cdot ((PSE_i - m_A)^2 + \sigma_A^2) + (1 - k_i) \cdot ((PSE_i - m_B)^2 + \sigma_B^2), \quad (2)$$

where  $\sigma_A$  and  $\sigma_B$  are the standard deviation of the two normal distribution functions.

For predicting slopes in the five conditions in the experiment, the weights,  $k_i$  in each condition,  $m_A$ ,  $\sigma_A$ ,  $m_B$ , and  $\sigma_B$  are required. The values of  $m_A$  and  $\sigma_A$  were parameters of the probability distribution function of the 100% on condition. They are estimated from the psychometric function in the target condition, where the flashes were presented only at the target disk, ignoring the other disks. We estimated the parameters,  $m_B$  and  $\sigma_B$  of the distribution for the 100% off condition and the weights,  $k_i$ s for the five conditions in terms of a least square method. The difference in PSE and SL between the prediction from the model and experimental results was minimized in the method (there are ten equations, two for each of five conditions and seven unknowns).

In this analysis, the relative contribution of PSE and SL errors can be varied: if a larger weight is given for PSE errors, obtained parameters predict PSE results well with a large error in SL, or vice versa. Since our interest is in slope prediction, here we show the predictions of SL under the condition where the prediction error of the PSE is approximately 2% on average. Figure 7 compares the slopes between the prediction from the statistical variation model and those obtained from the experiment. The prediction succeeded to explain neither the function shape nor the absolute values. The predicted slope does not follow the v-shaped function of experimental results. The difference between the prediction and the experimental results is approximately 15% on average. This suggests that the statistical variation is not an appropriate factor to explain the FLE variation among different flash locations. Weighting more on SL error provides better estimations of SL but the estimation of PSE becomes worse. No reasonable fitting is found for predicting both PSE and SL.

## General discussion

We showed that attention reduces the flash-lag effect (FLE). The FLE expressed in terms of the differential latency was reduced by as much as 30 ms when observers tracked a moving target. This FLE reduction by attention

is consistent with the previous reports. Attending to the moving stimulus, flash timing, and flash location have been found to reduce the FLE (Baldo et al., 2002; Chappell et al., 2006; Sarich et al., 2007). One exception is the study of Khurana et al., in which attention was observed to have little effect on the FLE (Khurana et al., 2000). Their experimental conditions were similar to those in Experiment 1 in the present study. They used five stimuli moving at 0.5 rps along the circular path of 4.3° from the fovea. Our results suggest that some effect of attention (about 20%) can be found under the condition. If we look closely at their results focusing on two conditions (RK-FU and RU-FU conditions in their Figures 2 and 3), which are consistent with our cue and no-cue conditions, a small effect of cueing can be seen. This small effect may be related to the small effect of attention found here. It should be noted that what Khurana et al. revealed are that attention does not eliminate the FLE and that the larger and clearer contribution of attention is found for reaction time to the flash onset. Therefore, we believe that there is no contradiction in the literature regarding the reduction in the FLE magnitude by attention, while perhaps explanation is required for the differences in the effects of attention between the FLE and reaction time.

In order to examine whether the FLE magnitude is related to the amount of attention, we compared the FLE magnitude between different conditions. We investigated the effect of the number of items to attend (Experiment 1) and the effect of the stimulus speed (Experiment 2). The measured FLE magnitudes suggest that the effect of attention is stronger (i.e., there was larger reduction by cueing) with faster motion and more objects to attend. This is consistent with the effect of attention suggested in MOT studies. The performance in MOT indicates that greater attention is required to track more objects, as well as faster moving objects (Alvarez & Franconeri, 2007; Pylyshyn, 1998). Therefore, we conclude that the FLE magnitude is related to the amount of attention oriented to the location around the FLE is measured. Amount of attention thus can be estimated from the FLE.

Our findings may appear to contradict a recent study of MOT experiments (Franconeri, Jonathan, & Scimeca, *in press*; see also Franconeri, Lin, Pylyshyn, Fisher, & Enns, 2008). Franconeri et al. found that the object speed itself did not deteriorate tracking performance, but a spatial factor such as crowding effect does. Do the present findings contradict to their findings? The answer is “no.” What the present results suggest is that effect of attention is larger when a task is more difficult whatever the reason (crowding or speed) is. Indeed, crowding effect may have made tracking more difficult for faster moving conditions in our experiments. For example, the space between objects in spatiotemporal diagram is smaller with faster motion and the smaller distances possibly make tracking more difficult. They investigated factors to limit tracking and we investigated the relationship between the difficulty of tracking task and the state of attention.



