ACTIVE ALLOCATION OF ATTENTION AND THE MOTION INDUCTION EFFECT

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ABSTRACT

Active Allocation of Attention and the Motion Induction Effect

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In motion induction a bar presented next to and shortly after a visual cue is perceived as growing away from this cue. With two simultaneous cues flanking the bar motion is seen away from each cue towards the middle of the bar. This illusion is attributed to attentional facilitation in the processing of stimuli presented subsequently at the cued location(s). The present study examined whether motion induction occurs with deliberate allocation of attention to a predefined cue presented together with multiple irrelevant cues and when the position of the test bar is unpredictable. Search for a target defined by a conjunction of features (color and orientation) was interrupted at different delays by a horizontal bar appearing between two randomly chosen items. Above chance percentage of motion reported away from a particular item in a pair indicated motion induction due to attentional selection of this item. The strength of attention at different cues was also independently measured by the change in detection latencies to a low contrast probe presented in the cue's vicinity. Motion induction at target gained strength until the optimal time for target detection which was longer for displays with more items. Following detection, motion induction at target decreased as attention disengaged. Early in search motion induction was also observed at nontargets with the target color. The pattern of results remained stable with reversal of the target features and was replicated with a new sample of subjects. Motion induction and the overall detection efficiency at target changed in a similar way over time, reflecting the underlying dynamics of deliberate attention. Results support the attentional origin of the illusion and indicate that with voluntary cueing of attention both inhibition at irrelevant locations and facilitation at relevant ones contribute independently to the effect. The present findings also suggest that attentional modulation at levels responsible for color encoding and object recognition can affect the motion detecting mechanism. Implications for theories of conjunction search are discussed as well.

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" (...) The surgeon would sometimes see the blood flow from the arm of the patient whom he was bleeding, *before* he saw the instrument penetrate the skin. Similarly the smith may see the sparks fly *before* he sees the hammer smite the iron, etc. There is thus a certain difficulty in perceiving the exact *date* of two impressions when they do not interest our attention equally (...)"

- William James, *The Principles of Psychology (I)*

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ACTIVE ALLOCATION OF ATTENTION AND THE MOTION INDUCTION EFFECT

Physically, an object is said to be moving if it changes its position in space over time. Yet subjectively, visual motion may be vividly perceived in the absence of physical displacement. In the motion aftereffect, for example, after viewing a moving visual pattern for a period of time, the same pattern appears to drift in the opposite direction when stopped. Also, in stroboscopic motion, discrete static stimuli arranged in an array and flashed briefly in quick succession yield the convincing impression of a smoothly moving single object. Although in the physical sense such motion is not "real", it appears real and is experienced as such. Accordingly, it is known as apparent motion.

Ever since the discovery of the motion aftereffect (Addams, 1834; Wohlgemuth, 1911) and stroboscopic motion (Exner, 1888; Wertheimer, 1912) apparent motion phenomena have been used as tools to understand how the visual system unifies signals distinct in time and space into a percept of continuous motion. Of foremost concern, however, has been the "hardware" for motion perception. As a result much is known about the stable properties of the visual system in respect to the structure and function of motion detectors, their ability to extract the speed, direction and orientation of motion and their distribution across the visual field. In contrast, there has been little consideration for the fact that visual processing unfolds within a dynamic biological system which adapts continuously to changes from within and from without.

Usually, the actions of awake organisms revolve around objects of immediate or more remote importance. We, humans, sense this behavioral order introspectively as "the stream of consciousness". Although the physical world in which we are immersed stimulates incessantly our various receptors we are not constantly aware of all this stimulation. For example, at any given moment in time our field of view is cluttered with various objects but only some of them come forth in perception whereas others melt in the background. Moreover, we may willingly bring new objects to the foreground and thus experience new aspects of the stimulation offered to our senses. It is believed that stimuli that are vividly perceived are also more fully processed by the brain than those which fuse with the sensory background. This leads us to the general notion of attention as some kind of flexible filter which channels the sensory input by selecting what will be processed, when and to what extent.

Attention, however, has been studied mainly from a cognitive point of view, in terms of the abstract capacity of a system to process different amounts and types of information. Sokolov's (1963) electrophysiological work on the "orienting reflex" in humans and Schneider's (1969) investigations of the "visual grasp reflex" in animals are, however, important exceptions which had emphasized the link between attention and orienting behavioral sequences. Nevertheless, typically, attentional processes have been examined independent of sensory modality and in respect to higher-order cognitive functions such as language and memory. Although Helmholtz (1850/1925) and James (1890) have noted long ago the strong influence of attention on visual experience, empirical research in this direction began only after it was shown that the movements of the "mind's eye" could be dissociated from eye movements (Eriksen & Hoffman, 1974; Posner, Nissen & Ogden, 1978). Interest in this topic grew lately, as it became possible to study directly the neuronal correlates of visual spatial attention in behaving organisms.

The present work explores the involvement of spatial attention in a visual illusion of motion (i.e. the motion induction effect). Such topic brings together two vast and distinct areas of research. The study of visual motion, on the one hand, and that of attention, on the other, have each their own vocabulary and their own historical roots. Often, however, the nature of visual phenomena defies formal distinctions and requires convergence of concepts and approaches.

This paper will first discuss the role of visual-spatial attention in perception with special emphasis on findings, concepts and operational definitions related to the present study. Next, the evidence for attentional influences on motion perception will be examined. Finally, the motion induction phenomenon will be addressed, followed by an introduction to the present study.

The Need for Visual Selection

If the abundant visual input is all brought into consciousness with the same clarity and all at once across all points in space this would make behavior impossible or chaotic since motor responses are limited to the physical dimensions of the body and at a given moment in time can be directed to only one or few locations in space (Deutsch & Deutsch, 1963). In humans, however, stimulus selection does not always serve immediate action but is also needed for the construction of internal representations. The primate brain itself is physiologically constrained and therefore limited in its capacity to process information in parallel across the visual field (Broadbent, 1958; Neisser, 1967). Sensory signals from the retina compete for access to perception within a network of 30 or more cortical visual areas (Felleman & Van Essen, 1991). Because the receptive fields of neurons could be viewed as a critical processing resource it is currently believed that competition is more vigorous at higher levels in the visual hierarchy as the receptive fields of visual neurons get larger with numerous visual objects falling within their scope (Desimone & Duncan, 1995). Whereas in the primary visual cortex (V1) individual receptive fields are small and sample the visual field quite densely, neurons in the extrastriate visual cortex integrate information across up to 25 degrees of visual angle. Further, neurons with large receptive fields are known to encode complex object features (Perrett, Rolls & Caan, 1982) but to do this unambiguously they must deal preferentially with only part of the input they receive at a given time. This imposes the need of selection, temporal priority in processing or in other words - attention.

Subjectively, attended visual objects appear to stand out from their surround. Metaphors are commonly used to describe this experience. The oldest analogy is that of a "spotlight" scanning the visual scene (Broadbent, 1982; Treisman & Gelade, 1980). A similar example is that of a zooming projector illuminating the world from the same angle but changing its spatial scope and resolution (Eriksen & St-James, 1986, zoom-lens model). In both cases attention is thought of as a light beam which intensifies part of a scene that is already visible to some extent. Implicit in these analogies is the prescientific idea of the mind emitting a beam of light and controlling it's direction. Attention, however, is an intrinsic dynamic property of neural processing in the awake brain and there is no internal agent to move it around. Maybe the best comparison so far is that with a flexible surface in which peaks and valleys are formed at different places and with different speed as a function of time (LaBerge & Brown, 1989, gradient model). The peaks may be thought of as the points of attentional focus. Interestingly, these metaphors convey quite accurately our current understanding of attention. They are all consistent with evidence from a wide range of experimental paradigms such as neurophysiology, spatial precueing and visual search.

Effects of Attention on Visual Perception

Although attentional modulation is invisible per se its effects on visual perception can be measured with psychophysical methods. The perceptual effects of attention to a spatial location are often examined within a paradigm known as cost-benefit analysis.

Visual Cueing and Cost-Benefit Analysis

This method was developed by Sperling (1960) in his work on iconic storage. It was first applied to attention research by Eriksen & Hoffman (1974) and further elaborated by Posner et al. (1978) and Posner (1980). The basic procedure involves abrupt presentation of a small spatial cue either shortly before presenting a stimulus display or together with it. The cued location may be valid or invalid with respect to the target location and subjects may or may not be instructed to attend to the cue. Normally, the gaze is centered at fixation while the cue and the stimuli appear elsewhere. Subsequently, performance in detecting, discriminating or identifying stimuli at the cued location is assessed in terms of accuracy or reaction time. Results without cueing, with valid and invalid cueing are then compared. The rationale behind this procedure is that prior to target presentation the cue sets the visual system in a focused attentional state in respect to the cued location. Thus the effects of cueing on target perception could be attributed to attention summoned at the cue.

Facilitation and Inhibition

By means of this method Posner and his colleagues (1978) delineated two fundamental aspects of attentional selection - facilitation and inhibition. It was demonstrated that perceptual latency decreased (compared to the no-cue condition) if the target location was correctly signaled by the cue and increased if the cue pointed at a wrong location. Thus there were perceptual benefits at the attended location and costs at locations from which attention was withdrawn. Furthermore, it was found that inhibition and facilitation were of the same magnitude if the probability of valid and invalid cueing was the same. The two processes, however, were considered independent because they exhibited distinct time courses with facilitation at valid locations preceding inhibition at invalid locations. In addition, with flashed, transient cues, facilitation was replaced later on by inhibition at the same location - a phenomenon known as "inhibition of return" (Posner & Cohen, 1984).

Subsequent research replicated these results across tasks and measures. It has been found, for example, that sensitivity of visual detection and discrimination increases with attention (Sagi & Julesz, 1986; Downing,1988; Müller & Rabbit, 1989) and so does visual resolution as measured by vernier acuity (Nakayama & Mackeben, 1989). Moreover, it was shown that the facilitation effects are strongest at the attended location and decrease gradually towards the periphery (Kröse & Julesz, 1989) thus revealing a spatial gradient of attention. The region of visual enhancement (zone of focal attention) was found to vary in size depending on the task and on the time elapsed after cueing. It is also known that attentional gradient may last in one place for periods of time as brief as 20-100 ms (Braun & Sagi, 1990). It is thus believed that during one eye fixation, focal attention may be reallocated and rescaled, perhaps several times, to different parts of the visual scene.

