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Spatial Spread of Visual Attention while Tracking a Moving Object

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We conducted three experiments to investigate the spatial spread of visual attention. In Experiment 1, we measured the contrast sensitivities at various locations (spatial sensitivity function) relative to the moving target that the observer attended to track in an attentive tracking display. A probe was presented at a distance from the target at a location randomly chosen from within a certain range. The range of probe presentation location varied to examine whether the observer changes the area of attention to cope with this range. The results show that the probe range influenced the shape of spatial sensitivity function. The change in shape of this function suggests that the observer covers a wider area with attention for large probe ranges than small probe ranges. In the following experiments, we investigated the effect of the distance between the tracking target and a probe at a fixed location relative to the target (Experiment 2), or between the target and the center of a probe range of fixed size (Experiment 3). Since the relative probe location in a session was fixed in the experiments, the observer would pay attention to the target and probe locations independently of the relative distance if he/she could focus attention at multiple locations. Spatial sensitivity functions obtained in Experiments 2 and 3 showed that this was not the case. In both experiments the sensitivity to the probe decreased with increase in the relative distance as in Experiment 1, where the probe was presented at a location randomly chosen within each range. This indicates that attention cannot be divided among multiple locations, at least under the present experimental conditions. We will discuss a possible interpretation of the present results with a limited attentional resource and its spatial distribution.

Key words: visual attention, tracking, zoom lens, sensitivity, spread of attention, split attention

1. Introduction

Our visual system receives massive amounts of information continuously, but does not process all information equally. The visual attention allows us to prioritize in the processing of visual information of a particular location or an object. How attention selects information is one of the most important questions of vision research. The selection is critical for appropriate action when predators or prey are surrounding, or when driving a car these days. We focus in this study on how attention spreads over the visual field. Several studies have suggested that attention spreads spatially and its size varies like a zoom lens.[1,6,7,16] Typically, the attentional facilitation was highest at a location where the observer attended, decreasing with distance from that location, and the spatial spread of the facilitation effect varied depending on stimulus conditions.[4,13,14,18] The concept of limited resource of attention is also related to spatial spread of attention. If there is a limit of attentional resource, size of spatial spread and degree of attention should be correlated. According to this hypothesis, we expect a stronger effect of attention when attending on a smaller region and weaker effect when on a larger region.[10] However, a zoom lens metaphor of attention may be too simple. Some studies suggest that attention may be split into more than one location.[2,5,8,11] For example, Kramer and Hahn have reported that performance of a task to compare targets presented at separate locations has not been influenced by distracters presented between the targets. This suggests that the observers are able to divide attention between the two target locations, which allows them to ignore distracters in between. However, the tasks used in previous experiments are rather complex.

To investigate how attention spatially spreads and examine whether attention can be divided in a simple condition, we conducted three experiments in a task to detect a flashed probe. To control attentional state we used a task of tracking a moving target. The tracking was assigned as the primary task and detecting the probe as the secondary task. If the visual system can divide attention spatially, the system can execute two tasks at different locations independently of the distance between those locations. If, on the other hand, the visual system cannot divide spatial attention, it may control attentional spread to achieve the best performance for the two tasks by shifting the center and adjusting the spatial extent. One possible way of controlling attention is to move the center to the location of the primary task while extending the area to cover the location of the secondary task.[18] Consequently, the performance of the secondary task decreases with increase in the distance between the two locations in this case.

