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Voluntary and stimulus-induced attention detected as motion sensation

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Abstract. Attention may be drawn passively to a visually salient object. We may also actively direct attention to an object of interest. Do the two kinds of attention, passive and active, interact and jointly influence visual information processing at some neural level? What happens if the passive and active attentions come into conflict? These questions were addressed with the aid of a novel psychophysical technique which reveals an attentional gradient as a sensation of motion in a line which is presented instantaneously. The subjects were asked to direct attention with voluntary effort: to the side opposite to a stimulus change, to an object with a predetermined colour, and to an object moving smoothly. In every case the same motion sensation was induced in the line from the attended side to the unattended side. This voluntary attention, however, can easily and quickly be distracted by a change in the periphery, though it can be regained within a period of 200 to 500 ms. The results suggest that the line motion can be induced in voluntary (top-down) as well as stimulus-driven (bottom-up) situations, thus indicating the truly attentional nature of the effect, rather than it being some kind of retinotopic sensory artifact or response bias. The results also suggest that these two kinds of attention have facilitatory effects acting together on a relatively early stage of visual information processing.

1 Introduction

It has been shown that focal attention facilitates performance in perceptual tasks (Eriksen and Hoffman 1972; Jonides and Yantis 1988; Kröse and Julesz 1989; Maylor 1985; Nakayama and Mackeben 1989; Posner 1980; Posner et al 1982; Sagi and Julesz 1986; Sternberg and Knoll 1973). With focal attention, for example, reaction time becomes shorter in detection tasks (Posner 1980; Posner et al 1982), as well as in various kinds of discrimination task (Nakayama and Mackeben 1989; Sagi and Julesz 1986).

What is unknown as yet is at what level of information processing this facilitation occurs. One possibility is that attention has no effect on the early processes of vision, but has facilitatory effects on later cognitive processes (Deutch and Deutch 1963). Alternatively, attention may directly facilitate early visual processing (Broadbent 1958; Hillyard 1985). Closely related to this issue is another interesting aspect of attention: it can be directed in a purely active, voluntary, fashion or in a purely passive, stimulus-driven, fashion. Are these two kinds of attention shift intrinsically related in that they interact at some level of visual information processing? We now report a set of experiments which strongly suggest that voluntary attention as well as stimulus-induced attention can facilitate early visual processing, at an early enough stage so that it can induce an illusory sensation of motion.

2 General methods

2.1 *Subjects*

Four subjects participated in the experiments; three were the authors (SM, OH, SS) and the other was a naive subject (MT).

2.2 *Apparatus and stimuli*
A microcomputer (NEC PC-9801RA) was used for stimulus presentation and encoding the subjects' responses. The visual stimuli were displayed on a colour CRT display; the frame rate was 60 Hz. The fixation point was a small spot of white light (0.15 deg × 0.15 deg). A horizontal white line (0.15 deg wide) was used as the probe for detecting the gradient of attention. The luminance of these stimuli was 61 cd m^{-2}. The stimulus for cueing attention varied across the three experiments (see below). These stimuli were presented on a dark background (luminance <0.2 cd m^{-2}).

2.3 *Procedure*
The subject sat in front of the CRT display in a dark room. The observation distance was 57 cm. The subject's head was constrained by a chinrest. Eye fixation was monitored in selected sessions of experiments with an infrared eye-movement monitoring system (RMS Hirosaki, R-21C-A).

The subject initiated each trial by pressing a key, which led to the appearance of the fixation point. The subject was instructed to keep fixating on the fixation point throughout the trial. A cue stimulus then appeared at either one of two possible locations, and after a cue lead-time the probe line was instantaneously presented between the two cue locations. The subject reported, by pressing one of two keys, in which direction the line appeared to be drawn [two-alternative forced-choice (2AFC) task]. Within a single block of experiments the following parameters were randomized across trials with equal probabilities: (i) the cue lead-time and (ii) the location (left/right) of the cue stimulus (the flashed cue in experiments 1 and 3; the cue with the attended colour in experiment 2). Twenty trials were obtained for each cue lead-time.

