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Smooth shifts of visual attention

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Abstract

To examine whether visual attention shifts continuously across the visual field, we measured sensitivity to a small flash presented at various locations while the observer was tracking a moving target in an ambiguous apparent motion display. The sensitivity peaked near the target and the peak shifted smoothly along the apparent motion path. Since the peak-shift speed varied with the speed of the tracked target, we conclude that the attention mechanism selects the location to facilitate processing by tracking the target disk continuously. Attention does not simply select a location for enhanced processing, but rather predicts the future location of the object of interest based on its velocity.

Keywords: Visual attention; Attentional spotlight; Attentive tracking; Sensitivity

1. Introduction

We experience paying attention to a location in the visual field and shifting it without eye movement. This implies that attention can select and shift the area of interest without physical restrictions of eye movement. One widespread metaphor for visual attention is that it acts as if one were shining a spotlight on the visual field. [1] This spotlight metaphor indicates that attention selects a place at which to enhance efficiency of visual processing and that the attentional beam moves smoothly as a physical spotlight would. A number of behavioral studies have reported this spotlight-like selection-by-attention, showing shortening the reaction time and increasing sensitivity at the attended area (Posner, 1980; Van der Heijden, 1992), and recent studies have related such effects to brain activities (Brefczynski & DeYoe, 1999; Somers, Dale, Seiffert, & Tootell, 1999). In contrast to attentional selection, this smooth motion of visual attention is controversial. Although several pioneering studies reported experimental results that might be interpreted as the smooth shift of visual attention (Shulman, Remington, & McLean, 1979; Tsal, 1983), their interpretation of results has been questioned (Eriksen & Murphy, 1987; Sperling & Weichselgartner, 1995; Yantis, 1988).

A typical experimental result conceived as a reflection of attention shift is the facilitation of visual processing at a peripheral location after pre-cueing the location. In such a condition, it should be efficient for the visual system to shift attention from one location to the other without paying attention in between. In contrast, when one is asked to continue paying attention to a moving object with eyes fixating a point (Cavanagh, 1992; Pylyshyn, 1998), smooth movement of the attentional beam would be useful to track the object. Possibly, attention moves smoothly in such situations. There are two studies that support this presumption. First, Shioiri, Cavanagh, Miyamoto, and Yaguchi (2000) measured perceived location of an apparent motion stimulus and showed that perceived location, so the internal representation of an apparent motion stimulus, moves smoothly during the interval between the stimulus presentations. Second, Yantis and Nakama (1998) measured letter identification performance at the midpoint along the motion path of apparent motion. They found deterioration or facilitation of the performance dependently on the temporal conditions of stimulation when the letter was presented along an apparent motion path. They interpreted the deterioration as the target signal

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[1] Attention to objects instead to spatial locations has been extensively investigated. Although, we restrict our discussion to shifts of spatial attention in this study to avoid complexity, our discussions about the smooth shift can also be applied to object-based attention.

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was masked by motion signal of the internal representation of the apparent motion stimulus and speculated that the facilitation was caused by attention to the apparent motion stimulus. If we can assume that attention moves with the internal representation of the apparent motion stimulus, which may cause motion masking independently of attentional facilitation, both results suggest the smooth movement of visual attention.

However, we do not know the assumption is correct. It is necessary to measure the effect of attention directly to investigate the movement of attention. For the purpose, we designed an experiment to investigate attentional facilitation in visual processing while tracking a moving target. The experiment measured spatial tuning of attentional modulation of sensitivity along the path of motion of the attended object as a function of time. An ambiguous apparent motion display (Fig. 1a) was used to isolate the effect of attention from all other effects of physical stimulation on the display (Cavanagh, 1992; Shioiri et al., 2000). The observer can see apparent motion of the disk, which is advanced step-by-step from frame to frame as shown in Fig. 1b. Since movement of the tracked disk exists in the observer's brain, but not on the display, a visual mechanism should join the flashed disks to create perceived movement. If attention contributes to joining, sensitivity would be higher to the stimulus presented near the apparent path of the tracked disk during inter-frame-intervals, IFIs (Fig. 1b). Sensitivity measurements of at variable locations during IFIs would provide the location with the largest attentional facilitation; consequently, change of that location over time would yield a trace of the attention shift. Although Yantis and Nakama showed suppression of processing test stimulus on the apparent motion path in their main experiment, our pilot experiment showed attentional facilitation occurs for detecting a small test stimulus. The significant difference between their and our experiments was the difficulty of the motion task. Our motion task required strong effort or active tracking, whereas it is likely that the observer saw motion more passively in Yantis and Nakama's experiment.