We measured contrast sensitivity at various locations relative to a moving object tracked by attention without eye movements, in order to examine these sensitivity changes as a function of spatial location relative to the tracked object. In Experiment 1, we measured sensitivity to a probe presented at various distances from the tracked object. If attention spreads across the visual field around the location of the tracked object, we expect that the sensitivity will decrease gradually with the distance from the location as reported previously.[4,18] In this experiment, we used different ranges of probe locations to investigate whether attentional spread varied with the area from which the observer has to gather information. If the spatial extent of attention varies with the field size to be covered, the spatial sensitivity function for the probe detection will change with the size of the area where the probe is anticipated to appear. In Experiment 2, we measured sensitivity to the probes also presented at various distances from the tracked object, however, in this experiment the probe location was fixed in a session so that the observer knew exactly where the probe would appear relative to the tracked object. This was to examine whether attention can be paid to the secondary task independently of the distance from the primary task location. When the probe location is known, the observer may be able to attend the locations equally, independently of the distance from the tracked object, if attention can be spatially divided. In Experiment 3, we varied the probe locations within a given presentation range as in Experiment 1, while different center locations of the range were used under different conditions. This was to investigate spatial spread of the attention around the center of the secondary task. If the attention can be divided into the locations of the primary and the secondary tasks, sensitivity should peak at the center of the probe range. If, on the other hand, attention spreads around the tracked disk independently of the location of the probe, the sensitivities to the probe under all probe conditions should follow a single function with a peak at the tracked disk.

2. Experiment 1

The purpose of Experiment 1 was to investigate the effect of the range of the locations of the secondary task. We expect that the spatial extent depends on the range of the stimulus presentation locations of the secondary task if the spatial extent of attention varies according to the tasks required as a zoom lens metaphor suggests. We also expect that sensitivity at the peak is higher with smaller range of secondary task locations according to a limited resource model of attention.

An ambiguous apparent motion display (Fig. 1) was used to isolate the effect of attention from all other effects of physical stimulation on the display.[3,17–20] Alternation of the two disk frames [Figs. 1(a) and 1(b)] provides ambiguous motion information, either clockwise or counterclockwise, and the observer can alternate the motion direction by attending to see whichever direction is chosen. Further, the observer can see apparent motion of one disk moving in a selected direction by advancing its location step-by-step from frame to frame as shown in Fig. 1(c) without eye movement [note that Verstraten *et al.* (2001) confirmed eye fixation during this type of attentive tracking[20]]. 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 the perceived movement. Shioiri *et al.* showed that sensitivity peaks near the apparent path of the tracked disk during inter-frame-intervals [Fig. 1(c)]. Sensitivity measurements at variable locations, therefore, would reflect the location and spatial extent of visual attention.[18)]

2.1 Method

The attentive tracking stimulus was presented with six disks alternating between two sets of positions with a blank

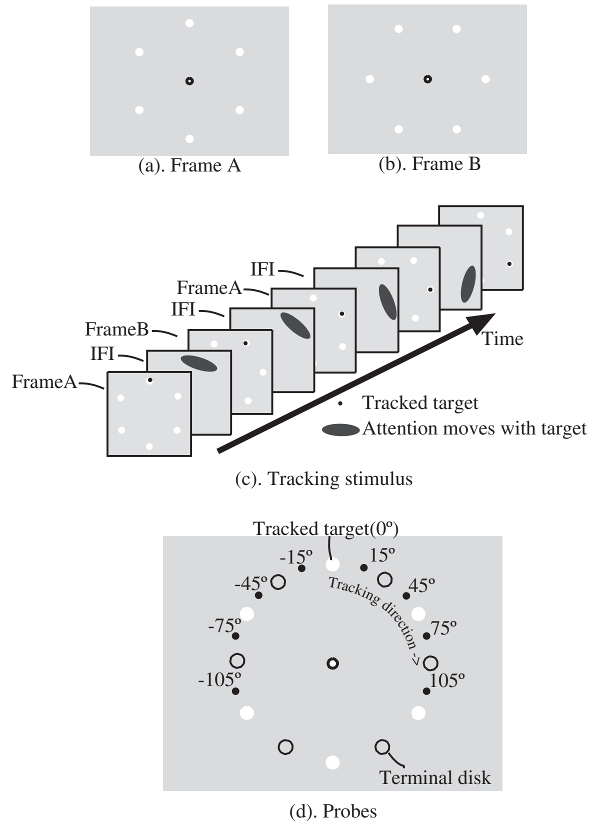

Fig. 1. Alternation of frame A (a) and frame B (b) provides an ambiguous apparent motion display. (c) Attention moves with tracking of the target. (d) A probe was presented during a blank frame period and the location varied from trial to trial (see text).