Taken together, results within this paradigm converge on the fact that attention to a location enhances and speeds-up the perception of stimuli presented subsequently at and around this location at the expense of stimuli at other locations. It was also shown that the perceptual enhancement at the attended location changes its spatial and temporal extent reflecting the interplay between the facilitatory and inhibitory components of attention.

Consistent with psychophysical findings, single-cell recordings in awake primates had shown increase in neuronal firing to attended stimuli and response suppression to nonattended ones. Such effects were obtained with neurons in the inferotemporal cortex and area V4 which were optimally tuned to both the relevant and irrelevant stimulus (Moran & Desimone, 1985). When both stimuli were presented in the receptive field of the examined cell it responded only to the attended stimulus remaining silent to the nonattended one as if its receptive field had shrunk around the attended location. Recent studies have also shown that the attentional effects on neuronal responses are larger if both stimuli are presented in the same receptive field (Luck, Chelazzi, Hillyard & Desimone, 1993) or in the same hemifield (Sato, 1988).

These findings are important. First, they reveal the possible neuronal correlates of the attentional facilitation and inhibition, observed psychophysically. Second, they suggest that the spacing of stimuli in the visual field would affect attentional selection by determining the amount of processing competition within the receptive fields of activated neurons along the visual pathway. The latter prediction has been confirmed by psychophysical evidence derived from experiments in which the target stimulus is presented among many others.

Allocation of Attention in Visual Search

The studies discussed so far examine the effects of attention confined to a particular location in space. Often, however, selection concerns certain visual attributes (e.g. orientation, color, size or shape) when their location in the visual scene is not known in advance. The visual search task has been traditionally employed to examine feature based attentional selection in displays with multiple stimuli. In contrast to the cueing paradigm, this approach is designed to examine the processes involved in visual selection rather than its subsequent effects on perception.

The visual search method was developed by Treisman & Gelade (1980) and is based on a task introduced by Neisser (1967). Normally, a target item is predefined either verbally or by visual exposure. Observers are then asked to determine whether the target is present in a scene that includes multiple irrelevant items.

The initial finding (Treisman & Gelade, 1980) was that increasing the number of distractors does not affect search times if the target differed from the distractors along a single perceptual dimension (e.g. color: red target among green distractors). In contrast, search times for targets defined by a conjunction of features along two dimensions (e.g. color and form) and sharing one feature with each distractor showed linear increase as more items were added to the display. Moreover, the amount of time needed to recognize the absence of a conjunction target increased at twice the rate as the time needed to recognize the presence of the target. This would occur if search is done item by items because, on average, the target is encountered after investigation of about half of the items, whereas certainty of absence requires investigation of all items.

The Feature Integration Theory and Its Current Status

Based on these findings Treisman and her colleagues concluded that selection of a conjunction target requires effort and relies on a limited-capacity process (i.e. attention) whereas a single-feature stimulus "pops-out" preattentively. These early results were accounted for by the feature integration theory of attention (Treisman & Gelade, 1980) which maintains that search for feature targets proceeds in parallel across all display locations whereas search is serial for conjunction targets. The serial process refers to the sequential movements of the attentional "spotlight" which focuses and dwells for some time on individual items. In contrast, in search for a feature difference along one dimension all items are processed simultaneously. Implicit in this claims is the assumption that attentional processes are serial but not parallel in nature and that the serial and the parallel mechanisms are independent. This theory also suggests that selection of features may occur independent of their locations or, in other words, that one may attend to the color of an object without knowing where the object is.

Subsequent research has seriously challenged most of the above contentions on both empirical and theoretical grounds (Green, 1991). It has been found that the steepness of search functions does not depend exclusively on whether the target is defined by a single feature or by a conjunction of features. Studies have demonstrated fast, pop-out effects for conjunctions of depth and motion, motion and color (Nakayama & Silverman, 1986) and for form-color conjunctions when the feature salience is great enough (Wolfe, Cave & Franzel, 1989). On the other hand, feature search may be made quite difficult if the feature difference is perceptually weak (Wolfe et. al, 1989). Grouping of similar distractors and their segmentation in surfaces was also found to contribute to the effortless selection of feature conjunctions (Duncan & Humphreys, 1989). Thus it was shown that with large target-distractor differences both features and conjunctions are conducted in parallel whereas with small target-distractor differences search is serial in both cases.

Parallel and Serial Processes

This new evidence blurred the dichotomy between parallel and serial selection and the claim that the two processes are independent. The slopes of visual search functions were shown to vary in steepness depending on the particular stimuli used and on their configuration. It was therefore acknowledged that the standard slope statistics provide only a general index of search difficulty but do not specify unambiguously the nature of the underlying process (Green, 1991). Subsequent models of visual search (Pashler, 1987; Wolfe et. al, 1989; Duncan & Humphreys, 1989; Treisman & Sato, 1990) acknowledged the importance of both parallel and serial processes in search for conjunctions of features. At present there is consensus that selection may operate on both individual items and groups of items but it is difficult to specify the interplay between these two modes across tasks and stimuli. Network models based on known interconnections between feature modules in the visual system promise to shed light on this complex interaction. Recently, Grossberg, Mingolla and Ross (1994) proposed an interesting account of conjunction search. These authors suggest that attention is serially allocated to emergent objects (comprising multiple items) which are delineated prattentively by parallel processes such as grouping, texture or surface segmentation. Selection is thought to proceed as recursive narrowing of attention over and within organized clusters of items. The model, however, is open to the possibility that top-down strategies may also aid the selection of multi-item groups (Pashler, 1987).

In addition, it was found that conjunctive searches are easier in scenes with well separated items than in scenes in which items are clumped together (Cohen & Ivry, 1991) whereas the opposite holds for feature searches. Thus contrary to the feature integration model, it was shown that location information plays a role in feature based selection. This is to be expected from the retinotopic organization of most structures in the visual cortex although location is registered with more precision at lower levels in the hierarchy.

The issue of whether attention may act simultaneously on more than one location or parallel processes are necessarily "preattentive" remains controversial. In their revised theory Treisman and Sato (1990) suggested that conjunction search is often made easier if subjects adopt the deliberate strategy of inhibiting one or more of the non-target features simultaneously across distractor locations. Wolfe et al. (1989) advanced a similar idea. They proposed that search is guided by selective enhancement of all distractors sharing the target relevant feature. Recent findings (Kaptein, Theeuwes & van der Heijden, 1995) support the hypothesis that in conjunction search multiple distractors may be selectively and concurrently enhanced (or inhibited). It was found that observers limit their search to a subset of elements with the target color independent of color salience and instructions. Other studies, however, have shown that it is often difficult to selectively attend one feature to the exclusion of another (Posner, 1978). This may be possible, however, if features are linked to locations rather than "free floating" which seems to be the case.

There is some neurophysiological evidence (Chelazzi, Miller, Duncan & Desimone, 1993) that inhibition of irrelevant items may precede the selection of conjunctive targets though in this experiment eye movements and spatial attention were confounded. Monkeys were presented with scenes including a randomly located target shape and up to four distractor shapes. They were rewarded for foveating the target shape. Consistent with Grossberg's et al. (1994) hypothesis, initially, inferotemporal cells selective to the target shape, as well as those selective to the distractor shapes fired as if a multi-item group was being attended. Just before a saccade to the target, the firing rate of cells selective to the distractor shape decreased to the baseline level.

Attention and Perceptual "Pop-Out"

Another source of controversies is the role of attention in the "pop-out" of feature singletons. It is commonly agreed that a discontinuity in the distribution of features across space is localized preattentively. Generally, pop-out effects are not slowed down by a concurrent attentionally demanding conjunction search (Braun & Sagi, 1990) and occur equally fast with and without precueing of the pop-out location (Mackeben & Nakayama, 1989). Todd and Kramer (1994), however, reported that unexpected "pop-outs" adversely affect search for a conjunction target when the target changes from trial to trial. In addition, Theeuwes (1992) found that the "pop-out" of an item with a unique color interferes with the "pop-out" of a unique form and vice versa. This is also consistent with previous results (Sagi and Julesz, 1985) indicating that the source of the feature discontinuity (i.e. the item which "pops-out") can be recognized only after the observer moves attention to the preattentively marked location. Thus the "pop-out" could be thought of as an "interrupt signal" which automatically captures focal attention to its location. Taken as a whole, these mixed findings suggest that selection of a feature-contrast along one dimension is not "resource-free" although it certainly requires much less effort than the selection of a conjunction of two or more features.

Sources of Attentional Control

For the purpose of the present work it is now important to reconcile the two approaches to visual-spatial attention discussed above. This is, however, a conceptually difficult task. The difficulty comes mainly from the fact that the paradigms of spatial-cueing and visual-search ask different questions and employ different operational definitions of visual-spatial attention.

Conceptual Conundrums

The cueing literature is silent as to how attention is drawn to the cue, whereas visual search experiments ignore the effects of selection on perceptual experience. Whereas cueing experiments measure attention by its subsequent effects on perception, studies in visual search identify attention with a serial process, limited in capacity, susceptible to interference by concurrent tasks and involving deliberate, active effort. The long-standing dichotomy between preattentive and attentive processes in the cognitive literature complicates things even further. With such dichotomy in mind, it could be argued that a single abruptly presented cue does not activate attention at all, because such cue "pops-out" against a homogeneous background and its perception is automatic. Any effects this cue might have on subsequent perception are thus attributed to "sensitization" but not to "attention".

To avoid logical contradictions, throughout this paper visual-spatial attention is broadly defined as perceptual selection confined to a location (region) in visual space. In this sense, attention is distinguished from expectations or other states of general preparedness. As discussed earlier, at any given moment in time some visual stimuli gain priority in processing over others and therefore have perceptual advantage. The neural signals they elicit are stronger than those induced by the rest of the sensory input (Desimone & Duncan, 1995). It is these stimuli that engage our attention at that particular moment. Thus an abruptly presented cue, a feature contrast or a conjunction target in visual search are all attended although attention is brought to them in different ways and stays at their location for different periods of time. Consequently, both an abrupt onset stimulus and an item in visual search may act as attentional cues and affect the perception of stimuli presented at the cued location.