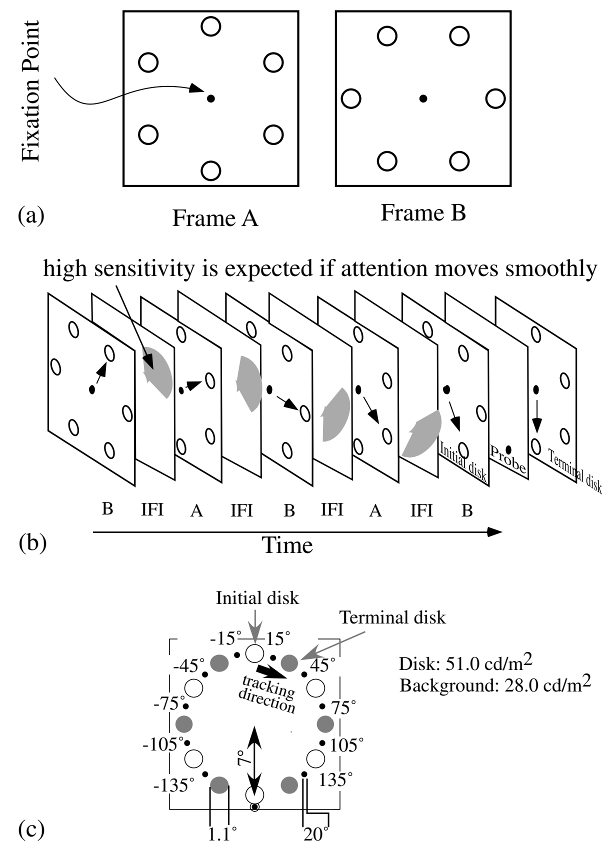

Fig. 1. (a) The frames of disks used for an ambiguous motion display. To generate an ambiguous motion display, two frames with six disks were alternated. While there is no net motion energy in either a clockwise or counter-clockwise direction in the display, the observer can see motion in either direction by choosing the direction by his/her will or attention. (b) A sequence of the alternation. The observer can select a disk to perceive its continuous rotation in the direction indicated by arrows. A marker (small red disk) was on a disk at the beginning of each trial to indicate which disk to track. The observer continued tracking the disk for four frames after disappearing of the marker, and then, the probe was presented. The disk tracked in the frame just before the probe was named the initial disk and the disk in the frame immediately after was named the terminal disk. Probe location was expressed by the rotation angle relative to the probe. After the probe presentation, the observer tracked the disk for an additional six frames. The marker was presented again at the last frame to check if the observer had tracked the right one. Trials with unsuccessful tracking were cancelled and re-run later. (c) Probe locations and stimulus dimensions. There were 10 locations of the probe on the circular path of the tracked disk. Open circles represent disks of frame A and gray ones the disks of frame B. Actual disks had identical luminance of 51.0 cd/m^2 on the background of 28.0 cd/m^2. Disk diameter was 1.1° in visual angle and the distance from the fixation point was 7°. The probe diameter was 20′.

2. Experiment 1: shift of the sensitivity peak

We measured the threshold for detecting a small test flash of a luminance decrement (a probe) presented at the midpoint between the two adjacent disks selected from 10 possible pairs (Fig. 1c) during an IFI. The tracked disk in the frame just before probe insertion was named the initial disk and the tracked disk in the next frame the terminal disk. We chose the midpoint between one pair of the adjacent disks to present the probe in order to equate the influence of disk flashing on the detection threshold. Effects of eccentricity and retinal location were also equal among locations since the probe was presented at the same eccentricity and the initial disk location varied randomly from trial to trial. The probe location was registered as the rotation angle around the center of the display relative to the initial disk. Frames were presented for 15 ms alternately with 105 ms IFI, which corresponded to 0.69 revolutions per second (rps). Either 0, 60, or 90 ms was used as the stimulus onset asynchrony (SOA) of the probe presentation relative to the initial disk. We would expect high sensitivity between the initial and terminal disks if attention were to shift smoothly. We used luminance decrements, instead of increments, for the probe. This minimized the confusion between the probe and the disks, which may reduce sensitivity to the probe. The experiment used the method of constant stimuli with a yes/no response; it determined the detection threshold by Probit analysis from the psychometric function of the detection rate with various probe strength levels expressed by Weber contrast (luminance ratio of the decrement to the background). Sensitivity was defined as the reciprocal of the contrast at the threshold. All SOAs and probe locations were mixed in a session. Each observer ran 15 sessions which provided 150 judgments for each threshold. Five observers with normal or corrected to normal vision participated.

