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Update article

Visual attention revealed by an illusion of motion

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Summary

Attention is a mechanism to select sensory information. It is a modulatory process which normally cannot be observed as overt responses. A new psychophysical method using an illusion of motion perception allowed us to visualize the field of the magnitude of attention and its dynamic changes. Based on our experiments using this method we suggest that (1) both passive (bottom-up) and active (top-down) attention exert their effects on the early stages of visual processing, (2) active attention can quickly and briefly be replaced by passive attention induced by an external event, but can be restored in about 400 ms, and (3) attention is directed to an object, not space, and follows the object as it moves.

Introduction

Attention is a mechanism to select sensory information. Based on the selected information we make actions and store memories. The actions and memories then are used to select sensory information. Through such a cyclic process the brain will adapt itself to environment and acquire automaticity.

However, we know little of attention. This is largely because we cannot observe or measure attention directly. When we fail to perceive a particular object among many that are in our view, we realize that attention was not directed to the particular object; we realize that sensory information has been selected for some reason; we realize that the brain is not like a mirror.

Many psychologists and physiologists have attempted to describe the nature of attention and to discover its mechanism, but many questions remain to be resolved. What aspect of sensory information is modified by attention? – Is it intensity (Bashinski and Bacharach, 1980; Egly and Homa, 1984) or speed (Eriksen and Hoffman, 1972; Posner, 1980; Sternberg and Knoll, 1973) that is modified? At what level of sensory processing does attention act? – Does attention act before perception (early selection; Broadbent, 1958; Hillyard, 1985) or after perception (late selection; Deutch and Deutch, 1963)? We can direct our attention to an object voluntarily; or our attention can be drawn to an event in our environment. Can these phenomena be called attention (Kahneman and Treisman, 1984; Schneider and Shiffrin, 1977; Yantis and Jonides, 1984)? Do they share common mechanisms? What is the objective of attention? – Is it space, object, or its attribute (Kanwisher and Driver, 1992)?

Our experiments on attention started when we discovered an illusion of motion (Hikosaka et al., 1993a). We have shown in the following experiments that the illusion represents the intensity (or its slope) of attention. We then would like to answer the questions raised above.

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Attention changes the speed of visual processing

A first assumption is that the sensory information to which attention is directed is processed faster than others (here we will not discuss possible physiological mechanisms underlying this phenomenon). A second assumption is the reciprocal inhibition between sensory neurons. This type of interaction is common in the central nervous system, known as surround inhibitory mechanism in the sensory system.

The first assumption – acceleration of sensory processing by attention – has been demonstrated in previous psychological studies (Sternberg and Knoll, 1973; Maylor, 1985; Stelmach and Herdman, 1991). When two stimuli (light, sound, touch, etc.) are presented simultaneously, they are not necessarily perceived as simultaneous. A stronger stimulus is perceived earlier (Roufs, 1963). Even when the two stimuli have the same intensity, they are often perceived asynchronous. It depends on where attention is directed.

We first undertook an experiment to confirm the above hypothesis (Fig. 1). While the subject was fixating the central spot (F), two visual stimuli (T1 and T2) were presented with a short interval (asynchrony). The subject's task was to answer which of T1 and T2 appeared earlier. This was easy when the asynchrony was large, but became difficult when the asynchrony was shorter than 50 ms, approaching 50% (chance level). But this was the case only when the subject directed his/her attention to neither of the stimuli.

The results changed dramatically by selective attention. Before the appearance of T1 or T2 we presented a small spot of light (C, cue stimulus) at the location of T1 or T2; this was intended to draw the attention of the subject to that location. As a result, T2 was perceived earlier than T1 even when they were presented simultaneously. For the two stimuli to be perceived simultaneously, T1 had to be presented physically before T2. We defined the intensity of attention by this asynchrony – the time interval at which the stimuli are perceived simultaneously. The asynchrony reached the maximum of 50–100 ms when the cue lead time (interval between the cue stimulus and the test stimulus, T1 or T2, whichever came on earlier) was optimal (100–150 ms).

However, judgement in this task was difficult. Many task trials were needed before drawing any conclusion. It is difficult to reveal the spatio-temporal characteristics of attention. Our new technique – *line motion method* – can overcome these difficulties (Hikosaka et al., 1993a).