From this perspective three aspects of visual attention may be of interest in experimental situations. One aspect, addressed by visual search, is the time course and nature of attentional allocation, as well as the amount of effort it involves. Another aspect, examined through spatial cueing, concerns the perceptual effects of attention at the singled out location at any point in the selection process. A third important question is what triggers attention in the first place.

Attention Controlled by the Stimulus

Attentional selection, as defined above, may or may not involve active, conscious effort. For example, the spatial and temporal context of a stimulus may lead automatically to its preferential processing at nearly all levels of the visual system. It has been demonstrated that novel stimuli trigger larger neural signals in the inferotemporal cortex of behaving monkeys thus gaining immediate processing advantage (Sokolov, 1963; Fahy, Riches & Brown, 1993). In contrast, stimulus repetition tends to suppress neuronal responses (Sokolov, 1963; Miller & Desimone, 1994). Also, localized temporal discontinuities such as the sudden onset or offset of a stimulus capture attention involuntarily even when the object is equiluminant with its background and is irrelevant to the task at hand (Yantis, 1993a; Yantis & Hillstrom, 1994). In addition, responses of many neurons to an otherwise optimal stimulus may be completely suppressed if similar stimuli are simultaneously present in the surrounding region (Allman, Miezin & McGuinness, 1985). Such lateral inhibition, which is stronger in dense displays, would certainly aid the "pop-out" of a stimulus with unique features among other items that are all identical.

Top-down Control of Attention

Of course the attentional system is not entirely dominated by bottom-up biases because its main purpose is to select information that is most relevant for current behavior even if this information is well masked by the rest of the sensory input. In such cases attention is guided by the description of the information currently needed which is stored in memory (i.e. the attentional template). Consequently, processing is in favour of stimuli matching this description. In laboratory conditions such goal-directed, active attention is usually induced by rewarding an animal for a certain behavior or instructing human subjects to search, respond to or simply attend to a particular stimulus.

The source of attentional control is an important factor which confounds the interpretation of many psychophysical and neurophysiological findings. For example, in cueing experiments if subjects are instructed to attend to the abruptly presented cue, both active and passive attention may be at work. Also, in search for feature singletons, the subjects' prior knowledge of the target may confound the bottom-up nature of the 'pop-out" effect. These problems are common because goal-directed attention is difficult to isolate experimentally. Contingencies in the experimental procedure may lead subjects to adopt systematic top-down strategies or expectations. Ideally, confounding top-down effects would be optimally reduced only if the target's appearance, identity and location are unpredictable from trial to trial.

Transient and Sustained Components of Attention

There is strong psychophysical evidence that voluntary and stimulus-driven attention have different time courses. Nakayama & Mackeben (1989) combined spatial pre-cueing with visual search to examine the time course of selection of a target defined by conjunction of features. These authors presented a cue at varying locations on the visual search display to indicate the probable target location. The cue was either briefly flashed before display presentation (transient cueing) or was turned on and left throughout the trial (sustained cueing). Subjects knew that if the target is present on a particular trial it will appear at the cued location. The accuracy of "target absent" and "target present" responses was the dependent measure. With this method it was found that sustained cueing slowly increased response accuracy until a ceiling level was reached whereas the transient effect was optimal upon stimulus presentation and decayed quickly after 100 milliseconds. In addition, the development of the sustained effect was easily interrupted if a salient, though irrelevant visual event occurred throughout the trial and was very sensitive to task manipulations. By contrast, no amount of voluntary effort could change the time course of stimulus-driven attention (Müller & Rabbit, 1989) which was also insensitive to task manipulations (Nakayama & Mackeben, 1989).

These results isolated two aspects of attentional selection - a transient one which is passive and stimulus driven and a sustained one which is under active voluntary control. The interaction between the two mechanisms is not yet well understood but the existing evidence suggests that though short lasting, stimulus-driven attention is mandatory and resists interruption. In Bartlett's terms (Bartlett, 1958), transient attention could be thought of as a ballistic process, like swinging a bat that has a "point of no return" (Posner, 1980). It was proposed that it is reflexive, phylogenetically older and maybe strongly connected to motor systems controlling orienting behavior. Otherwise, although the two attentional mechanisms have different time spans, they both seem to have similar effects on perception. This suggests that the neural mechanisms underlying the two types of attention are relatively distinct although the neural basis for such distinction have not yet been specified.

On the Locus of Attentional Selection

The last question that needs to be addressed in respect to visual-spatial attention concerns its site of action in the visual processing stream. This issue, known as "the bottleneck problem" has been debated ever since Broadbent (1958) proposed that attentional selection occurs early, because perception is a limited process which requires selection to proceed. As a result, unattended stimuli are not fully perceived. By contrast, late-selectionists (Deutsch & Deutsch, 1963) assumed that perception is an unlimited process that can be automatically performed in parallel. According to this approach selection occurs late, only after full perception, in order to provide the relevant response. Recent neurophysiological evidence, however, questions the usefulness of such debates.

By means of positron emission tomography (PET) attention-induced activation was directly observed in many subcortical and cortical areas with the pattern of activation changing with the nature of the task and the brain site in question (Corbetta, Miezin, Dobmeyer, Shulman & Petersen, 1991; Corbetta, Miezin, Shulman & Petersen, 1993). Structures along both the ventral and dorsal processing streams have been implicated in the control of visual spatial attention. Selective enhancement of neuronal activity has been reported in the superior colliculus, the pulvinar, posterior parietal cortex, area V4 and the inferotemporal cortex (Desimone & Duncan, 1995). Attentional effects, however, which are independent of eye movements have been confirmed mostly in area V4, the inferotemporal cortex and in the posterior parietal cortex. The evidence comes from lesion studies in humans and animals, single-cell electrophysiological recordings and analysis of neural activity from brain imaging studies in alert primates. Thus results so far suggest that the attentional mechanism is distributed along different stages of information processing leading to perception or motor acts. Potentially, therefore, one may expect attention to affect any aspect of visual experience.

Attention and the Visual Perception of Motion

Can attention alter the visual experience of motion? Only recently this question has been addressed by both neurophysiology and psychophysics. The present work joins others in seeking the answer.

Neurophysiological Findings

Single unit recordings in a variety of visual structures reveal an overwhelming number of cells which respond vigorously to moving stimuli (Nakayama, 1985). Only some of these cells, however, respond selectively to the velocity and direction of motion and not to variation along other stimulus dimensions. These class of cells are generally referred to as motion detectors. Motion sensitive cells are mostly found in the magnocellular levels of the lateral geniculate nucleus (LGN), in the striate cortex (V1) and in extrastriate areas MT and MST. From all these structures area MT is considered to be specialized for the analysis of visual motion and neuronal responses in MT correlate well with the perception of motion (Newsome, Mikami & Wurtz, 1986). MT is, however, strongly interconnected with V1, as well as with other extrastriate areas in the cortex. Because motion detectors cover the visual field at different levels in the visual hierarchy it is believed that visual motion is extracted in successive stages (Nakayama, 1985; Cavanagh & Mather, 1989).

Given that the brain mechanisms implicated in both motion perception and attention are distributed it is reasonable to expect that, similar to other aspects of perception, the visual experience of motion is also modulated by attention. Surprisingly, neurophysiological studies on alert primates (Wurtz, Richmond & Newsome, 1984; Desimone & Duncan, 1995) do not offer conclusive evidence for attention related activity in areas implicated in the analysis of visual motion such as the primary visual cortex (V1) and the extrastriate area MT. This does not mean, however, that these areas are immune to attentional manipulations.

The present lack of evidence may be due to inconsistencies in the sources of attentional control (i.e. bottom-up versus top-down factors) or to inappropriate stimulation. It is known, for example, that cells in the striate cortex (V1) encode local translational motion of luminance edges, whereas more global forms of motion, such as the coherent expansion, rotation or translation of random dot patterns are registered in extrastriate areas MT and MST (Snowden, Treue & Andersen, 1992). Yet many experimental stimuli contain both global and local motion components. In fact, recently, by means of functional magnetic resonance imaging (f-MRI) it was demonstrated (Watanabe, 1996) that with attention directed to the global motion of dots MT (but not V1) was more active than in the control condition when observers passively viewed the display. Conversely, with attention to the local motion V1 was more active than in the passive condition. These results suggest that motion processing may be modulated by attention but the stage at which attention acts depends on the task.

Effects of Attention On the Visual Perception of Motion

Indeed, classical investigations (Wertheimer, 1912) and some recent psychophysical results suggest that attention influences motion perception. It was reported, that performing an attentional task while viewing a moving pattern affects the strength of the subsequent motion aftereffect (Chaudhuri, 1990; Iordanova, Riscaldino; Gurnsey & von Grünau, 1996; Watanabe, 1996) though others had failed to replicate this result (Boutet, Rivest & Intriligator, 1996). Also, it was shown that attentive tracking of certain features (e.g. color, texture) may determine the perceived direction of motion in otherwise ambiguously moving stimuli (Cavanagh, 1992; Lu & Sperling, 1995).

Of particular interest for the present study are the well documented effects of attention on the perception of temporal order (Stelmach & Herdman, 1991; Hikosaka, Miyauchi & Shimojo, 1993a) and stroboscopic motion (Hikosaka et al., 1993a; Stelmach, Herdman & McNeil, 1994).

Effects of Attention on the Perception of Temporal Order

The temporal order paradigm is simple. Two stimuli are presented to the left and to the right from fixation and observers are asked to judge the order in which they appear. Before each trial, a brief cue indicates the location to which subjects are instructed to attend (i.e. left, right or fixation). Thus attention is directed either to one of the two stimulus locations or away from both (i.e. to the center). With this method Stelmach and Herdman (1991) found that when the two test stimuli came on at once, the attended stimulus was perceived to appear before the unattended one. Conversely, the two stimuli were judged to appear simultaneously when the attended stimulus followed the unattended one by about 40 milliseconds. These results were replicated by Hikosaka et al. (1993a) with control on eye-movements, more precise cueing of the test location and without attentional instruction. The observed effects were attributed to stimulus driven, transient attention. Taken together, they indicate that the information from the attended location reached perception 30-70 milliseconds earlier than the information from the nonattended location.