frame (Fig. 1). While fixating on the center, observers tracked one of the six disks. A small brief flashed luminance decrement was used as a probe stimulus that the observer was asked to detect. The probe had 0.7° diameter and was displayed on the middle timing of a blank frame between the consecutive disk frames. It was located on the orbital path of disk rotation and the center of two adjacent disks. We used four different ranges of probe presentation location: ±15°, ±45°, ±75°, and ±105°, which are referred to as 2-point, 4-point, 6-point, and 8-point conditions, respectively. The probe was presented at only one location in a trial. Under the 2-point condition, it was presented at one of two locations (+15° or −15°). Under the 4-point condition, similarly, the probe was presented at one of four locations (+45°, +15°, −15° or −45°). It was presented in a similar manner under 6 and 8-point conditions. The disk luminance was 51 cd/m^2 on the background of 28 cd/m^2 [Fig. 1(d)]. The disk diameter was 1.1° and the diameter of the disk array circle was 14°. The viewing distance was 60 cm. The stimuli were generated on a color graphic display of 640 × 480 pixels resolution (66.7 Hz non-interlace) controlled by a Macintosh Quadra 950 computer.

The presentation duration of each disk frame was nominally 15 ms (one refresh of display) and ISI was 105 ms (seven refreshes). This corresponded to angular velocity of 0.7 rounds per second. In the initial five cycles of disk frame alternation (for 1.09 s from the rotation start), a target disk to be tracked was indicated by highlighting it with a red marker. The target was identical to the other disks after the disappearance of the marker and, therefore the target was defined only in the observers' visual system. The observer had still tracked the target disk after the red marker disappeared. Contrast sensitivity was measured with the method of constant stimuli, where probe contrast was 0.11, 0.17, 0.23, 0.29, or 0.34, chosen randomly in each trial. The probe was darker than the background and the contrast was Weber contrast (decrement/background) following a previous report.[18] The probe was presented at the middle timing of a blank frame, two cycles after the marker disappearance. Three cycles after the probe presentation, the display stopped with the red marker at the target disk. The observers responded whether they saw the probe or not. When they noticed that they had lost the target, checking the red marker at the final display, the trial was cancelled and a replacement trial was added.

The probe location range was constant throughout a session and the observer had knowledge of it. Four observers with normal or corrected-to-normal visual acuity participated (20 of 20 trials). They had training sessions of attentive tracking without the secondary task until their performance of tracking became 100%.

2.2 *Results*

Figure 2 plots the contrast sensitivity as a function of probe location for each probe range condition. The contrast sensitivity was reciprocal of the contrast threshold, which was the contrast for 50% of probe detection. The results show that sensitivity peaks at +15°, where the target was supposed to be located at the time the probe was presented if the visual system interpolates linearly (against rotation angle) between the target disks sequentially presented. The shape of the sensitivity function varies depending on the probe range. The highest sensitivity was found under the 2-point condition and the lowest under the 8-point condition. The spatial extent also seems to vary among conditions. It appears to be wider under the 8-point condition than under the 6-point condition, although spatial extent cannot be evaluated under the other conditions.