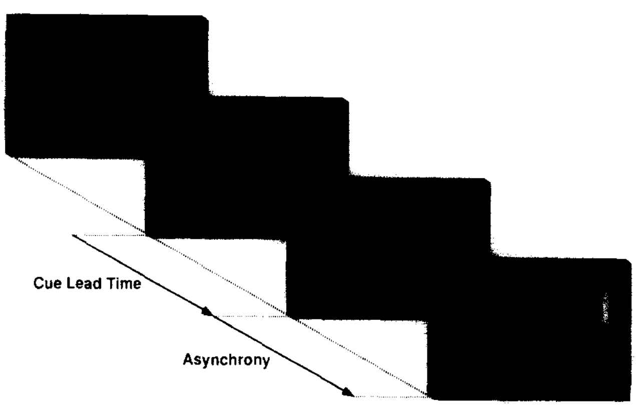

Fig. 1. Temporal order judgment task. While the subject is fixating the central spot (F), two stimuli (T1 and T2) come on with a random short interval. If a cue stimulus (C) precedes one of the two stimuli, the cued stimulus (T2) tends to be perceived earlier than the uncued stimulus (T1).

Attention can be detected by an illusion of motion

The principle of the line motion method is shown in Fig. 2, top. While the subject is fixating the central spot of light, a cue stimulus comes on either on the right or on the left. A line then comes on between the two possible cue positions. Interestingly, the line is perceived as if it were drawn from the cued side (although it comes on physically at once). Our psychophysical study started from the discovery of this motion illusion. Why should this indicate attention?

Recent physiological studies have shown that there is a motion detecting mechanism in the visual association cortex. One such prominent area is the area MT (or V5) (Van Essen et al., 1981; Zeki, 1974; Newsome et al., 1989). Let us consider the process by which the visual information from the line in Fig. 2 is fed into the motion detector. A line can be regarded as a linear aggregate of spots of light. If the spots come on sequentially from right to left (Fig. 3, right), the corresponding visual signals reach the motion detector sequentially, which will activate the motion detector. If the spots turn on simultaneously (Fig. 3, left), the visual signals reach the motion detector simultaneously, so that no motion will be detected. This is the case, however, only when the visual signals are processed at the same speed among the different spots. What happens if attention is directed selectively to one side of the line? As shown in the temporal order judgement task (Fig. 1), the attention will increase the speed of visual processing locally (Fig. 3, center), i.e., the attended signal will reach the motion detector

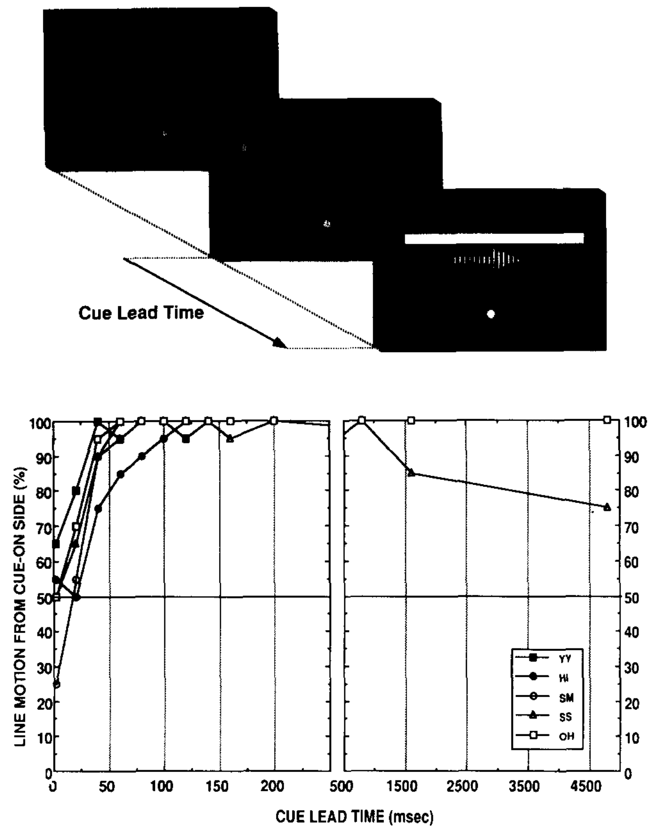

Fig. 2. Line motion task. Top: If a cue stimulus (C) is followed by presentation of a probe line, illusory motion is perceived in the line as if it were drawn out from the cue stimulus. Bottom: The percentage of trials in which the line appeared to be drawn from the cued side (ordinate) was plotted against the cue lead time (abscissa). Data from five subjects are shown with different symbols. Twenty trials were obtained for each cue lead time in each subject. The chance level was 50%.

earlier. In the experiment in Fig. 2, attention was attracted passively by the cue stimulus. If we assume that the effect of attention decays outward from its locus (which in fact was found to have a exponential-like distribution in a later experiment), the visual signals will reach the motion detector sequentially from the attended side (e.g., right in Fig. 3, center) to the unattended side (e.g., left). There is no difference from the viewpoint of the motion detector between the attention-induced asynchrony (Fig. 3, center) and the asynchrony induced by real motion (Fig. 3, right); the motion detector will be deceived.