Effects of Attention on the Perception of Stroboscopic Motion

Temporal-order presentations include two frame sequences in which observers often perceive stroboscopic motion. In fact, judgments of temporal order are usually based on the impression of motion, rather than on the sequence of two independent events. Thus instead of asking observers to judge the order in which stimuli appear one may ask them to judge different aspects of the perceived motion. With this modification Stelmach et al. (1994) reported that motion was seen away from the attended stimulus when the two stimuli were flashed simultaneously. Moreover, the same bias was observed even if the temporal sequence was in the opposite direction up to a limiting stimulus onset asynchrony (SOA) of about 50 milliseconds at which motion was still perceived but its direction was ambiguous. In other words, attention captured by the onset of the cue (Yantis, 1993) altered the perceived direction of stroboscopic motion in comparison to a control condition when subjects attended to a middle point between the two test locations. In a similar experiment attentional cueing by abrupt onsets created stroboscopic motion in an array of simultaneously flashed bars and biased the direction of stroboscopic motion in sequentially flashed bars (Hikosaka et al., 1993a). It should be noted that the cue was a very small dot which was completely occluded by the subsequent stimuli. The attentional bias was strongest at SOA of 50 milliseconds and decreased in 400 milliseconds. Thereafter, the effect did not disappear but remained stable. Consequently, it was suggested that both transient and sustained attentional mechanisms contribute to the observed motion bias.

Possible Attentional Mechanisms in the Encoding of Visual Motion

The above findings indicate that attention narrowed to a location in space "deceives" the motion detecting mechanism to elicit a motion signal in the absence of temporal asynchrony in the stimulus input or when the asynchrony is in the opposite direction. For example, let us consider the case when motion is seen in an array of stimuli with simultaneous onsets. Without precueing this stimulus setup does not evoke perception of motion. The crucial point here is that directed attention does not simply increase motion sensitivity but generates a motion signal with no physical counterparts. It was proposed, therefore, that attention modulates the input signals to the motion detector, rather than the motion detector itself (Hikosaka et al, 1993a; Stelmach et al, 1994).

In essence, a motion detector integrates signals arriving at different times from different points on the retina. Regardless of the particular model in mind (Reichardt, 1961; van Santen & Sperling, 1985; Adelson & Bergen, 1985) a motion detector relates the spatial difference between inputs with the temporal delay between them to compute motion. In other words, motion is registered only if the input signals are separated in both space and time. Accordingly, a motion detector signals motion when inputs are fed into it sequentially in one direction and remains silent if inputs, though separated in space, come at the same time. Consequently, to account for the perception of motion in an array of stimuli which all come at once, one must assume that signals from the attended side arrive at the motion detector before signals from the nonattended side, resulting in motion away from the cued location (Stelmach & Herdman, 1991; Hikosaka et al, 1993a; Stelmach et al., 1994).

A more difficult question is how attention causes this temporal asynchrony. Obviously, this must involve relative speed-up of signals from the cued location so that they reach the level of motion detection before signals from the nonattended location. This, however, may happen in different ways.

Decreased Processing Latency

One possibility is that attention shortens the delay between the presentation of a stimulus and the onset of processing without affecting the rate of signal transmission (Stelmach et al, 1994). This, however, presents a conceptual problem since, strictly speaking, visual processing starts as soon as light hits the retina, which is a physical event and has nothing to do with attention. In any case, wherever this "onset of processing" might be, such account would predict that the processing advantage for attended stimuli relative to nonattended ones should not be affected by the amount of time available for processing. Reinitz (1990), however, demonstrated that with more time available detection performance increased more rapidly for attended than for nonattended stimuli.

Speed-up of Signal Transmission

A second hypothesis, advanced by Stelmach and his colleagues, and consistent with the above evidence is that attention affects directly the rate of signal transmission. More, specifically, based on the experiments discussed above, it was suggested that attention sharpens the temporal profile of the signal from the attended location which, in turn, increases the rate of this signal's transmission. A sharper profile indicates that signals encoding the attended stimulus peak earlier, last for a shorter time and, as a result, advance faster. This account however, does not specify whether attention modulates the signal along its entire path from retina to "perceptual cortex" or only segments of it.

Local Signal Amplification

A third alternative is that signals elicited by stimuli at the cued location are amplified (Zanker, in press). Depending on the nature of the cueing event this amplification may be bottom-up or top-down in nature, may occur at any level of encoding and would speed up subsequent transmission since stronger signals reach the perceptual threshold faster. In other words, the transmission modulation and the amplification hypotheses are complementary, rather than mutually exclusive. What seems to create controversies, as pointed out earlier, is whether bottom-up local amplification is attentional in nature. We maintain that it is, in the sense that it affects subsequent perceptual events.

To summarize the most important points, cueing by both abrupt onsets and offsets creates illusory stroboscopic motion in two or more stimuli presented simultaneously at distinct spatial locations. The effect is attributed to attention summoned at the cue in a bottom-up manner. It is hypothesized that attention generates illusory motion by speeding up the processing of signals at the cued location prior to their entry in the motion detector. Such speed-up may be due to accelerated transmission rate or local amplification of the attended signal and these two possibilities are not mutually exclusive. In both cases, signals from the attended location would reach the motion detector before signals from the nonattended location. The attention induced asynchrony of inputs from different spatial locations would thus signal motion.

Evidence suggests that similar mechanisms may contribute to the motion induction illusion which is the subject of this study.

The Motion Induction Phenomenon

Some History

It was noticed long ago that a spatially extended stimulus, flashed on abruptly as a complete unit, does not appear to come on all at once. If this stimulus is presented centered at fixation, it is perceived to expand away from its center towards its periphery. Similarly, an abrupt offset of the same stimulus would be seen as contraction towards the center. In both cases, motion is perceived within the stimulus, although no physical motion has occurred. This has been called gamma motion (Kenkel, 1913).

Gamma motion, however, may have unpredictable direction if the stimulus is flashed at different random locations across the visual field. More importantly, another permanently displayed stimulus located close to the object with abrupt onset (offset) can "polarize" gamma motion (Kanizsa, 1951, 1979). Polarization means that the direction of movement is now systematic, that is, away from (or toward) the permanent stimulus, rather than the original expansion (contraction).

The motion induction effect is a specific case of polarized gamma motion. It is also known as "the line motion effect" or "the shooting line illusion" and was first demonstrated by Hikosaka, Miyauchi and Shimojo (1991, 1993a) in the context of their research on the effects of attentional cueing on stroboscopic motion.

Simple and Double Motion Induction

In the initial demonstration of simple motion induction (Hikosaka et al., 1993a) a spot was presented, followed after a short delay (1-4800 ms) by an elongated horizontal bar, touching the spot with one of its ends and presented either to the right or to the left of the spot. The spot remained on throughout the trial (i.e., sustained cueing). With this set-up (Figure 1) the bar was perceived to grow smoothly away from the spot regardless of its position in respect to the spot (i.e. left or right). Subjects were asked to fixate a middle position below the stimulus line and report the direction of motion in a forced choice manner. Optimal motion was perceived at cue lead times (CLT) from 50-100 ms up to the longest delay (4.8 sec).

With transient cueing (spot duration=2 msec, Figure 2), however, the effect dropped to chance level after 1 second. Motion induction was also induced by the abrupt offset of the cue, whereas on the other side of the bar a second dot persisted throughout the complete stimulus sequence (Figure 3). In this case the effect gained strength for up to 100 msec, remained optimal for up to 300 msec and reversed direction thereafter (i.e. motion was now seen away from the permanent cue). It was concluded, therefore, that motion

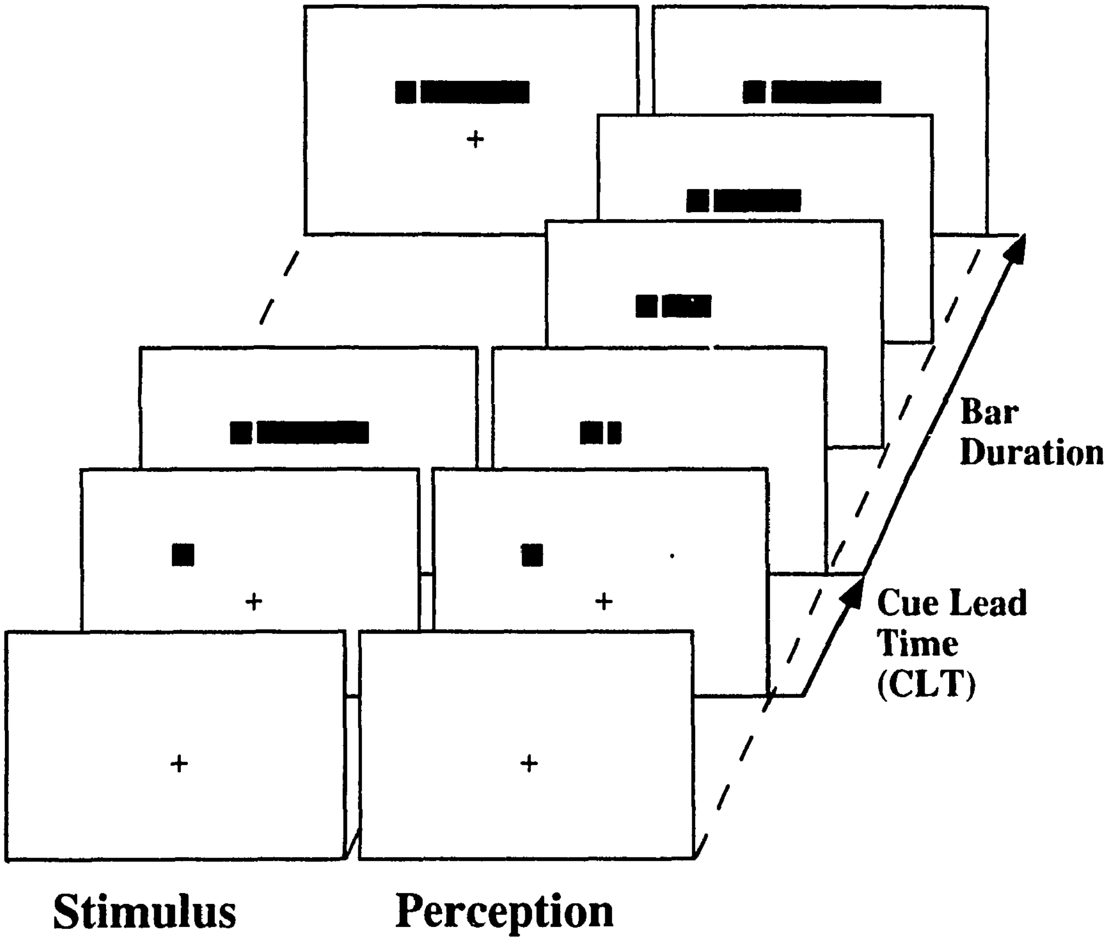


Figure 1. Simple motion induction with sustained onset cueing.