Fig. 2 shows contrast sensitivity as a function of probe location in the three SOA conditions, separately. When the probe was presented with the initial disk (0 ms SOA), sensitivity showed a peak at about the location of the initial disk (0°) with gradual decreases at both sides (open squares). The peak location tended to shift to the direction of the terminal disk as SOA increased (filled circles and pluses). To estimate the location with the peak sensitivity, we fitted a Gaussian function to each set of data as shown by the solid line in Fig. 2. Although the estimated peak appeared to depend heavily on the outlying points, the estimation is robust for the choice of data points. Fitting the function to the central five data provided similar results. Fig. 3 shows the estimated peak (filled circles) averaged over the estimation from the sensitivity function of individual observers (thus, the data are not identical, though very similar, to the peaks of the fitted function in Fig. 2). The estimated peak closely follows the gray line, which shows the path of a constant angular velocity. The manner of the peak shift indicates that the location with the largest attentional facilitation shifts smoothly, following the path of apparent motion of the tracked target. When the location of attention is defined functionally as the location with the largest attentional facilitation, we can conclude that attention moves continuously to track a moving object.

The smooth shift of the attentional facilitation can be interpreted by smooth shift of visual attention. Alternatively, it can be interpreted by a space-invariant smooth transition between two-attention states: the state of attending to the location of one disk and the state of attending to the location of the next disk. In this case, the sensitivity function during IFI may be determined by the weighted sum of the two sensitivity functions at two discrete locations (Sperling & Weichselgartner, 1995). If the magnitude of attentional facilitation gradually decreases at one location with gradual increase of magnitude at the other, the summed function may show a peak at the location between the two. Present results cannot distinguish the two interpretations.

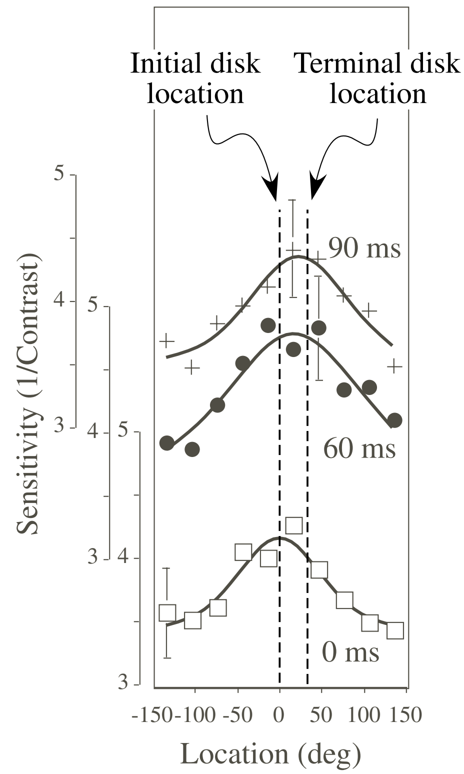

Fig. 2. Sensitivity as a function of probe location in angle of rotation around the fixation point relative to the initial disk. The positive direction on the abscissa indicates the direction of tracking. Each point shows average sensitivity of five observers. Three curves represent results with the probe presentation of 0, 60, or 90 ms after the initial disk. Data points are shifted vertically for clarity. The standard error of the mean across five observers was calculated; the largest one is shown in each data set. The solid curve is the Gaussian function fitted to the sensitivity data by a least square procedure. The peak of the function shifts rightward, i.e., the direction of tracking, as SOA increased during IFI.

A critical difference between the two interpretations is the time course of the peak shift in different spatiotemporal conditions. If attention moves smoothly, we expect that the peaks shifts along the line of constant angular velocity independently of spatial and temporal conditions of the tracking target. The smooth transition model, on the other hand, assumes that attention shifts with a constant time independently of distance and the speed of target movements (Sperling & Weichselgartner, 1995). Experiment 2 investigated the effect of spatiotemporal parameters of the tracking disk in the ambiguous motion display.