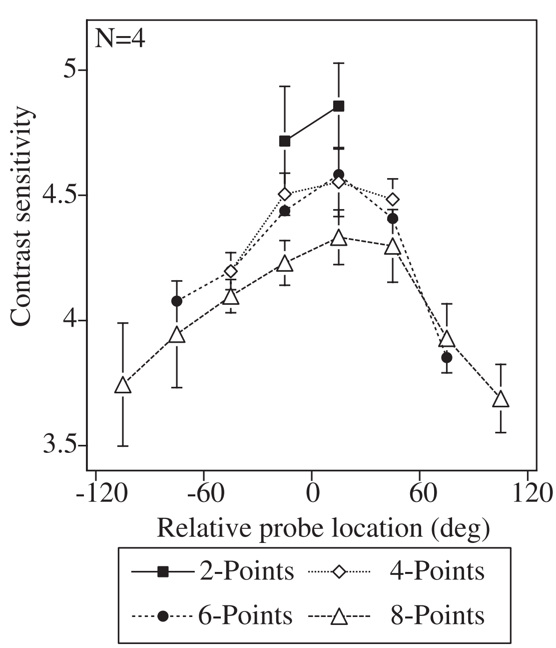

Fig. 2. Results of Experiment 1. Contrast sensitivities as a function of relative probe location. Each symbol stands for the probe range condition.

The results that spatial extent of attention changes with possible probe locations are consistent with the prediction from the presumption that the visual system controls the degree and extent of a limited attentional resource adapting to the given tasks. The limited resource model predicts that the visual system may narrow the extent of attention to obtain high sensitivity when the probe range is small. Similarly, the visual system may widen the extent of attention, but with low sensitivity, when probe range is large.

3. Experiment 2

The purpose of Experiment 2 was to investigate whether attention can be focused at multiple locations simultaneously. If we can manage to focus attention on two locations simultaneously and completely independently, the effect of attention for probe detection could be constant no matter how far apart the two locations are. In this case, the location of the secondary task relative to the location of the primary task should not influence the performance of the task as long as the observer knows the location [Fig. 3(b)]. On our experimental paradigm, we expect that contrast sensitivity is constant across conditions with different distances between the probe and target locations. This contrasts with the bell-shaped function obtained in Experiment 1, where the observer had to pay attention to a certain range to detect the probe. On the other hand, if we cannot focus attention at multiple locations (i.e., single attentional focus), the performance of the secondary task would be determined by the attentional state mainly adjusted to the primary task [Fig. 3(a)]. In this case, we expect gradual decrease of contrast sensitivity of the probe with the increase in distance from the tracking target.

3.1 *Method*

Experimental procedures were the same as those in Experiment 1 except probe conditions. We measured contrast sensitivities at several locations relative to the tracking target as in Experiment 1. The difference from Experiment 1 was that the probe location was fixed throughout each session so that observers knew where to attend to detect the probe. For example, under the 15° condition, the probe was always presented at 15° ahead of the tracking target. The apparatus, stimulus, and procedure were the same as those in the previous experiment. Five new observers with normal or corrected to normal visual acuity participated.

3.2 *Results*

Figure 4 shows contrast sensitivity as a function of the probe location relative to the tracking target. The result