A bar is presented as a whole next to a cue.

The bar is perceived as growing out of the cue.

(optimal CLT=50-100 msec; sustained up to 4.8 sec).

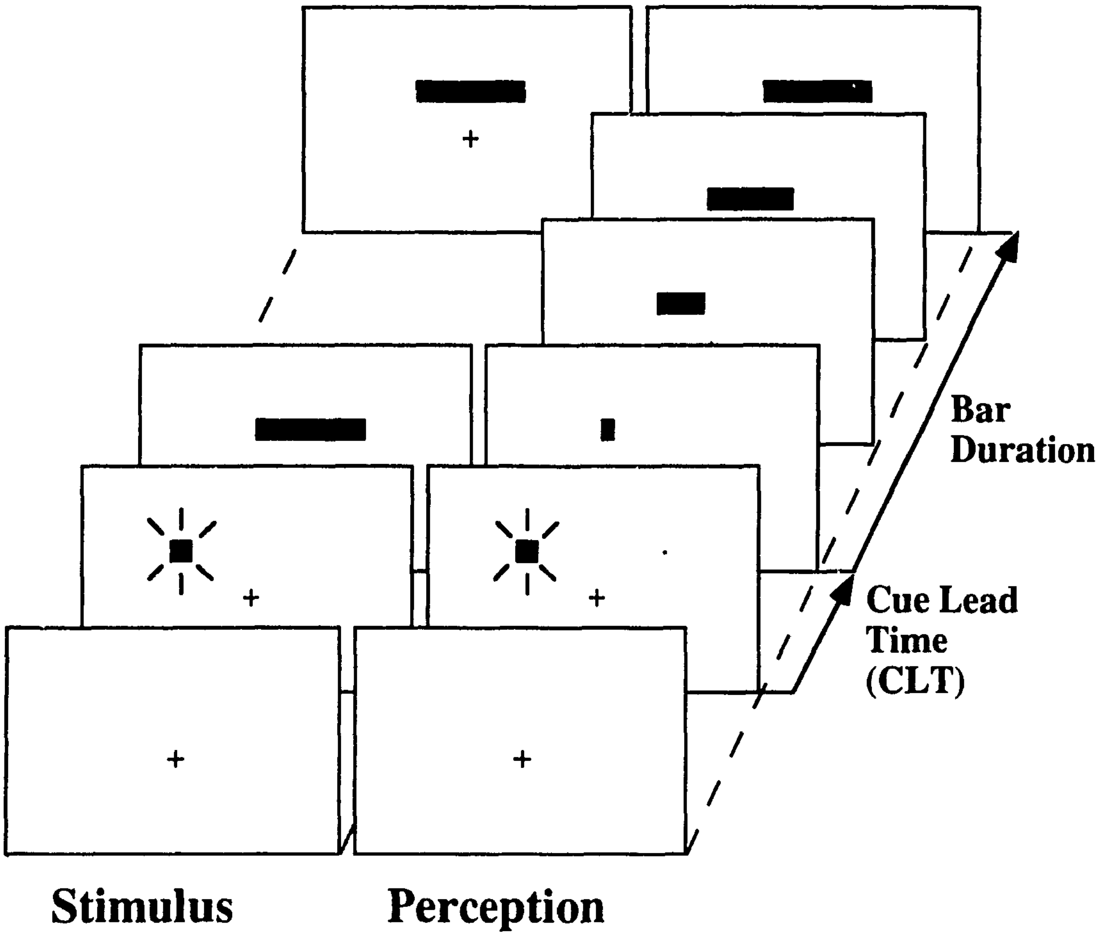


Figure 2. Simple motion induction with transient cueing.

A bar is presented as a whole next to the point of the flash.

The bar is perceived as growing out of the flash.

(optimal CLT=100 msec; extinguished by 1sec).

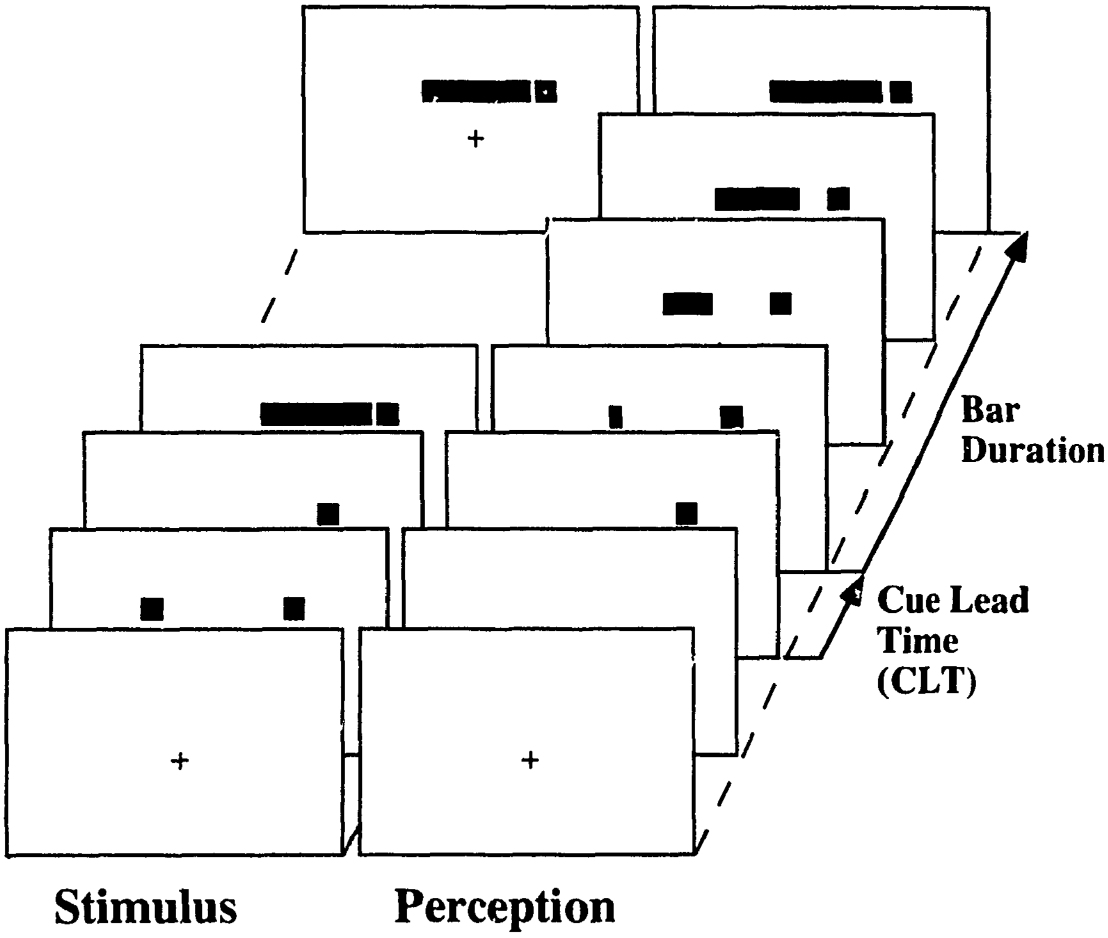


Figure 3. Simple motion induction with offset cueing.

A bar is presented as a whole after the offset of a cue.

The bar is perceived as growing out of the offset point.

(optimal CLT=150 msec; at CLT>300 msec reverses direction).

induction contains both transient and sustained components which could be separated experimentally.

Double motion induction was introduced and examined in detail by von Grünau and Faubert (1992) and Faubert and von Grünau (1995). When the bar was preceded by two spots, one at each side (i.e. split cueing), and the two spots came on at the same time the bar appeared to grow from both ends towards its center where collision was perceived (see Figure 4). With a time delay (Stimulus Onset Asynchrony, SOA) introduced between the onset of the two cues, the point of perceived collision shifted from the center of the bar in direction away from the cue that was presented last. Cue lead time between the last spot and the bar was fixed. The shift increased in magnitude with increasing SOA between the two cues.

Furthermore, it was shown that simple motion induction may occur with the simultaneous onset of multiple cues when the bar is presented subsequently at an unpredictable location next to any one of the cues (von Grünau, Dubé & Kwas, 1996a) or when multiple bars are presented at all cued locations (Faubert, 1996). These effects cancel out if the bar is presented always exactly in the middle between two cues (double motion induction).

Varieties of Motion Induction

Simple motion induction may be observed under a large variety of conditions with stimuli defined not only by luminance contrast but also by contrast in color, motion, stereodepth and texture (von Grünau & Faubert, 1994). In addition, the effect is also observed when the cue and the bar are defined by different attributes. Although, luminance and color defined stimuli produce the most compelling impression of motion, the simple motion induction depends very little on the particular visual attribute channel that carries the stimulus information.