2.4 *Data analysis*
We calculated for each cue lead-time the percentage of trials in which the motion was perceived from the side of the target cue, and plotted it against the cue lead-time.

3 Experiment 1: 'Pro-stimulus' and 'anti-stimulus' attention
Our first experiment is illustrated in the top diagrams of figure 1. After flashing of one of the boxes, a line was presented between the boxes. We had found previously that the line, which was presented instantaneously, appeared to be drawn from the flashed side to the opposite side (Hikosaka et al 1991). Correlating this observation with another experiment, in which temporal order judgment was used, indicated that the illusory motion could be explained by local facilitation of visual information processing due to the light flash, which may reflect stimulus-induced attention (Miyauchi et al 1991).

Attention can, however, also be voluntary. Can such voluntary attention also be detected by the line-motion method? This is the question which led us to experiment 1. Unlike in the previous studies (Hikosaka et al 1991; Hikosaka et al, in press) in this experiment we asked the subject to direct and hold his attention voluntarily, without moving his eyes, to the flashed box in the first block of trials (pro-stimulus attention) and to the box opposite to the flashed one in the second block of trials (anti-stimulus attention). In both sets of experiments, we manipulated the cue lead-time, ie the delay between the flash and the onset of line presentation, to assess the rising time course of attentional effects.

3.1 *Stimuli and procedure*
While the subject fixated a centre spot, two dark-gray open boxes appeared in the upper visual field. One of the boxes, randomly chosen, was flashed (filled with white light) for 17 ms. After a randomized time delay (cue lead-time; 0 ms to 2176 ms, in 13 steps), a white probe line was presented between the two boxes. The subject was

required to direct his attention to one of the two boxes as quickly as possible; to the flashed box in the first experiment (figure 1a) and to the non-flashed box in the second experiment (figure 1b), as indicated by filled arrows in the top diagrams of figure 1. The subject's task in these and the following experiments was to report the side from which the line appeared to be drawn (a 2AFC task).

The pro-stimulus condition and the anti-stimulus condition were carried out as independent sessions, always in this order, for each subject. Each session of experiment consisted of 260 trials (20 trials × 13 steps of cue lead-time).

The boxes were 0.5 deg × 0.5 deg, separated from each other by 4.9 deg, and were located 4.1 deg above the level of the fixation point. The luminance of these stimuli was 61 cd m^{-2}. In a selective set of this and the later experiments, we recorded eye movements and aborted those trials in which gaze shifts (greater than 0.5 deg) were detected. The data obtained with this procedure were nearly identical to those in the original experiments, thus negating the possibility of artifact related to eye movements.

3.2 *Results and discussion*

The results are shown in the bottom plots in figure 1a (the pro-stimulus condition) and figure 1b (the anti-stimulus condition) where the percentage of line motion from the flashed side is plotted against cue lead-time for each subject.