The line motion method proved very sensitive. A motion detector can be regarded as a sensitive detector of sequence (Biederman-Thorson et al., 1971; Nakayama, 1985). But it works only when the sequential events occur in close proximity. Thanks to the high sensitivity of the motion detector, the experiment in Fig. 2 allowed us to detect subtle differences of the speed of visual processing. The illusory motion in the line represents the spatial gradient of attention.

We then found that the motion sensation depends on the time interval between the onset of the cue stimulus and the onset of the probe line (cue lead time) (Fig. 2, bottom). It was strongest when the cue lead time (CLT) was about 100 ms. It was much weaker with CLT of 1 s and no motion sensation was perceived with 0 ms CLT. This was shown by plotting, for each cue lead time, the ratio of trials in which the motion was perceived from the cued side. Such transient nature of attention (when it is induced by an external event) has been demonstrated using different psychophysical methods (Nakayama and Mackeben, 1989; Posner et al., 1982).

More quantitative data were obtained by a cancellation method (Miyauchi et al., 1991, 1992). Consider the situation shown in Fig. 3, center. If the spots constituting the line are presented sequentially from left to right with appropriate time intervals, the attention-induced asynchrony of visual processing should be can-

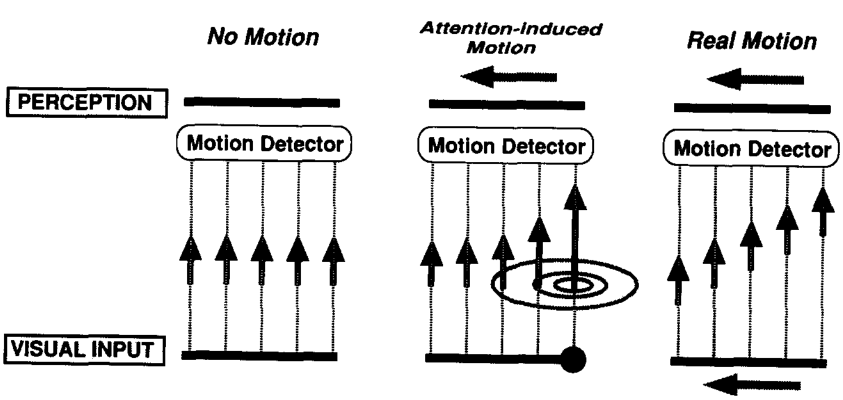

Fig. 3. Hypothetical information processing underlying perception of a line. Focal attention accelerates visual processing locally, so that visual signals reach the motion detector sequentially, as in the case of real motion.

celled. Our results indeed showed that this is the case. The physical asynchrony required for the cancellation can thus be defined as "the differential of the magnitude of attention" between the end points of the line.

With the cancellation method we can see the distribution of an attentional field. First, for example, we presented two spots of light and asked the subject to attend to the right spot. A short probe line was then presented at a random position, to the right or left of the attended or unattended spot. If the subject perceived motion in the line, he adjusted the asynchrony of line drawing until he perceived no motion. The value of the asynchrony required for the cancellation would indicate the differential of the function representing the attentional field; the attentional field was thus obtained by integrating the differential values across space. Our results showed that both onset and offset of a spot of light produced a strong focus of attention which decayed outward quasi-exponentially.

Where does attention act?

We have shown that attention locally accelerates visual information processing. Where in the central visual areas does the acceleration occur? Our line motion method gives some clue to this question. For a motion to be perceived, attention must act at a level (or levels) *before* the motion detector (see Fig. 3). If we assume that the motion detector is in the area MT (Newsome et al., 1989), the site of attentional effect should be before MT.

How much before is the site of attentional effect? Is it before or after visual signals reach the visual cortex?