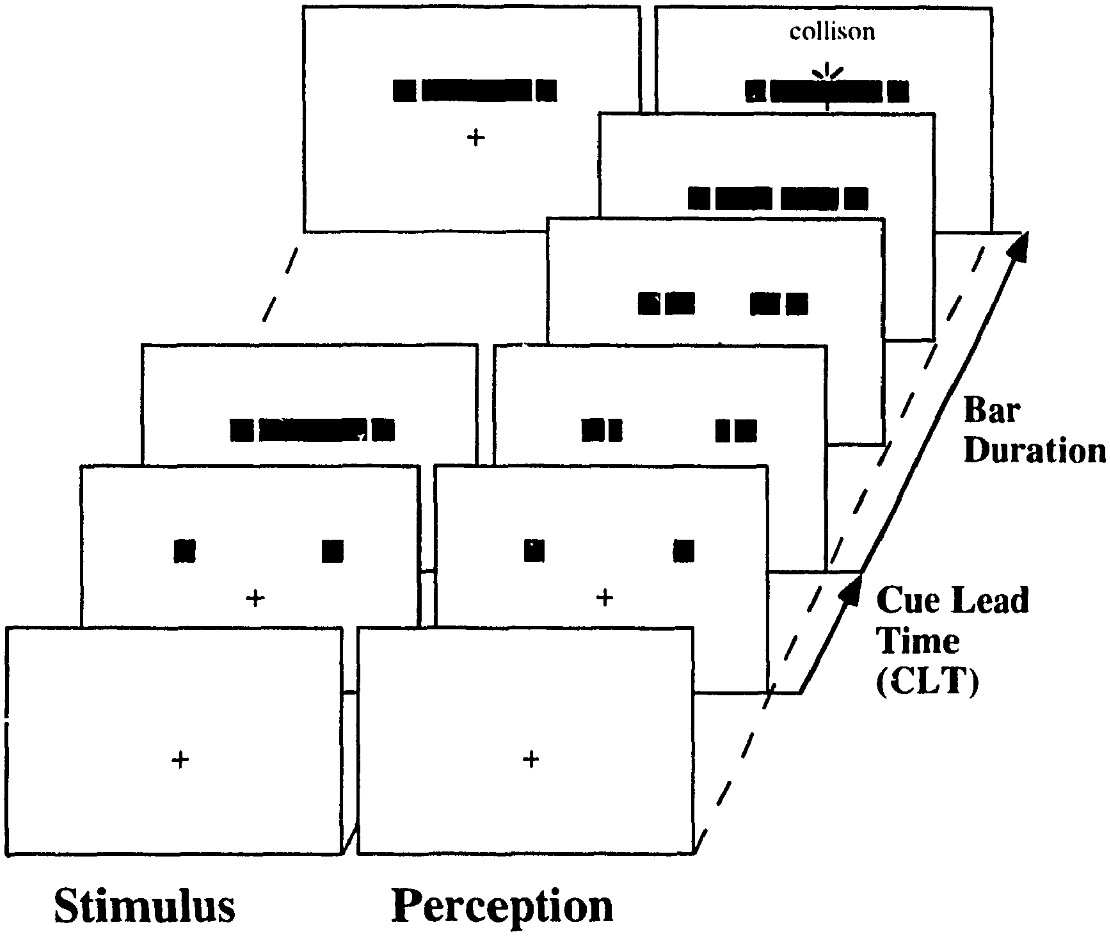


Figure 4. Double motion induction with simultaneous split cueing.

A bar is presented as a whole in the middle between two cues.

The bar is perceived as growing from both ends towards its center.

In contrast, double motion induction is strongly dependent on the attributes defining the cues and the bar, as well as on their geometrical arrangements (Faubert & von Grünau, 1995). For example, with simultaneous cueing, motion is always seen away from the cue defined by the same attribute as the bar.

Most interestingly, motion induction can occur even in the absence of a physical cue, when subjects have learned or are instructed to attend to an empty location in the visual field (Shimojo & Tanaka, 1995). Moreover, this visual illusion may be also evoked by an auditory, or somatosensory cue (Shimojo, Miyauchi & Hikosaka, 1992).

The fact that motion induction occurs in so many different contexts suggests that both low-level and high-level mechanisms contribute to the effect. Thus motion induction, in spite of its similarity to stroboscopic motion, has some unique and intriguing features.

Motion Induction and Stroboscopic Motion

Motion induction and stroboscopic motion are similar in that they are both forms of apparent motion and both occur within a two-frame temporal sequence. Stroboscopic motion, however, is seen between frames, whereas motion induction occurs within the second frame only. In particular, motion induction is seen within the bar and not in the space between the cue and the bar. Most importantly, whereas good stroboscopic motion is experienced only within a restricted range of spatio-temporal separations, the parameters of motion induction are much more variable - the illusion may occur at quite long temporal delays and at larger separations between the cue and the bar, depending on experimental context . Also, regardless of whether the cue is onset or offset, the motion is always away from the cue, rather than away from the offset of one stimulus towards the onset of another stimulus as in stroboscopic motion. Furthermore, whereas under isoluminant conditions motion induction is only slightly reduced, stroboscopic motion is severely reduced or eliminated (Ramachandran & Gregory, 1978). Finally, in contrast to stroboscopic motion, motion induction can be triggered crossmodally and in a voluntary manner, even in the absence of a cueing stimulus.

The Attentional Account of Motion Induction

The attentional cueing hypothesis (Hikosaka et al., 1993a) proposed to account for the illusory temporal order and stroboscopic motion observed with static stimuli was used by many to explain a large variety of motion induction phenomena. Because the line stimulus can be conceived as an array of discrete stimuli with the separation between them removed the attentional account of motion induction is a straightforward extension of the one already discussed with respect to the illusory temporal order and the stroboscopic motion experiments.

The Attentional Speed-up Hypothesis

In the case of simple motion induction, it was assumed that the abrupt onset (offset) creates a transient gradient of activation centered at the cued location which spreads to the neighbouring region. Processing of stimuli presented subsequently is accelerated according to the strength of the attentional gradient. Based on the attention literature, it is assumed that the gradient is strongest at the cued location and decays with increasing distance away from it. Consequently, the end of the bar closest to the cue is processed first, followed by the adjacent parts until the other end is reached. This creates a sequential input to the motion detector and yields the perception of motion within the bar away from the cue. Thus a steeper attentional gradient would produce a longer time differential between the arrival of signals from the bar ends at the motion detector. In other words, a strong attentional gradient, would yield slower (and more conspicuous) illusory motion.

The above explanation may be readily applied to the double motion induction case (Faubert & von Grünau, 1995). The fact that motion is perceived simultaneously away from each cue (when cues come on together) suggests that attentional facilitation may not be restricted to a single location in space. In other words, it is possible that two or more gradients arise at different locations at the same time. With two cues presented simultaneously, processing speed is accelerated to an equal extent at both locations. Consequently, a bar between the two cues will grow away from both ends with collision in the middle. With a time delay between the two cues the attentional gradient at the cue presented last would be steeper than the gradient at the other location which is to be expected from the transient nature of attention due to the cue's onset. Consequently, the perceived motion away from the cue presented last would be stronger thus pushing the point of perceived collision towards the other cue.

Furthermore, since it was shown that a cue presented to one eye induces illusory motion within a bar presented to the other eye (Hikosaka et al, 1993a) it was suggested that attention modulates signals *before* they reach the motion detector (presumably in MT) but *after* the point of binocular convergence (i.e. after LGN). With split cueing, however there was a short lasting advantage for the cue presented to the same eye as the bar (Faubert & von Grünau, 1995) suggesting some monocular contributions to the transient effect. Other results (Zackon, Casson, Stelmach & Faubert, 1995) obtained with monocular testing reveal important hemifield asymmetries at short delays and suggest that subcortical structures such as the superior colliculus may at least partially mediate the transient effect of the cue. On the other hand, the persistence of motion induction at longer delays, suggests attentional modulation at higher levels in the cortex. Thus at the present time the locus of the hypothesized attentional modulation is unknown but seems to depend on the time delay between the cue and the bar, as well as on the nature of the cueing event.

Evidence for Gradient of Attention in Motion Induction

The attentional hypothesis of motion induction is parsimonious and consistent with the well documented increase in perception efficiency by spatial precueing . Research from different laboratories supports the major premise that signals from different parts of the bar reach perception at different times, according to their proximity to the cued location.

The strongest support comes from studies which had canceled the illusory motion within the bar by physical or stroboscopic motion in the opposite direction (Miyauchi, Hikosaka & Shimojo, 1992; Steinman, Steinman & Lehmkuhle, 1995). In this way the perceptual asynchrony (i.e. motion) is directly quantified by the amount of physical asynchrony (speed) in the opposite direction needed to null the effect. To assess the hypothesized gradient of attention, the bar can be broken into segments of equal length and the motion induction nulled in each of the segments at different distances from the cue. With segments of the same length the time difference (Δt) component of the nulling physical velocity may be taken to measure the perceptual asynchrony between the two ends of each bar. As hypothesized, this method revealed a spatial gradient of attention by integrating the nulling physical asynchronies (Δt) at varying distances from the cue (Miyauchi et al, 1992). In addition to the region of facilitation cantered at the cue others had mapped an inhibitory surround further away in the periphery, where the direction of illusory motion was reversed (Steinman et al., 1995).

Similar results were obtained when a luminance gradient within the bar was used to cancel the illusory motion (von Grünau, Saikali & Faubert, 1995; von Grünau, Racette & Kwas, 1996b). Since it is known that brighter stimuli are processed faster than dimmer ones (Roufs, 1963) the luminance differential within the bar needed to cancel the illusory motion was used as a measure the strength of motion induction. Detection times for a range of luminances were independently measured and thus the nulling luminance difference was converted into a temporal difference indicating the difference in processing times between the two ends of the bar. It was also found that increasing the bar length increased the processing time difference up to a point after which further increase in bar length decreased the processing time difference. This was interpreted as evidence for an antagonistic center/surround attentional field around the cued location.

The facilitation field was shown to spread up to 6-7 deg around the cued location (Steinman et al., 1995). The extent and steepness of the attentional gradient, however, varied as a function of cue lead time.

Transient Effects in Motion Induction

Typically, the basic motion induction phenomenon is demonstrated with an abruptly presented cue which remains on display throughout the entire stimulus sequence. Based on the time course of the illusion, it was hypothesized that sustained cueing by abrupt onsets engages both the transient and the sustained mechanisms of attention (Nakayama & Mackeben, 1989). It was also shown that the two components could be separated experimentally since only the transient component was present with a flashed cue and with cue offset which are both transient events (Hikosaka et. al, 1993a). Therefore, it was proposed that the transient effect of the cue may be mediated by responses of off- and on-neurons with transient properties found mostly within the magnocellular visual pathways.