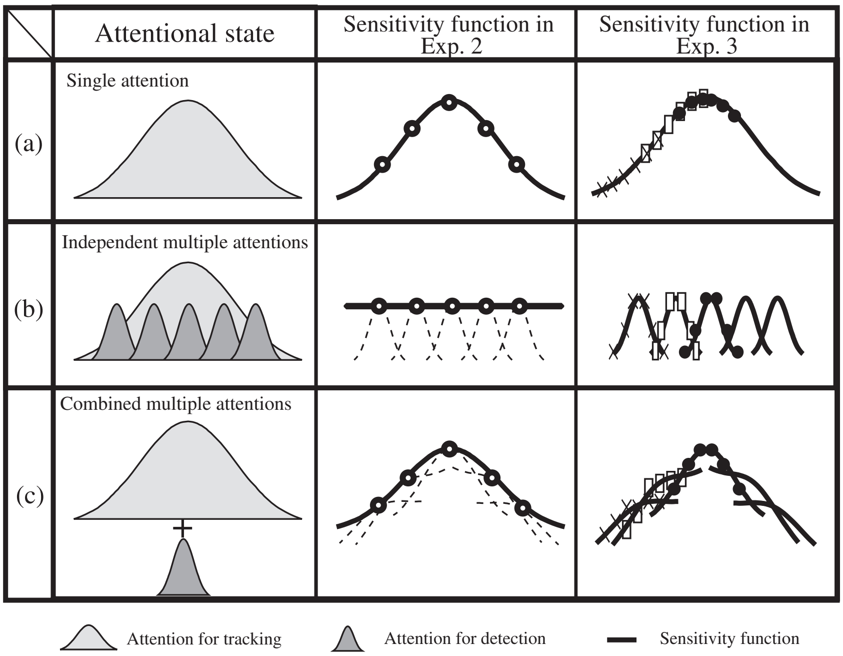

Fig. 3. Prediction of sensitivity functions based on a model of attentional state. Light gray areas indicate the attentional state determined by target tracking and dark gray areas indicate that determined by probe detection. Thick lines show the sensitivity distribution expected in Experiment 2 and 3 in each case. (a) With a single bell-shaped function of the attentional state, the sensitivity function under the condition of Experiment 2 will be a bell-shaped function and the function in each probe center condition of Experiment 3 will be a different part of a single bell-shaped function. (b) With two separate functions of the attentional state for the target and probe, the sensitivity function of Experiment 2 will be a flat function. The functions of Experiment 3 will be a bell-shaped function with different peak locations. (c) If the effect of the two functions is combined, the sensitivity function under the condition of Experiment 2 will be a bell-shaped function and the functions in different probe centers under the condition of Experiment 3 will be functions that are the sum of the two functions.

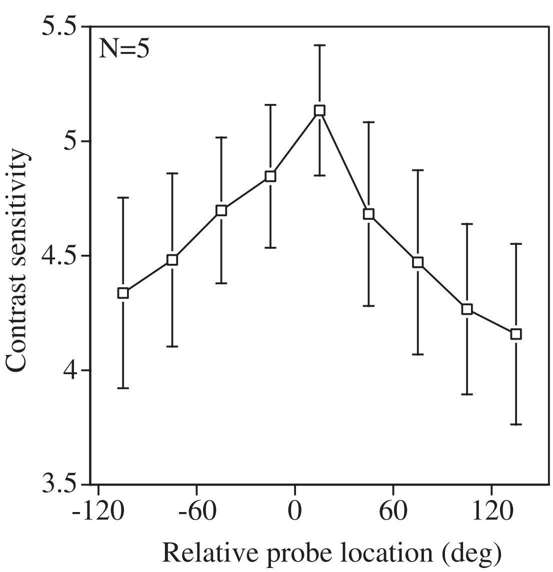

Fig. 4. Result of Experiment 2. Contrast sensitivities as a function of relative probe location.

shows that the contrast sensitivity function peaks when the probe is presented at the apparent target location and decreases with the distance from the location. This indicates that the contrast sensitivity varied depending on the probe location even though the observer knew where the probe would be presented. Attention seems to focus on the target disk instead of splitting into the probe and target locations. This result is consistent with the presumption that attention cannot be focused on multiple locations simultaneously.[9,15) However, attention for the primary and the secondary tasks may not be independent. If the attentional resources allotted for the two tasks are integrated to determine the threshold of the probe detection, the sensitivity function is expected to be bell-shaped [Fig. 3(c)]. We conducted the next experiment to investigate this issue.

4. Experiment 3

The results of Experiment 2 suggest that the distance from the primary task influences the degree of attention paid to the secondary task. However, this does not imply that attentional state at a location of secondary task is fully determined by the distance from primary task location. If, for example, attentional resources allotted for the two tasks are integrated somehow at each location for probe detection, the sensitivity function will possibly be a bell-shaped function. In Experiment 3, we measured sensitivity functions with the probe presented within a certain range as in Experiment 1. The size of the probe range was fixed while the center of the range varied.

If a single bell-shaped function determines the probe threshold, the sensitivity function under each probe condition should be a part of that function [Fig. 3(a)]. If, on the other hand, the addition of the resources for tracking and the probe detection determines probe threshold, the sensitivity function should deviate from the bell-shaped function with the greatest difference at the center of the probe range [Fig. 3(b) or 3(c)]. This prediction includes the spatial split of attention and the relative amount of the contribution to the probe detection.