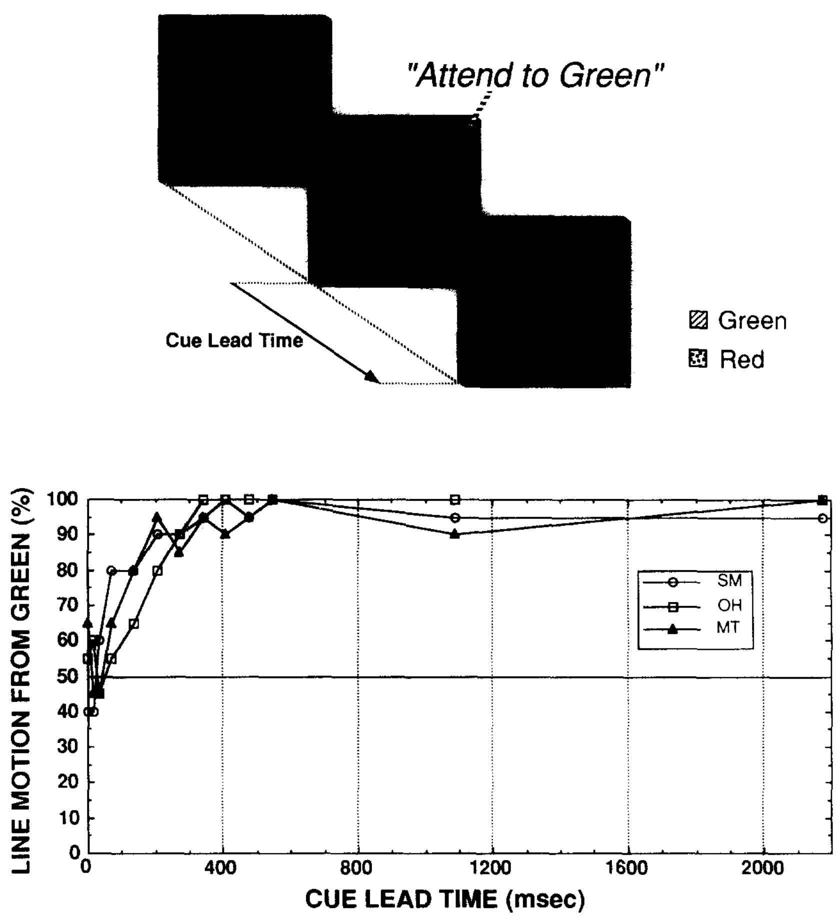

Fig. 4. Active attention produces a similar motion sensation in the line. Top: Two squares, red and green, appeared simultaneously at two positions randomly while the subject was fixating. The subject was required to direct and keep attention to the green square in one block of trials and to the red square in another block. Bottom: The result of the experiment in which the green square was attended. The percentage of trials in which the line motion was perceived from the *green* square was plotted against the cue lead time for each subject. Data from three subjects are superimposed.

Is it before or after binocular convergence? We designed a dichoptic viewing experiment to answer this question (Hikosaka et al., 1993a). In the experiment as shown in Fig. 2, we presented the cue stimulus and the probe line to different eyes (e.g., cue to right eye, line to left eye). We found that the same motion sensation was perceived in this condition. This suggests that the effect of attention acts at the level after binocular convergence – perhaps in or after the primary visual cortex (V1) (Hubel and Wiesel, 1962).

These results led to the hypothesis that attention acts on some visual cortical areas between V1 and MT. But there are multiple routes from V1 to MT including a direct connection from V1 to MT, a route via V2 and V3, and a pathway via V4 (Ungerleider and Desimone, 1986). We do not know which pathway is affected by attention. In addition, we cannot exclude the possibility that motion sensation may occur at stages later than MT (Colby et al., 1993). What is nevertheless certain is that attention expresses its effects at relatively early stages of visual processing. This conclusion supports the "early selection theory of attention" (Broadbent, 1958; Hillyard, 1985). However, this by no means excludes the possibility of "late selection". It seems feasible that attention affects visual and cognitive processing at different, multiple levels.

Voluntary attention similarly affects early visual processing

Attention has two aspects – passive (bottom-up or stimulus-induced) and active (top-down or voluntary). Suppose while you are reading this paper a cockroach runs at the edge of your table. Your attention will automatically be drawn to the roach. This is a passive type of attention. You nevertheless could redirect attention to reading, ignoring the creature. This is an active type of attention.

What we have examined so far was the passive type of attention. The sudden appearance of a spot (as in Fig. 2) draws your attention automatically; so does a cockroach. What happens in the situation where you concentrate on reading in spite of the presence of the roach? Is there anything in common between these two types of attention?