Magnocellular Contributions

Although more research is needed in this direction, some reports in the literature support the hypothesis that the magnocellular system mediates the effect of localized abrupt luminance changes on the subsequent perception of the bar. The magnocellular stream favors processing of rapid motion, flicker, low contrast and low spatial frequencies. Accordingly, it has been found that motion induction is stronger with low contrast cues than with readily visible color defined cues isoluminant to the background (Steinman, Steinman & Lehmkuhle, 1995). It was also shown that cues presented at flicker adapted locations are less effective in triggering motion induction than cues presented at non adapted locations (Iordanova, Kwas & von Grünau, 1995).

Is Attention Really Necessary?

Recently, it has been argued (Zanker, in press), that there is no need to implicate attentional mechanisms to explain the basic motion induction phenomenon. It was shown that the direction of illusory motion could be derived directly from the properties of simple motion detectors. In simple motion induction with sustained onset cueing, for example, the centroid of the intensity distribution actually shifts in space from Frame 2 (cue) to Frame 3 (cue-bar) which would trigger a motion signal directed away from the cue (Figure 1). Analogously, in double motion induction (Figure 4) the intensity profile would remain centered between the two cues in both Frame 2 (cue-cue) and Frame 3 (cue-bar-cue). Consequently, no motion or ambiguous motion will be perceived within the bar.

Although this argument is sound, there are two problems with it. First, whereas it predicts the overall direction of illusory motion, it cannot account for the quality of the motion percept, especially in the double motion induction case. It was argued (Zanker, in press) that in simple motion induction motion is not seen between cue and bar because the directional signal is spatially diffuse and would be subjectively attached to solid objects. In double motion induction, however, there is a systematic perception of two motions going in opposite directions, whereas the motion detector alone predicts perception of no motion.

Second and more important, this model requires additional assumptions to account for the illusory motion triggered away from a cue with abrupt offset (Figure 3) because in this case, the shift of the intensity centroid would be away from the persisting dot rather than, as perceived, away from the offset cue.

Finally, the fact that with sustained cueing the illusion persists at full strength for 5 and more seconds after the onset of the cue is not easily explained either. Stroboscopic motion breaks down at such large temporal delays since motion detectors have certain limits for temporal integration.

Thus this alternative explanation, in its present form, is relevant only for shorter cue lead times and only for motion induction due to abrupt luminance increments.

Sustained Effects in Motion Induction

Research has been primarily concerned with the transient nature of motion induction. It is its sustained characteristics, however, that relate the illusion to gamma motion, rather than to stroboscopic motion. By "sustained" is meant that the effect gains strength up to a critical CLT and remains at its optimal level over the tested range of longer CLTs, with no tendency to decline. Sustained motion induction, however, may have a different nature depending on the task of the observer and the nature of the cueing event.

Stimulus Bound Effects

In respect to the initial demonstrations, it was suggested that the persistence of simple motion induction up to 4.8 seconds with sustained abrupt cueing reflects localized residual activation maintained by the mere presence of the cue (Hikosaka et al, 1993a). These authors were confident that the sustained component is not due to maintaining attention deliberately at the cued location since observers were explicitly instructed not to do so. Indeed, the sustained component in motion induction was also present when the bar appeared at an unpredictable location and was preceded by the simultaneous onset of multiple identical cues (von Grünau et al., in press). This effect was present but somewhat variable immediately after the onset of the cues (45-75 msec) and, similar to the transient effect discussed earlier, remained at a steady optimal level at CLTs longer than 100-150 milliseconds. In this situation it is unlikely that subjects attended voluntarily and simultaneously to each one of the cued locations. One may say that this situation is attentionally neutral in that no item is preferred over the others. The local facilitating influence of the cue at long CLTs, therefore, could be attributed to "non-attentional factors", such as sensitization (von Grünau et al., 1996a). It could also be argued that attention was evenly distributed and bound to the same extent at each of the cued locations. The only difference between these statements is semantic and they are equivalent to the original proposal of residual activation due to the mere presence of the cues.

Stimulus Driven Attention

A sustained effect of a different kind was observed when one of the cues in the homogeneous multi-item displays above (von Grünau et al., 1996a) was replaced by a cue with an odd orientation (Figure 5) which is known to "pop-out" in an effortless bottom-up manner (Treisman & Gelade, 1980). After a variable CLT the bar was presented exactly in the middle between two randomly chosen cues. When the bar appeared between two identical cues motion induction was at chance level, with any local stimulus bound effects being canceled. A sustained effect away from the "pop-out" cue was thus isolated. It gained strength up to 200-300 msec (a bit longer than the 100 msec with transient cueing) and maintained stable optimal level up to the longest CLT used (i.e. 600 msec). This effect was attributed to involuntary capture of attention at the pop-out location (von Grünau et al., 1996a). In fact, rather than assuming that attention was not there and was afterwards captured, it is obvious that the probability of illusory motion reflected the time course of the cueing event, which in this case was the stimulus-driven perceptual selection of the odd cue. On one hand, the sustained nature of the effect may simply reflect the lasting salience of the "pop-out" cue with respect to its surround. It is also likely, however, that after perceptual selection had taken place (i.e. at delays longer than 200-300 msec) observers had maintained attention at the selected location in a voluntary manner which would also explain the sustained nature of the effect.

The attentional explanation of this effect was again debated on the grounds that a feature discontinuity is detected "preattentively" (Zanker, in press). The observed illusory motion was modeled by a motion detector with a local gain-control mechanism.

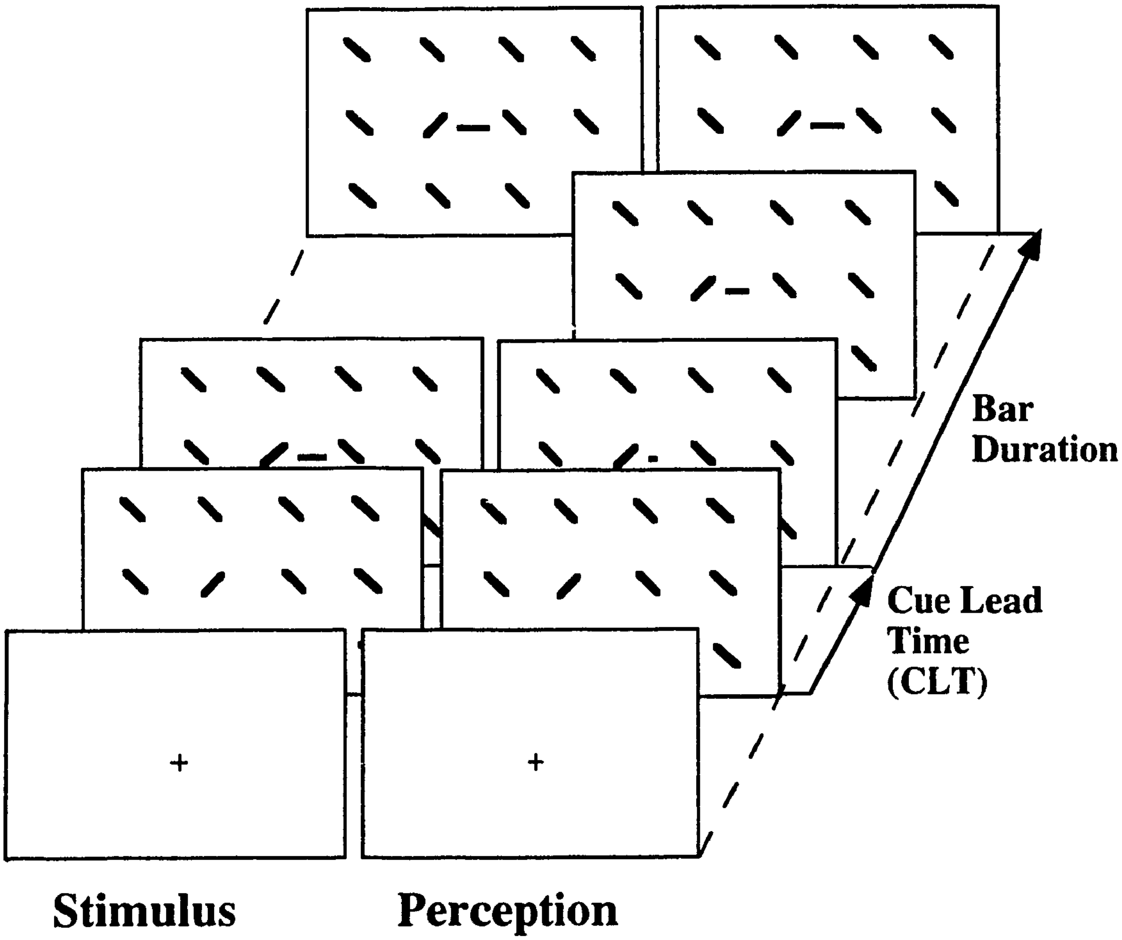


Figure 5. Motion induction with "pop-out" cueing in multi-item displays. A bar is presented as a whole next to the "pop-out" cue. The bar is perceived as growing out of the "pop-out" cue. (optimal CLT=200-300 msec; sustained up to at least 600 sec).

It was suggested that the local signal registering the feature discontinuity is amplified, thus having more weight in determining the response of the motion detector. This, however, does not preclude speed-up of the feature contrast signal, beyond the level at which it is encoded, since stronger signals advance faster along the processing pathways. In fact this model implies that the source of the hypothesized speed-up of processing is signal amplification rather than direct modulation of the rate of signal transmission (Stelmach et al., 1994). This is in line with the recent proposal (Lu & Sperling, 1995) for a separate attention-based motion system, within which motion detectors receive direct input from "salience maps" registering feature contrasts, textural discontinuities etc.. In essence, the local gain mechanism is a mechanism of attentional modulation, which, as admitted (Zanker, in press), may be controlled in both a bottom-up and a top-down manner.

Voluntary Attention

Consistent with the above, Hikosaka, Miyauchi and Shimojo (1993b) obtained a sustained effects by means of voluntary cueing of attention. They presented the bar between two cues of different equiluminant colors which were simultaneously presented. In this situation the transient effect of cue onset was balanced since it would occur equally often away from either one of the cues. Observers were asked to attend to the cue with a predefined color while maintaining their gaze at fixation. The direction of illusory motion was thus entirely determined by voluntary attention - and accordingly, motion was away from the cue with the attended color. This effect took more time to develop (400 msec) than the one driven by stimulus "pop-out" (200-300 msec). It remained sustained after 400 msec but was easily interrupted for 200-500 msec if the irrelevant cue was flashed.