It should also be noted that we should not compare the effect of stimulus conditions in the present experiments with those in MOT experiments directly. We evaluated neither the performance of tracking nor the accuracy of stimuli localization. Our results show the effect of cueing on the localization bias and we regard the effect as the cuing effect of attention following conventional cuing paradigm. This is different from studies that evaluate tracking ability.

An important question is how attention influences FLE. Attention likely facilitates processing of the flash when the target is tracked. However, attention may also facilitate processing of the moving target. No difference is expected in differential latency with the same facilitation effect in the flash and the moving object. Attention

is required to influence the flash selectively in order to explain the effect of attention on the FLE. One possible interpretation is based on the assumption that the flash triggers localization of moving objects (Baldo & Klein, 1995; Brenner & Smeets, 2000; Krekelberg et al., 2000). Let us assume that the differential latency is critical for the FLE and that the localization of the moving object follows detection of the flash. A moving target must be localized to compare the relative location against the flash in flash-lag experiments. This may or may not be done automatically and continuously at a certain stage of the visual system. Subjectively, localizing a moving stimulus at a certain time appeared to require an active process. For example, we can remember the locus of a shot in a soccer game but can hardly remember the location of the ball in

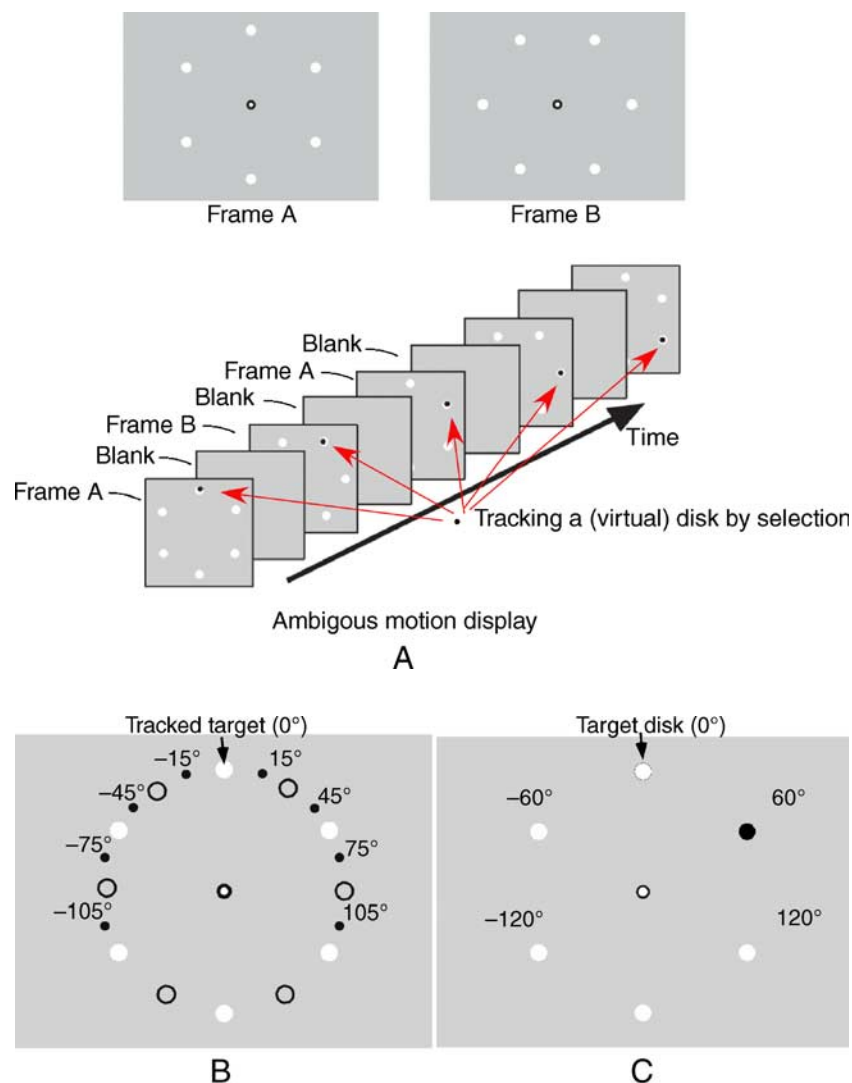


Figure 8. Stimuli used in previous experiments (Matsubara et al., 2006). (A) Ambiguous motion display used in the two experiments. The observer tracked a disk in alternation of the Frames A and B, where apparent motion of disks was perceived. One cycle of the alternation consisted of a 15-ms frame presentation and 105-ms interframe interval of gray field (0.7 rps in terms of apparent rotation of disks). The stimulus dimensions were the same as in the present experiments. (B) Probe locations relative to the target disk in threshold measurements (Matsubara et al., 2006). (C) Saccade cue locations relative to the target disk in saccade latency measurements (Matsubara et al., 2007).