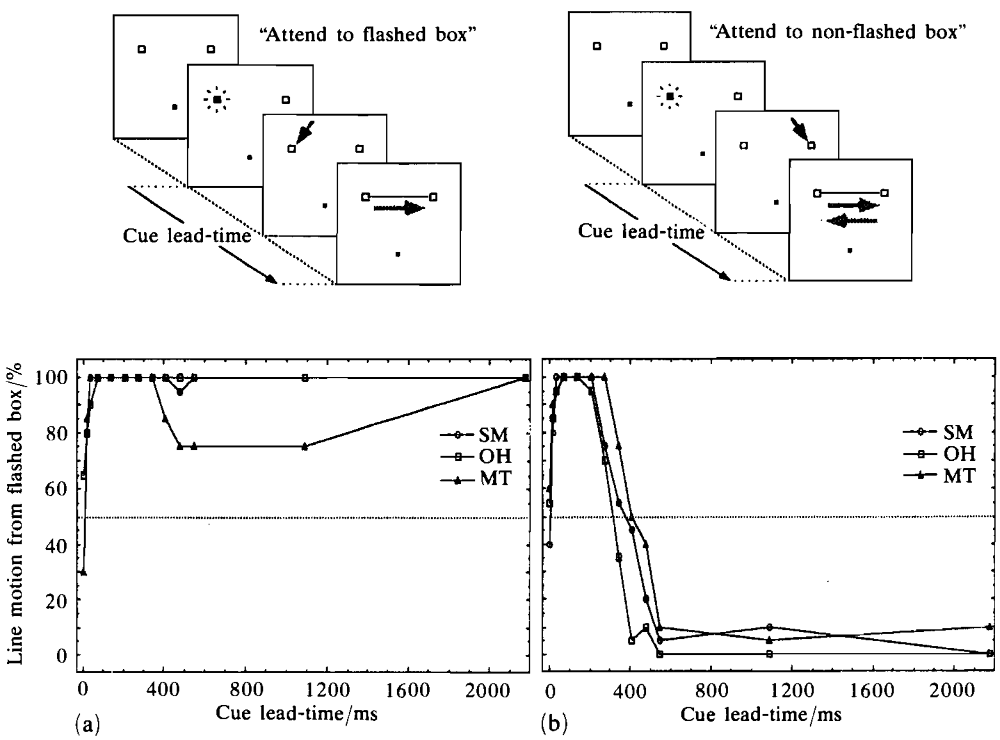

Figure 1. Pro-stimulus and anti-stimulus attention (experiment 1). (a) Line motion induced by pro-stimulus attention. While the subject fixated a centre spot, one of two boxes was flashed. The subject was required to direct attention to the flashed box as quickly as possible. After a randomized time delay (cue lead-time), a probe line was presented between the two boxes. The shaded arrow indicates the perceived direction of motion. (b) Line motion induced by anti-stimulus attention. The subject was required to direct attention to the non-flashed box. The percentage of trials in which the line was perceived to be drawn from the flashed side is plotted against cue lead-time for the two conditions in the bottom graphs. Data from three subjects, two experienced (SM, OH) and one naive (MT), are superimposed. The chance level is 50% (indicated by a dotted line).

Let us first see the results in the pro-stimulus condition (figure 1a, bottom). The probability of the motion sensation built up quickly as a function of cue lead-time, reaching its peak (100%) in about 50 ms. As we have suggested elsewhere (Hikosaka et al 1991; Miyauchi et al 1991), the illusory motion is most likely to be induced by local acceleration of visual information processing, thus reflecting a stimulus-induced attentional gradient.

Even with longer cue lead-times (2 s or longer), the motion was still perceived as being from the flashed box in most trials. We noted, however, that the motion sensation was weaker relative to that at shorter cue lead-times (<400 ms). In fact, the naive subject showed some deterioration in performance at longer cue lead-times. We suspect that the long-lasting effect was not caused by stimulus-driven attention, but rather by voluntary attention. This idea was supported by the results of the next experiment (experiment 2).

Now let us examine the results in the anti-stimulus condition (figure 1b, bottom). Interestingly, the direction of apparent motion was from the flashed side at shorter cue lead-times (<200 ms), as in the previous experiment. This was so even though the subject tried to attend to the unflashed side from the beginning of each trial. At longer cue lead-times (>400 ms), however, the direction of line motion was reversed: now the line appeared to be drawn from the non-flashed (attended) side. An intensive effort was required to obtain a complete reversal in this case. Because the stimulus situations were identical in the two cases—pro-stimulus and anti-stimulus attention—the difference in the direction of line-motion sensation should be created solely by the mental set of the subject. The voluntary reversal of attention is much slower to develop than is stimulus-induced attention, even though the effect on motion sensation is phenomenologically the same.

The primary object of attention in this set of experiments was location in space. However we often pay attention to a property of an object eg its shape or colour. Our second question was whether spatial attention can be invoked on the basis of such a specific visual attribute. In the next experiment (experiment 2) we addressed this issue.

4 Experiment 2: Attention directed to an object, based on a specific visual attribute

Our second experiment was designed to examine spatial effects of voluntary attention to an object which had a specific visual feature. For example, when an observer anticipates and is prepared for a red object, would he/she be able to shift attention quickly to such an object when it is presented together with various other objects? And would this kind of attention also lead to the same kind of line-motion effect, as the pro-stimulus and anti-stimulus cases in the previous experiment? We also wanted to see how this kind of effect of voluntary attention is related to that of the stimulus-driven attention in the visual field. These are the specific questions addressed in this experiment.