To put this question more physiologically, does active attention act on cognitive processes which would occur after sensory processes? Or does it act on the early levels of visual processing, as does passive attention? If the latter is true, we would expect that illusory motion can be perceived by active attention.

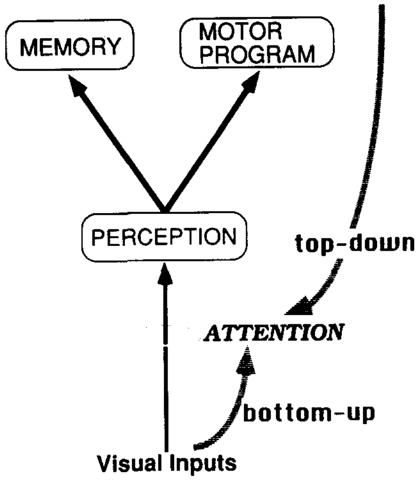

Fig. 5. Two modes of attention (bottom-up and top-down) share common action sites in early visual processing.

The latter hypothesis proved true by the experiment shown in Fig. 4 (Hikosaka et al., 1993b). While the subject was fixating a center-lower spot, a red and a green square came on; their sides were randomized. The subject was required to attend to either one of the squares (e.g., green square) as quickly as possible after their onset. Eye movements were not allowed. After a random period of time (cue lead time) a probe line was presented between the two squares, and the subject reported from which side the line was perceived to be drawn. When the cue lead time was long enough ($>$ 300 ms), the subject clearly perceived motion whose direction was from the attended square (e.g., green square). In the next block of experiment we changed the square to be attended (e.g., red square); the direction of the illusory motion was reversed (e.g., from red to green).

To summarize the above result, active attention produces illusory motion sensation, as does passive attention, and its direction is from the attended object to the unattended object. This suggests that active (top-down) attention, as well as passive (bottom-up) attention, locally accelerates early visual processing (Fig. 5). This, of course, does not preclude the possibility that attentional effects are exerted at stages later than perception (e.g., motor program or memory storage).

It has generally been thought that these two modes of attention – active and passive attention – have different mechanisms (Schneider and Shiffrin, 1977). Our experiment suggested, on the contrary, that the two types of attention can be classified into a single category, *attention*, because they share common action sites.

Neural mechanism of active attention

The information producing active attention originates probably in non-sensory areas, especially frontal and parietal cortical areas (Posner and Petersen, 1990). If our hypothesis shown in Fig. 5 is correct, the information must reach the early stages of visual processing. Are there such routes?

It is known that connections between different cortical areas are almost always mutual. There are polysynaptic connections from V1 via area MT and parietal association cortex to the frontal association cortex. This suggests that there are reverse connections from the frontal association cortex to V1 (Van Essen and Maunsell, 1983). Such reverse connections may play an important role in active attention. It may take a considerable amount of time before such polysynaptic, transcortical connections become fully activated. In fact, in the experiment shown in Fig. 4, the active attention developed gradually, reaching its peak after 300 ms. This contrasted with passive attention (Fig. 2) which developed within 100 ms.

Interaction between passive and active attention

What happens if these two types of attention occur simultaneously? To answer this question we modified the experiment shown in Fig. 4 (Hikosaka et al., 1993b). While the subject was attending to, say, the green square, the red square was flashed. If the probe line was presented just after the flash of the red square, robust motion was perceived from the side of the red square, opposite to the direction which would have been perceived had it not been for the flash. This reversal of illusory motion indicates that the flash-induced passive attention overcame and nullified the preexisting active attention. The reversal occurred immediately after (< 50 ms) the flash and continued at least for 400 ms. The subject had to exert a strong effort in order to re-reverse the direction of attention to the green square.

This result leads to the following suggestion. Active attention can easily and quickly be distracted by a local change in the visual field. Passive attention dominates over active attention, at least at the early stages of visual processing. But passive attention is generally short-lasting, and thus could be replaced by active attention. Thanks to this type of interaction, we can concentrate on a task and yet can respond quickly to an external event. This, on the other hand, produces a *blind spot* in our behavior; a magician can perform his trick because he diverts the attention of the audience using a tool as a distracter.