4.1 Method

Experimental procedures were the same as those in Experiments 1 and 2 except for probe conditions. As in the previous experiments, we measured contrast sensitivities at several locations differing in distance from the tracking target. The most important difference was the range of probe

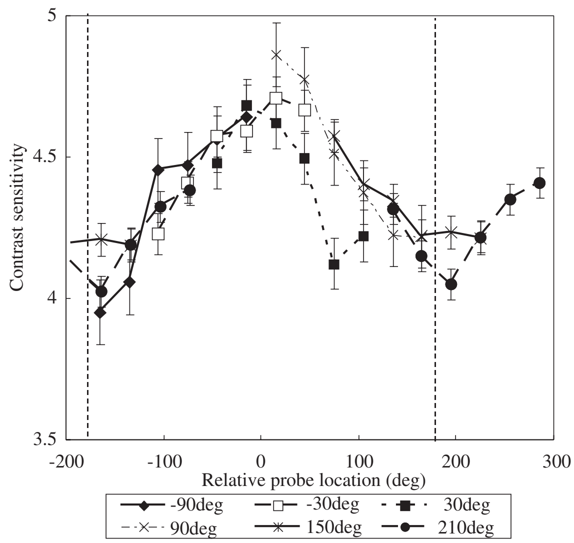

Fig. 5. Results of Experiment 3. Contrast sensitivity as a function of probe location. Each symbol stands for each probe range center condition. The dashed vertical lines at $-180°$ and $+180°$ indicate that the two locations are the same.

presentation. We used six probe sets with the range same as the 6-point condition in Experiment 1 while the probe center location varied. The range condition was either $-165°\sim-15°$, $-105°\sim45°$, $-45°\sim105°$, $15°\sim165°$, $75°\sim225°$, or $135°\sim285°$ with a center of $-90°$, $-30°$, $30°$, $90°$, $150°$, or $210°$. The same five observers as in Experiment 2 participated. The apparatus, stimulus, and procedure were the same as those in the previous experiments.

4.2 *Result*

Figure 5 shows the contrast sensitivity as a function of probe location. Different symbols stand for the different probe set conditions. The vertical dashed lines indicate $\pm180°$ locations. The data outside of these lines are as replica of some of the data between the lines. For instance, $+195°$ is the identical location as $-165°$ because of the stimulus is circular array. The results show that all sensitivity functions roughly follow a single function peaking at $+15°$ that is the apparent target location. The results suggest that the attention distribution is mainly determined by the primary task. Although sensitivity deviates slightly among the conditions our quantitative analysis does not support that this is the result of the combination of attention allotted to the two tasks (see §5).

5. Discussion

The results of Experiment 1 showed that sensitivity at the target location was higher and spatial extent of the attentional facilitation was smaller when the probe range was narrower. This can be explained by a model with limited attentional resource. Attention focuses on the target sharply to increase sensitivity there when one has to detect visual events in only a small area around the target to track. On the other hand, attention focuses broadly but with lesser degree, when one has to detect events from a larger area. These are consistent with the presumption that spatial spread and the degree of attention are controlled by a limitation of the total amount of attentional resource. The visual system may allocate the limited attentional resource in order to perform given tasks efficiently.

The results of Experiment 2 showed that sensitivity to the secondary task depended on the distance from the location of the primary task given even though the observer knew the probe location. This suggests that attention cannot be given to multiple locations, being consistent with a zoom lens model of controlling attention. The results of Experiment 3 supported this presumption: they showed that distance from the target location is the main determinant factor of sensitivity to probes. The question we ask here is whether a zoom lens model with a limited resource interprets the results from the three experiments. The model explains three main findings: first, the relationship between spatial spread and sensitivity found in Experiment 1; second and third, the model of a single attention focus explains the bell-shaped sensitivity functions found in Experiments 2 and 3.