4.1 *Stimuli and procedure*

The stimulus and procedure are illustrated in the top diagram of figure 2a. While the subject was fixating a centre spot, two boxes (one red and one green) appeared simultaneously either in the upper or in the lower visual field (alternately across trials); the side at which the colours appeared was randomized across trials. The subject was required to direct his attention to the green box and maintain it through one block of trials (upper graph) and to the red box through another block (lower graph). Before each block started, the subject was instructed by the experimenter on which colour he should focus his attention. After a cue lead-time selected at random from 13 steps, the probe line was presented between the boxes. Each block of experiments consisted of 260 trials (20 trials × 13 steps of cue lead-time).

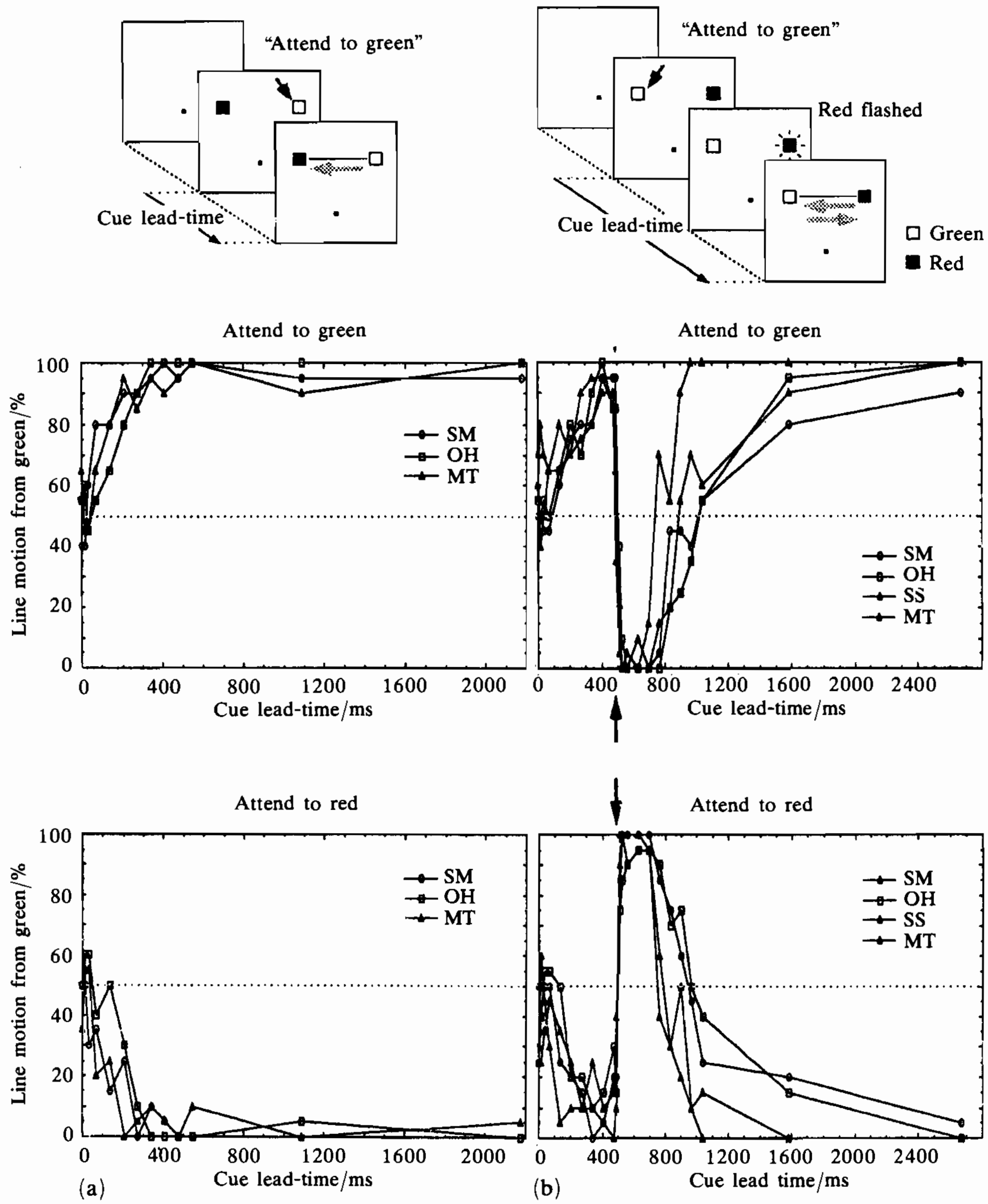

Figure 2. Attention directed to an object, based on a specific visual attribute (experiment 2). (a) Attention directed to a voluntarily selected object. Two boxes, red and green, appeared simultaneously at two positions randomly while the subject was fixating. The subject was required to direct and keep attention to the green box in one block of trials (upper graph) and to the red box in another block (lower graph). The percentage of trials in which the line motion was perceived from the green box was plotted against the cue lead time for each subject. Data from three subjects, two experienced (SM, OH) and one naive (MT), are superimposed. (b) Transient distraction by a flash. The only difference in this condition was that the box with unattended colour was flashed 493 ms after the onset of coloured boxes. The abscissae and the ordinates in the upper and lower graphs are identical to those in (a). The vertical arrows indicate the instant of the flash. Data from four subjects, three experienced (SM, OH, SS) and on naive (MT), are superimposed.

The boxes were 0.5 deg × 0.5 deg, separated from each other by 4.9 deg, and were located 4.1 deg above or below the level of the fixation point. The red and the green stimuli had been made equiluminant by employing the minimum-flicker technique for estimation of equiluminance (Wagner and Boynton 1972). This procedure was applied to each subject before the main experiment so that the luminances of the stimuli for the main experiment could be adjusted for each individual subject. As a result, the luminances of these stimuli varied across subjects (11.7 cd m^{-2} to 13.0 cd m^{-2} for the red; 14.3 cd m^{-2} to 15.1 cd m^{-2} for the green).