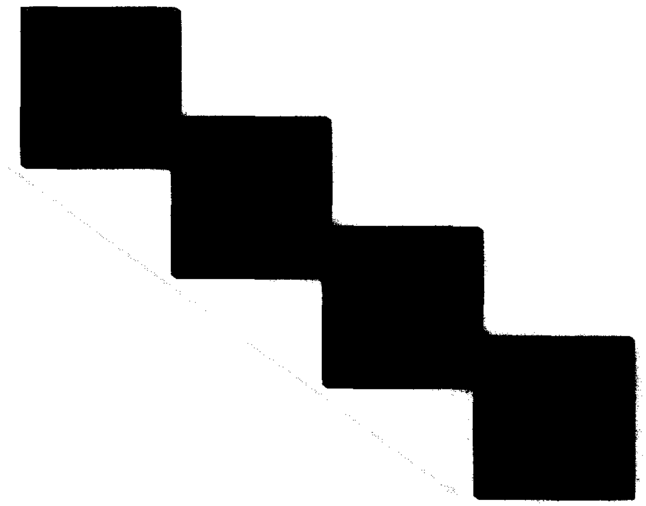

Fig. 6. Attention may follow a moving object, not staying at the cued location. One of four rotating spots is flashed, and after a random amount of rotation a probe line is presented between the flashed spot and the flashed location. Motion is perceived from the flashed spot, not flashed location.

Attention is directed to an object, not a location

What is the objective of our attention? Consider the experiment in Fig. 2. The onset of the cue stimulus (spot of light) draws our attention. Is attention directed to the location of the spot? Or is it directed to the spot itself? In this experiment the location and the object were not differentiated.

We thus carried out the following experiment (Fig. 6) (Hikosaka et al., 1993b). While the subject was fixating a central spot, four blue spots appeared and rotated around the fixation point. One of the four spots was brightened briefly, and then all the four spots continued to rotate. After a random amount of rotation (90, 180, 270, or 360 degree) a probe line came on, connecting two of the four spots. Consider the situation in which the line came on after a 90 degree rotation. As seen in Fig. 6, one end of the line is at the flashed location, while the other end is at the flashed spot. Our results showed that motion was perceived always from the flashed spot. There was a tendency that the magnitude of attention decreased at the flashed location. To summarize, once attention is drawn to a moving object, the attention does not stay at the initial location but follows the object as it moves.

One could even ask whether *spatial* attention ever exists. It is certainly difficult to direct attention without an object. Can we direct attention to left-up, for example, in total darkness? If possible, we may depend on visual imagery. What our experiment suggests is as follows. Spatial attention dissociated from object is very weak, if it exists. Once attention is directed to an object, it moves in space as if attached to the object. A similar feature is found in eye movement: our eyes would make a saccade to a moving object and then follow it by smooth pursuit. It might be speculated that attention and eye movement have common neural mechanisms to catch up with and follow an object of interest.

What could be the neural mechanism underlying the dynamics of attention? The distribution of attentional field must move as the object of interest moves. The area MT is the best candidate to detect the motion of the object, but single neurons in MT generally have broad receptive fields (Mikami et al., 1986); in other words, they can tell which direction the object is moving but cannot tell exactly where the object is. The supposed movement of the attentional field would therefore require the contribution of visual neurons which have finer receptive fields as seen in V1 or V2. Here again the reverse connections in visual cortical areas may play an important role.

Alternatively, subcortical areas, such as the superior colliculus (Goldberg and Wurtz, 1972) and pulvinar (Robinson and Petersen, 1992), may contribute to the dynamic aspect of attention. The superior colliculus is a key structure for orienting response (Ewert, 1980), particularly saccadic eye movement in primates (Robinson, 1972). The similarity between attention and eye movement, described above, suggests the contribution of the superior colliculus in attention. The superior colliculus is known to determine the vector and velocity of saccadic eye movement by focal activity (contributed by a population of neurons) in its intermediate layer (Sparks, 1986). It has further been indicated that the focal activity moves during a saccade (Guitton et al., 1993). Such a moving hill mechanism might also underlie the movement of attention.

If the objective of attention is object, not space, we then have to ask what an object is. An object is something that is individual and dissociable in the external world. An object is described as having many attributes, i.e., visual, tactile, smell. The visual attribute is further divided into submodalities, i.e, color, shape, size, texture, movement. The sensory system breaks up given sensory inputs into such submodality features, each of which is analyzed in specialized cortical areas (i.e., visual motion by area MT). The goal of sensory systems in the brain, however, is to perceive an object by integrating these highly processed attributes. What is important here, in our opinion, is that attention is also aimed at object, not space or other attributes. This is in line with the observation that attention is necessary for perception of an object (Treisman and Gelade, 1980). Only after mutual interactions of sensation and attention can we construct the percept of an object.

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