3. Experiment 2

We repeated measurements with a larger spatial separation and with a slower track speed to examine

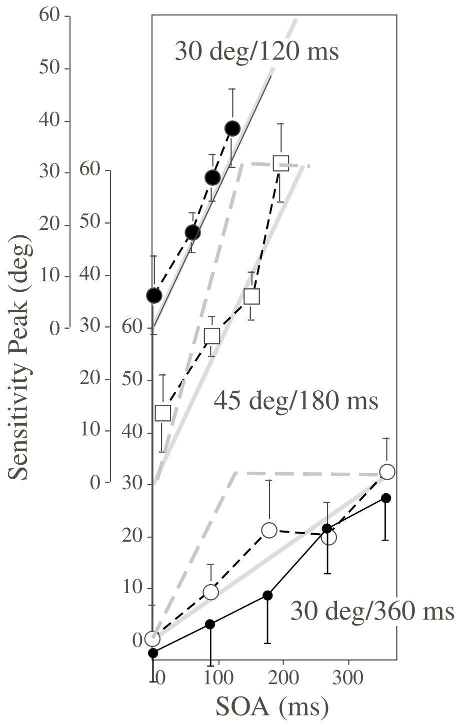

Fig. 3. The estimated sensitivity peak as a function of the probe presentation time or SOA. The ordinate is expressed by angular rotation relative to the initial disk with the direction of tracking being positive. The three functions, shifted vertically, represent the three different spatiotemporal conditions. Filled circles represent the condition of Experiment 1, in which the six-disk frames were alternated (30° disk separation) with a display cycle of 120 ms (15 ms frame and 105 IFI). Open squares represent the large displacement condition of Experiment 2, in which the four-disk frames were alternated (45° disk separation) with a display cycle of 180 ms (15 ms frame and 165 IFI). Only six probe locations (±75°) were used in the condition to reduce the experimental time. Open circles represent the slow speed condition of Experiment 2, in which the six-disk frames were alternated with a display cycle of 360 ms (15 ms frame and 345 ms IFI). Probe appeared at all of the eight midpoints in this condition. Filled small circles in the slow speed condition represent perceived locations of the tracked target measured for three observers in different sessions (see text). The rightmost point in each condition is the replica of the leftmost point with one cycle shift in time and position. Error bars represent standard errors of mean across observers except for the perceived location data, whose error bars represent the standard deviation of the alignments averaged over three observers. The solid gray lines indicate the path with constant angular velocity and dashed gray lines indicate the path with the constant time to shift between the disks independent of disk separations and IFIs (time to start shifting is fixed at 0 ms).

how the shift of the sensitivity peak would depend on these parameters. In the large displacement condition, four-disk frames were alternated with presentation of 15 ms separated by IFIs of 165 ms, which corresponded to the disk rotation speed in the original condition (0.69 rps). In the slow speed condition, six-disk frames were alternated with presentation of 15 ms separated by IFIs of 345 ms. The corresponding speed was one-third that of the original condition (0.23 rps). Five observers with normal or corrected to normal vision participated in each condition. Two of them were from Experiment 1 and ran the two conditions; three were new observers, who were different for the two conditions.

The gray lines in Fig. 3, interpolating the disk locations linearly, indicate the prediction of peak shift from smooth shift model. The dashed gray lines indicate the prediction from a smooth transition model, where the time to shift from one location to the other is 120 ms to cope with the result in the original condition. The time at which the shift starts is arbitrarily chosen to the time of the disk presentation (0 ms). However, the shape of the function does not depend on the time insofar as we assume (1) a constant time to shift attention between adjacent disks and (2) a constant timing for initiating the shift, which is expected if the shift of attention is initiated by presentation of the disks. The shift of the sensitivity peak obtained from the experiment follows the path of the linear interpolation of disk locations in the two conditions (open symbols in Fig. 3). The times to shift attention one disk separation are approximately 1.5 and 3 times longer in the large displacement and slow speed conditions, respectively. These results agree with the prediction from the smooth shift model. We conclude that the attention shifts smoothly while tracking a moving object, predicting its future locations based on the object velocity. Note that this does not deny the possibility of discrete shift of attention, which perhaps occurs to direct attention to the event location, such as a cue presented in the periphery. Perhaps, there are two different types of attention shifts, smooth and abrupt attention shifts, just as there are two different types of gaze shifts, pursuits and saccades (Sperling & Weichselgartner, 1995).