In another session (figure 2b), we used an additional manipulation: here stimulus parameters, procedure, and the subject's task were identical to those in the previous session, except that the unattended box was flashed for 17 ms (filled with white; the instant of flash is indicated by vertical arrows in the two graphs in figure 2b) after 493 ms from the onset of the coloured boxes (see figure 2b). Thus, the red box was flashed in the green-target trials (the upper graph of figure 2b), and the green box was flashed in the red-target trials (the lower graph of figure 2b). The purpose of this manipulation was to examine the effects of voluntary and stimulus-driven attention being in conflict. The cue lead-time was randomized in 23 steps; each experiment consisted of 460 trials (20 trials × 23 steps). The distracting flash was not presented when the cue lead-time was less than 493 ms.

These two sessions were carried out with each subject in this order.

4.2 *Results and discussion*

The results were highly consistent across naive and nonnaive subjects: motion of the line was perceived as being from the box with the target colour, whether it was red or green (compare the two graphs in figure 2a). However, the development of motion sensation was much slower than that evoked by a flash (see the graph in figure 1a): the motion effect started to appear at about 100 ms and was complete at about 400 ms, a time course consistent with that in the anti-stimulus attention experiment. The effect was completely reversed when the target was changed in the next block of the experiment, even though the stimuli were physically identical between the blocks (compare the two graphs in figure 2a), thus indicating the voluntary nature of the effect.

The same effect of motion sensation was maintained as long as the subject kept attending to the target box (figure 2a, top). However, this was true only when there was no sensory distraction. Attention could easily and quickly be distracted by flashing the non-target box (figure 2b, top). The line-motion effect was completely reversed for a period of 200 ms after the flash, and gradually returned to the target side, owing to the subject's intensive effort. Thus, voluntary attention could be reversed briefly but completely by a transient stimulus change elsewhere in the visual field.