There is an additional prediction of the model related to the difference between Experiments 1 and 2. It is possible that the most extreme position of a probe range determines the spatial extent of visual attention. In this case, the model predicts that sensitivity at a location in Experiment 2 is similar to that at the same location under the probe range condition either of whose extreme locations is the same as that location. This is because the most extreme position in Experiment 2 is the probe location chosen for a condition. Comparison of the correspondent data in Figs. 2 and 4 revealed that sensitivity is higher in Experiment 2. This is not consistent with the simple prediction from a zoom lens model. Asymmetrical distribution of attention may explain the results. There is only one probe location behind or ahead of the target in Experiment 2. A larger portion of attentional resource may be allotted to the location with asymmetrical distribution between behind and ahead of the target, where the probe appeared in both sides of the target. It is not necessary to assume symmetric function. Indeed, the sensitivity functions from Experiment 1 show some asymmetry, skewing to the moving direction of the target to make sensitivity reduction steeper ahead of the target. Similar tendency is seen in the previous report,[18] but careful investigation is required to examine the issue, which remains for future investigation.

For quantitative predictions, we estimated sensitivity functions with a zoom lens model under a limited resource condition. We assume that the attentional distribution under each of the different conditions is approximated by a Gaussian function. We assume that the width and amplitude of a Gaussian function (standard deviation) represents attentional width and degree of attention, respectively. Although the results show a slight asymmetry, we do not use an asymmetrical function because we prefer to make the model simpler and also because we are not sure how real the asymmetry in the results is. Since the effects of the probe conditions are similar in both sides of the target, we believe that using an asymmetrical function would not change our

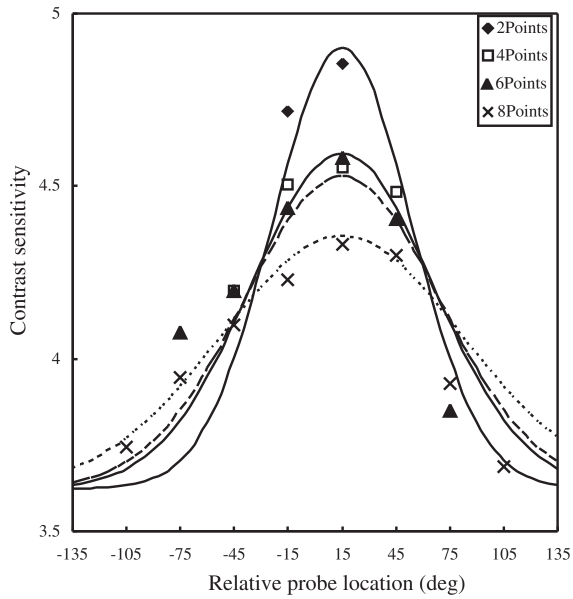

Fig. 6. Prediction of the results from a zoom lens model with a limited resource. The curves are Gaussian functions fitted to each data set of probe conditions with restrictions that area under the function was constant and the peak was at 15°. The constant area, which corresponds to a limited resource, predicts the result well.