4. Discussion

Results of Experiments 1 and 2 support smooth shifts of visual attention, showing that the sensitivity peak shifts smoothly in time. That the peak shifts with constant velocity independently of the disk distance and moving speed indicates that a model of attention shift with a constant temporal period is inappropriate. In the model, we assume that the attention shift starts with a fixed time relative to the initial disk. However, if the initiation of attention shift varies stochastically from trial to trial, the peak of the sensitivity function may apparently shift smoothly even though attention shifts discretely at each trial. One possible method to distinguish this from the smooth shift of attention is to compare the spatial extents of sensitivity functions with different SOAs. If spatial tuning of the sensitivity function were sharp relative to the disk separation, a discrete shift model would predict a broader sensitivity function for the probe presented during IFI (e.g., SOA = 60 ms) than that for the probe presented with the disks

(SOA = 0 ms). A smooth shift model would predict the same shape of the sensitivity function with all SOAs. We cannot apply this method to present results because the spatial extent is broad relative to disk separation. Averaging sensitivity functions at the initial and terminal disk locations predicts a sensitivity function at the midpoint of an IFI with a similar spatial extent to that of the originals.

It has been shown that this method can be used to distinguish the smooth shift and smooth transition models for estimation of the perceived location of the attentively tracked disk in an ambiguous motion display, which provides localization precision higher than the disk separation (Shioiri et al., 2000). Although the perceived location of tracked disk does not necessarily correspond to the center of visual attention (Khurana & Kowler, 1987; Khurana, Watanabe, & Nijhawan, 2000), it is possible that the location is controlled by attention; it thus provides the information of the attention center. Assuming that the perceived location of the tracked target corresponds to the location of attention, we measured the perceived location of the tracked target during IFI. The slow motion condition was used and three of the five observers who participated in the sensitivity measurement participated in this experiment.

The perceived location of the tracked disk shown in Fig. 3 (filled small disks) was obtained with an identical experimental procedure to that of Shioiri et al.'s alignment procedure. Based on the observer's judgments of whether the target was ahead or behind of the location at which a probe stimulus pointed, we determined the perceived disk location. The perceived target location follows the line of linear interpolation as the sensitivity peak, although it is slightly behind the sensitivity peak. This is consistent with the presumption that the perceived location and the sensitivity peak are determined by the same mechanism. Precision of the alignment is represented by the error bars in Fig. 3, which indicate the standard deviation of settings averaged over the three observers. Clearly, observers were able to localize the target with higher precision than the disk separation independently of SOAs. The transition model with stochastic variation predicts the standard deviation of 15.6° for the result at 180 ms SOA when the original function has a standard deviation of 4.2°, which value is the average of the three observers. This prediction is much larger than the actual average standard deviation of 7.6° at that SOA. This supports the smooth shift of attention under the assumption that the perceived location of the tracked target corresponds to the center of visual attention.

A question will arise if we accept that the center of attention determines the perceived target localization or vice-versa. The question is why the spatial extent of attentional facilitation is broader than the localization precision of the target. One possible answer is that the spatial extent of attentional facilitation is controlled independently of the center of attention. It has been reported that the extent of attention changes dependently on the tasks or stimuli (Eriksen & Murphy, 1987; Ikeda & Takeuchi, 1975; LaBerge, 1983). To interpret such changes, a zoom-lens-like mechanism of the attention extent was hypothesized (Eriksen & Murphy, 1987). In present experiments, spatial distribution of the possible probe locations may have changed the extent of attention. It is possible that the observer changed the spatial extent of attention to cover the probe range efficiently. To examine the influence of probe ranges, we compared spatial tunings in the three conditions, across which probe ranges differed. The probe location covered ±135° in the condition in Experiment 1, ±75° in the slow speed condition, and ±165° in the large displacement condition. The space constants, sigmas of the Gaussian function fitted to the averaged data was 61°, 41° and 63° (average over all SOAs) for the original, slow speed and large displacement conditions. Spatial extent of the attention effect tends to become large with increased range of probe location. This supports the presumption that the observer changes the spatial extent of attention to coverthe probe range while keeping the center of attention on the tracked object.

In summary, our results revealed that attention moves smoothly, at least functionally, with a tracked moving object, predicting its future location.

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