5 Experiment 3: Object-bound attention

In all the experiments described above, the allocation of attention could be performed on a static retinotopic coordinate system, regardless of whether it was allocated in bottom-up or top-down fashion. What happens if the object is moving? Can attention follow a moving object, yielding the same visual motion effect?

For example, consider a situation where spots are rotating around a fixation point, as illustrated in the diagram at the top of figure 3. Further imagine that one spot is flashed and the rotation maintained as shown in the figure. If the motion sensation is based on the retinotopic gradient of attention, the motion would be expected to be perceived only from the original retinotopic position of the flash (from the right to the left in this case). If, instead, attention is object-bound so that it can be carried with the moving spot, the motion should appear always from the attended spot (from the left to the right). These were the specific predictions directly tested in experiment 3.

3.1 *Stimuli and procedure*

The stimuli and procedure are illustrated in the diagram at the top of figure 3. While the subject was fixating the central white cross (0.05 deg × 0.05 deg, 61 cd m^{-2}), a pattern of four blue spots (0.05 deg × 0.05 deg, 7.0 cd m^{-2}) appeared, rotating in counterclockwise direction (at a velocity of 60 deg s^{-1}). The angular distance between the fixation point and the spots was 2.5 deg. One of the spots was illuminated (in red, 11.5 cd m^{-2}) for a short period (765 ms), but thereafter was identical with the others. The four-spot pattern kept rotating and the subject was required to follow the flashed spot (indicated by asterisk in figure 3) with attention, but not with eye movement. After a randomized amount of rotation, the probe line was presented between the flashed spot and one of the adjacent spots. The flash occurred at one of the four corners of rectangular locations and the probe line was always horizontal with one side at the flashed spot. The whole experiment consisted of 80 trials (20 trials × 4 steps of cue lead-time).

5.2 *Results and discussion*

The results are shown in the graph at the bottom of figure 3. Naive and nonnaive observers were unanimous in that motion was seen from the attended spot. The sensation did not depend on the time or the angle of rotation after the flashing. This applied even when the line connected the attended spot and the original retinotopic location of flash. Thus, attention can be bound to a moving object, rather than to the

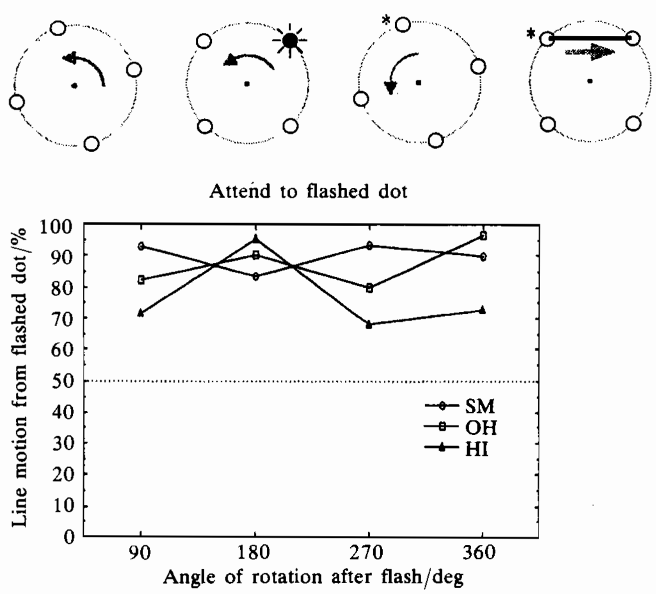

Figure 3. Attention following a moving object (experiment 3). The stimulus sequence in each trial is illustrated at the top (from left to right). While the subject was fixating at the centre spot, four blue spots appeared, rotating in the counterclockwise direction. One of the spots was flashed, but thereafter became identical with the others. The four spots kept rotating and the subject was required to follow the flashed spot (indicated by asterisk) with attention. After a randomized amount of rotation, the probe line was presented between the flashed spot and one of the adjacent spots. The percentage of trials in which the line motion was perceived from the attended spot is plotted in the graph against the angle of rotation over which the flashed spot travelled until the line was presented. Data from three subjects, two experienced (SM, OH) and one naive (HI) are superimposed.

retinotopic position of a transient stimulus change. Moreover, the motion sensation could not be attributed to any kind of retinotopically specific effect, such as temporal energy summation, masking, or apparent motion.