the locus at a certain time without trying to localize it. If the moving object is not localized automatically, the visual system has to decide when to localize. Under the conditions of the FLE experiment, the process of localizing a moving object perhaps starts at the time when the flash is detected. Following the detection, attention is focused around the flash and processing of the moving object is under attentional focus. In this scenario, the effect of attention is on detecting the flash and there is no difference between the cue and no-cue conditions after flash detection. This predicts that attention influences the flash stimulus selectively and reduces the FLE.

We investigated the spatial spread of visual attention by measuring the FLE in Experiment 3. In the experiment, the reduction of the FLE in the cue condition was found at locations at a certain distance from the attentional focus. This indicates that attention spreads over a certain region around its center, agreeing with the studies that have shown similar spreads of spatial attention with different measures (Matsubara, Kaneko, Shioiri, & Yaguchi, 2006; Matsubara et al., 2007). We compared our results with those from two previous experiments that used similar tracking tasks. The first experiment measured the contrast threshold at several locations. The task was to detect a probe stimulus presented briefly while the observers were tracking a disk attentively in an ambiguous motion display (Cavanagh, 1992; Shioiri, Cavanagh, Miyamoto, & Yaguchi, 2000; Shioiri et al., 2002; Verstraten et al., 2000). Figure 8A depicts the tracking stimulus. The ambiguous motion display consisted of two frames of six disks arranged so that their alternations generate apparent motion in ambiguous direction (either clockwise or counterclockwise). The observers were asked to track a disk indicated (the target disk) and to respond whether they notice the probe presented about 600 ms after the start of tracking (yes/no responses). Spatial variation of contrast threshold was measured along the motion path, presenting the probe at nine locations relative to the target disk (Figure 8B). They showed lower threshold (higher sensitivity) at around the target disk. The second study measured the latency of saccadic eye movements. The tracking condition was the same as that in Matsubara et al. (2007; Figure 8A), but the task of the observer was different. The observer was asked to make a saccade to a saccade cue. The saccade cue was a change of the luminance of one of the disks (from white to black) about 600 ms after the start of tracking (Figure 8C). They showed the spatial variation of saccade latency around the target disk location (shorter latency for saccades directed closer to the target).

Figure 9 shows a comparison of the attention distribution profiles estimated in the three studies. The vertical axis is normalized so that the average and standard deviation across the data (contrast sensitivities, saccade latencies, or the FLEs) at different positions become zero and one (i.e., the difference from the average divided by standard deviation, or the *z*-score). The shape of the

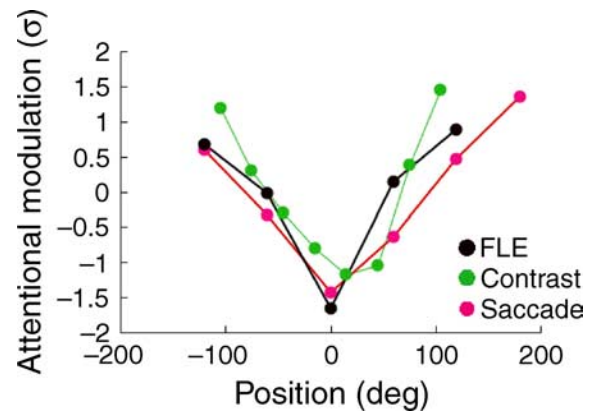


Figure 9. Comparison of attention effect among three studies with different measurements: contrast sensitivity (Matsubara et al., 2007), saccade latency (Matsubara et al., 2006), and FLE. Attentional modulation is defined as the difference from average across conditions divided by standard deviation (*z*-score) in each study.

function is similar for the three estimations. This confirms that the spatial distribution of attention effect on the FLE reflects the spatial spread of attention, instead of any effect specific to the FLE measurements. We can assume that the observers' attentional state is similarly controlled in the three experiments because the three experiments used similar tasks of attentive tracking. The consistency across studies is shown in Figure 9. Figure 9 indicates that the measurements of attentional state using the three techniques are similarly *reliable*. In terms of task simplicity, the flash-lag technique has an advantage. Judgments of relative location of a flash is easier than detecting a probe at threshold level and the measurement does not need special equipment such as an eye tracker. The flash-lag effect can be used conveniently to investigate states of visual attention *in many cases*.