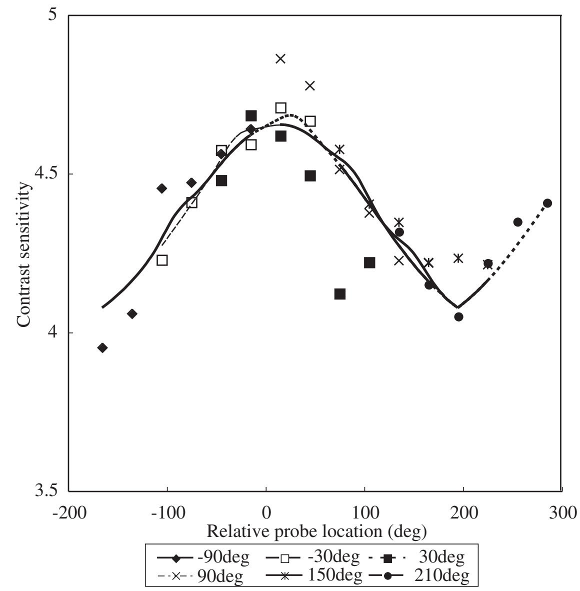

Fig. 7. Prediction of the results based on a model of two attentional foci with constant total resource. The curves show functions fitted to each probe condition as a sum of two Gaussian functions. One Gaussian function expresses attentional spread determined by the primary task. The center of the function was fixed at 15°. The other function expresses attentional spread determined by the secondary task. The center of the function was at the center of the probe ranges. The standard deviation and the amplitude were the same for functions for all probe ranges. The sums of the areas of the two functions were constant while the relative amount of the areas was a fitting parameter.

general conclusions. According to the model with a constant resource, we assume that area of the function was the same among different conditions. We estimated the spatial extent (the standard deviation) and the amplitude of Gaussian functions in terms of a least squares procedure. Restrictions of the estimation are the fixed minimum (the value at infinity) and the area of the function for all probe conditions. The former represents the same sensitivity at the location without attention and the latter represents a constant limitation of attentional resource. These values were the average values of the Gaussian fitting to the 6- and 8-point conditions without any restriction. The purpose is to examine how well the estimation using the model can explain the results.

Figure 6 shows the Gaussian functions that approximate the results of Experiment 1 in each probe range condition under the assumption of the constant resource. The spatial extent of the 8-point condition is wider than that of the 4- or 6-point condition. On the other hand, the amplitude estimated in the 2-point condition is the highest among the conditions, and amplitude becomes lower with increase in the size of probe range. These features are consistent with the results and support the presumption that the visual system controls the degree and extent of the limited attentional resource adjusting to perform given tasks efficiently.

We used a similar estimation procedure to examine whether two attention foci with different distributions are required to explain the results of Experiment 3. In this approximation, we assumed that a limited resource is divided into two attentional distributions approximated by Gaussian functions. The ratio of one to the other can be varied while the sum of those areas is constant under a limited resource model. We define one Gaussian function for tracking (primary function) and one for probe detection (secondary function). Further, we assumed that the addition of the two functions determined the sensitivity to probe at each location as the model in Fig. 3(c). When the primary function can predict the sensitivity functions under all probe conditions, this indicates that attention is not divided among multiple locations. In contrast, the ratio of secondary function indicates the amount of the divided attention for probe detection. Although a single function has difficulty to explain all of the data in Fig. 5, this does not imply that two functions with a limited resource explain the data better. The ratio of the two functions for best fitting to the data provide information on how much effect of attentional division is required to explain the data variation among the probe conditions.

The center of the primary function is fixed at the target location and that of the secondary one is fixed at the center of each probe condition. Spatial extent, amplitude and area of the two functions are varied to fit the data while they are the same under all probe conditions. From a limited attentional resource, the sum of the areas of the primary and secondary functions is constant.

Figure 7 shows the sum of the Gaussian functions that approximate the results under each condition with the primary and secondary functions. The ratio of the area of the secondary function against the sum of the areas of the two functions was estimated as 0.7%. Therefore, the possible contribution of the dividing attention is as small as less than 1%. This leads us to conclude that it is not necessary to consider a secondary function with focus on a location different from that of the primary one to explain the results in Experiment 3, and supports the conclusion that attention cannot be divided to focus on more than one location.

It should be noted that the present results are based on rather difficult primary task and the difficulty of the tasks required may change the results. In the present experiments, the attentive tracking with the speed used in the experiment required great effort, particularly for naive observers. Indeed, there is a report that suggests the task difficulty influences spatial distribution of attention.[12] If this applies to dual task experiments such as ours, easier tracking may increase the effect of attention allotted to probe detection, sharing more resource to the task. The present results, therefore, do not rule out the possibility of division of attention when easier tasks are required. In general, however, they support the presumption that visual attention acts like a zoom lens, changing the center and extent of attentional focus.

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