6 General discussion

To summarize, we found that voluntary attention produces an illusory sensation of motion in much the same way as does stimulus-induced attention. The results suggest that voluntary attention, like stimulus-induced attention, locally accelerates visual processing though with a slower rising profile. When these two types of attention come into conflict, voluntary attention is easily distracted by stimulus-induced attention, as suggested previously (Jonides and Yantis 1988).

A possible argument against this conclusion would be that the judgment of the line-motion sensation was highly subjective, and thus could be influenced by some kind of response bias. Such response bias, however, would not develop gradually as did the effect which we observed, because by the time the subject responded, the location of the box without the flash (the 'anti-stimulus' condition in experiment 1; figure 1b), or with the pre-instructed colour (in experiment 2; figure 2a) should have become obvious to the subject, regardless of the cue lead-time. Moreover, the response bias could not explain the highly consistent time course of 'transient distraction' by a flash of the unattended object in experiment 2 (see figure 2b).

The notion that the responses of the subjects reflected real facilitatory effects of spatial attention, not merely response bias, was supported by our other series of experiments. First, we found a similar kind of facilitation effect when two vertical short-bar targets instead of a horizontal line were presented after the attention cue was turned on or off, and the subject was asked to judge the temporal order of the two targets (Hikosaka et al, in press; Miyauchi et al 1991). The facilitatory effect, or the tendency of the cued target to appear earlier, as a function of cue lead-time was highly similar to that obtained in this study. Second, the illusory line-motion sensation can be cancelled by actually drawing the probe line from the opposite side (Miyauchi et al 1992). The asynchrony required for the cancellation was taken to be the local gradient of attention. Thus the obtained spatiotemporal characteristics of attention were similar to the result found in this study. These results in general would be much harder to explain by simple response bias or some other kind of cognitive factor. But they can be seen to be consistent with the assumption that the attention-driven motion-sensation is caused by local facilitation of early visual processing, thus causing asynchrony in inputs to motion detectors at a higher level.

Where in the brain might these effects be executed? Though this is a difficult question, there are at least two clues which may narrow down the candidate area. First, it is likely to be after binocular convergence. We have shown, using a dichoptic viewing task, that a visual stimulus presented to one eye produces the same illusory motion in the probe line presented to the other eye (Hikosaka et al, in press). The second clue is rather simple and was included in our paradigm; that is, the fact that attentional gradient could be reflected in the sensation of motion in a line. Since neural correlates of motion perception are found in the MT area in the monkey prestriate visual cortex (Newsome et al 1986; 1989; Zeki 1974), the simplest prediction would be that attention-induced illusory motion perception occurs at or before the MT, perhaps as early as V1, V2, or V3 (Van Essen and Maunsell 1983). Subcortical areas, such as the superior colliculus and pulvinar (Robinson and McClurkin 1989), may also be involved in the attentional mechanism. Neurons in the superior colliculus have binocular visual responses (Cynader and Berman 1972) which can be modulated by attention (Gattas and Desimone 1991) and are an important source of visual signals in the MT (Rodman et al 1990). These cortical and subcortical areas would also be involved in the neural circuits where interaction occurs between stimulus-induced attention and voluntary attention.

The results of our study lead us to suggest that local acceleration of visual information is the mechanism underlying attention. But this does not necessarily mean that the local acceleration occurs at the fixed spatial (or retinal) location. Our last experiment indicated that once attention is focused on a moving object it naturally follows the object rather than remaining at the attended location; attention is directed to an object rather than to space. Whether attention is object-based or location-based has recently been an issue of great interest. Our results provide evidence for the object-based nature of attention, consistent with other reports (Kanwisher and Driver 1992).

The motion-sensation effect which we report in this paper is very robust and sensitive both in time and in space domains. It thus seems to qualify as a powerful tool to investigate effects and interactions of voluntary and stimulus-induced attention at early levels of visual information processing.

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