Experiment 3 also revealed that the range of the possible flash locations influences the profile of the attention spread. The effect can be assessed by comparing the reduction of the FLE at the target with cueing. When the flash locations were set to larger regions (the 5-L condition), the reduction of the FLE at the target was smaller than that when the flash was presented only at the location of the target (the 1-L condition). Figure 10 shows the relationship between the FLE at the target and the flash range. This is consistent with the results of Matsubara et al. (2006). They found a lower threshold (higher sensitivity) at the attended location when the probe was presented only at the target than when the probe was presented at one of many locations within a given area (the ranges used were  $\pm 15^\circ$ ,  $\pm 45^\circ$ ,  $\pm 75^\circ$ ,  $\pm 105^\circ$ , see Figure 8B). We have analyzed the results of Matsubara et al. and present data with the same normalization as in Figure 9. Figure 10 shows the attentional modulation as a function of the size of the region that attention is required

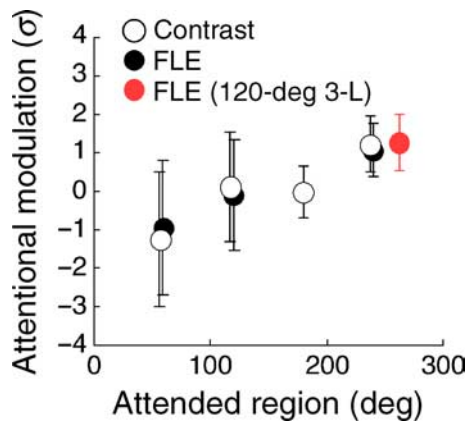


Figure 10. Comparison of attention effect (z-score) at the target location estimated with contrast threshold (Matsubara et al., 2007) and that with FLE. The result of the FLE (120° 3-L) indicates the FLE at the target in the 120° 3-L condition and shifted to the right from the actual position of 240°.

to cover. The modulation increases with increase of the size and the functions are similar in both experiments. This analysis confirms that attention spreads over the region within which task-related stimuli are presented.

Interestingly, several studies have found that attention can be divided between different locations, rather than spread over a large field. For example, reaction time studies showed that observers can devote attention to several non-contiguous locations (Awh & Pashler, 2000; Kramer & Hahn, 1995). Evidence was also found for attention being paid to distinct regions from brain activity measurements (McMains & Somers, 2004; Müller, Malinowski, Gruber, & Hillyard, 2003). We should recognize, however, that these results do not exclude the possibility of attention spreading over the region around the cued locations, as our results do not rule out the possibility of the division of attention. Indeed, hints of attention spread can be seen in data from some reports on the division of attention. Awh and Pashler (2000), for example, demonstrated psychophysically that visual processing was facilitated in the middle of the cued regions, although the effect was smaller than that at either of the cued locations. Similarly, in an fMRI experiment, McMains and Somers (2004) showed the attention effect at the intervening regions, which was smaller than that at the locations of the attended stimuli. That is, studies that suggest division of attention often show effect of attention spread. It is likely that attention is a flexible system that can be divided into separate regions in some cases and can be spread over contiguous region in other cases (Awh & Pashler, 2000). If it is an easier strategy to pay attention to a contiguous region in the visual field (the midlocation placement strategy; McCormick, Klein, & Johnston, 1998), observers may adopt this. This may be the case when strong attention is required to perform a task such as tracking an object in fast motion, as in the present experiments.

## Conclusion

We found that the effect of attention on the FLE increased with the number or the speed of the objects. This suggests that the amount of attention oriented to cued location can be estimated by measuring the FLE at the location. On the basis of these findings, we attempted to measure the spatial spread of visual attention using FLE measurements and obtained results on spatial spread similar to those estimated by different methods.

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Corresponding author: Satoshi Shioiri.

Email: shioiri@riec.tohoku.ac.jp.

Address: Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Sendai, 980-8577, Japan.

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