To summarize, the variety of effects discussed suggests that motion induction reflects the time course of the local activation associated with the encoding of the cueing event. Motion induction develops quickly (100 msec) and decays fast with transient cueing, is sustained as long as the cue remains on display, is somewhat slower with "pop-out" cueing (200-300 msec) and even more so with voluntary cueing of attention (400 msec). In all cases the signal triggered by the cueing event is stronger relative to its context which amplifies signals from stimuli presented subsequently at the cued location. This is equivalent to saying that attention drawn to the cue, amplifies signals to subsequent stimuli presented at the attended location, which, in turn, speeds up their transmission to the motion detector.

The strength of the attentional account of motion induction is that it provides a common framework for understanding the diverse phenomena described above. Its major drawback is that attention is a slippery concept which may be operationalized in different ways. Basically, we have maintained throughout this text that at any moment in time as long as we are awake (with eyes open) we are attending to a limited area in visual space. Yet others may prefer to draw a line between preattentive (automatic) and attentive (voluntary) selection. Interestingly, attempts to model motion induction in a bottom-up manner have lead to postulating a mechanism modulating the input to the motion detector - which is a way to formalize attention. In cases when the illusion is triggered at will, however, avoiding the concept of attention would not simplify the problem.

Rationale and Outline of the Present Study

The contributions of voluntary attention to the large number of "motion induction effects" discussed above complicates interpretation of results obtained at longer delays. It is well known that voluntary attention is hard to control and is very sensitive to inference, systematic biases and subtle demand characteristics of the experimental situation. In the case of pop-out cueing, for example, sustaining motion induction beyond 300 milliseconds may have been due to both bottom-up and top-down factors. Voluntary attention is a flexible process and may work in various ways thus generating "spurious varieties" of motion induction. It is therefore important to examine the extent to which the illusion is sensitive to systematic and predictable top-down selection.

The present study examines in detail the time course of motion induction with active, voluntary cueing of attention while controlling for stimulus factors such as cue salience and cue persistence. This issue is not well researched, except for scattered observations in the literature and the single experiment described above (Hikosaka et al., 1993b). With only two possible locations and with a distinction along a single stimulus dimension (i.e. color), however, attentional selection is trivial. It is possible that expectant attention was maintained at the two possible locations which had made it easier to select the cue with the target color. It was thus hypothesized that the critical CLT of 400 milliseconds reported for optimal motion induction with voluntary cueing (Hikosaka et al., 1993b) may not generalize across different stimulus contexts. Usually, deliberate attentional selection unfolds in conditions of greater uncertainty when more than two alternatives are present in respect to the attributes defining the target-cue and its possible location.

In the present experiments cueing took place in the course of deliberate search for a target defined by a conjunction of features (color and orientation) among multiple irrelevant cues. Based on the method developed by von Grünau et al. (in press), all items in the visual search display were presented simultaneously and acted as potential cues. In this study, however, the target was well masked among the other items since each irrelevant cue shared one of its features with the target (i.e. either its color or its orientation). Two color values (red, green) and two orientation values (- 45°, + 45°) were used to define each item. Thus the target was unique only in its particular combination of features and could not be passively singled out. Also, items were equated in luminance and evenly and widely spaced which was intended to control for selection based on stimulus salience or incidental stimulus groupings. The bar interrupted search at variable delays after display onset and appeared at an unpredictable location exactly in the middle either between two distractors or between the target and a distractor. In this way any effects due to the abrupt onset of the cues or to their presence were balanced. Thus we were confident that if motion induction occurs it would be due only to attention directed deliberately at a particular cue location. On each trial subjects reported the direction of perceived illusory motion within the bar in a 2AFC manner. Reaction times to the target presence were also recorded.

The four experiments in this study addressed several questions. First, attentional allocation was expected to be far more demanding with stimuli defined along two dimensions, with more than two "noise" elements on display and with unpredictable locations of the target and the test bar. It was hypothesized, therefore, that in such situation voluntary attention will engage at irrelevant items before focusing at the target cue, and consequently, motion induction at target (if observed) would peak at longer delays after cues' onset than the time reported by Hikosaka et al.(1993b). More specifically, it was expected that the probability of motion induction at target would be highest at cue lead times close to the average search time needed for target detection when it is most likely that the target is selectively attended. Also, this optimal time was expected to lengthen systematically with increased perceptual load (i.e. number of search items) and increased uncertainty in respect to the bar position.

In addition, to ensure that the examined motion induction effects are due to deliberate allocation of attention and are not stimulus specific, the combination of features defining the target was reversed between experimental blocks while the two sets of distractors remained the same. It was expected that the change in target identity will not affect the pattern of results as long as observers are instructed to search for the new combination of features.

The incidence of motion induction at subsets of distractors with either one of the target's features was also of interest. As suggested by some (Kaptein et al., 1995), before target selection attention may be selectively allocated to a subset of items with one of the target-relevant features, whereas distractors with the irrelevant feature along the same dimension may be actively ignored. If this is the case, one may expect that motion induction will as well occur at any member of the selected subset when the other item flanking the bar belongs to the target-irrelevant subset.

Finally, using the same displays and search task, attention at randomly chosen search items was assessed independently at different times during search. Observers were asked to detect a low contrast small segment of the bar appearing either next to a search cue or in the middle between two cues. On target present trials, search irrelevant items acted as invalid cues and the target acted as a valid cue. Reaction times obtained on target absent trials were used as a baseline measure. It was expected that detection would be facilitated in the vicinity of the target and inhibited at distractor locations. By combining visual search with the cost-benefit paradigm we assessed not only the magnitude and spatial extent of attentional facilitation and inhibition at the different cue locations but also the time courses of these processes during search. In this way it was possible to relate directly the time course of deliberate allocation of attention at the target with the time course of motion induction at target in the same search situation.

EXPERIMENT 1

The first experiment examined the dynamics of attentional selection during visual search in its own right, apart from its potential contribution to the motion induction effect. Such preliminary work was important since the same task and displays were combined with the motion induction paradigm in Experiments 2 and 3. The results from Experiment 1 determined the choice of temporal parameters in later experiments and outlined a working model of attentional allocation which guided subsequent interpretations.

In the present study the target shared its color and orientation with nontarget items but was unique in its conjunction of color and orientation. The strong version of the feature integration theory of attention (Treisman & Gelade, 1980) predicts that search for such target should be slow and serial with the attentional spotlight scanning items one by one in a sequential manner. Reaction time to the target's presence or absence is thus expected to increase linearly as more items are added to the display. In addition, if items are searched one by one at random, the target's presence should be detected twice as fast as its absence (i.e. self-terminating search).

As noted earlier, however, search for conjunctions does not always conform to the above predictions. The steepness and linearity of search functions were shown to depend on the distinctness of features, on the particular items used and on their density and layout (Wolfe et al, 1989). Moreover, the software program used in subsequent experiments required some modifications to the standard visual search paradigm: items were evenly spaced, arranged in a rectangular matrix and their number was varied between but not within conditions. Therefore, it was important to analyse explicitly the search functions produced by the present task. In addition, Experiment 1 investigated whether reversing the target features (i.e. red/right oblique vs green/left oblique) while keeping distractors the same would change the search process in a qualitative way.

Method

Subjects

Ten subjects, ages between 24 and 39, volunteered in all conditions of Experiment 1. They were all right-handed and had normal or corrected-to-normal vision. Six of the observers had no previous experience in psychophysical experiments.

Apparatus

Stimulus presentation and data collection were controlled by a Macintosh IIci computer equipped with a NuVista+ graphics board and a high resolution 13"Apple Color Monitor. The experiment was set up via specialized software programs (VSearch/Color^{TM}3.3.2., IMaker^{TM}3.3.2.), developed and copyrighted by the UBC VSearch Lab. Reaction time was measured in milliseconds with temporal resolution of 15 milliseconds. Stimulus luminance was adjusted with a photometer.

Head position was fixed with a chin and forehead rest at a 57 distance from the screen.

Stimuli

Search items

All search items were oblique elongated bars with identical width and height (see Figure 6 & Figure 7; dimensions are given in degrees of visual angle). They differed in color (red vs. green) and orientation (-45^0 : left oblique vs. $+45^0$: right oblique). The two color values and the two orientation values were chosen to be optimally distinct along their respective dimension. Within a given condition one item was defined as a target and two others - as distractors. The target was distinct from the distractors by its unique combination of color *and* orientation.

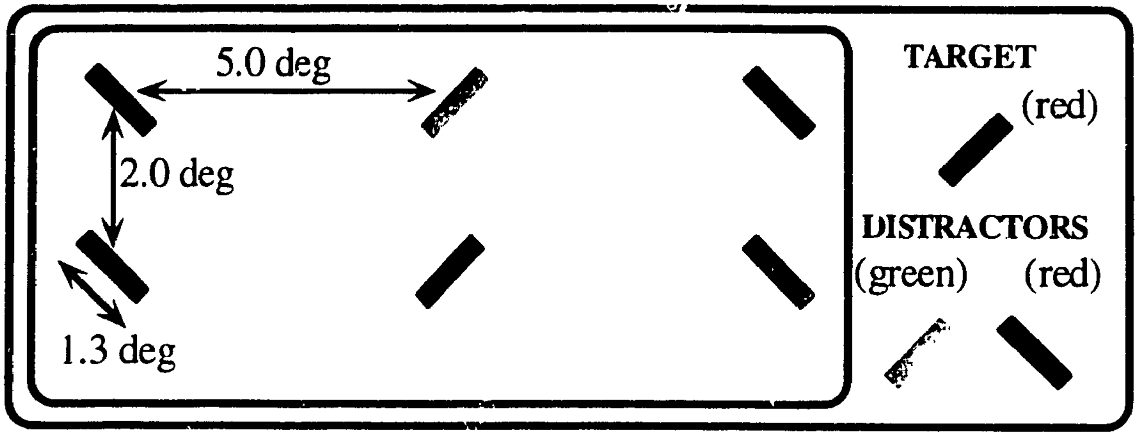


Figure 6. Display sample with a red right-oblique (+45°) target (Experiment 1).

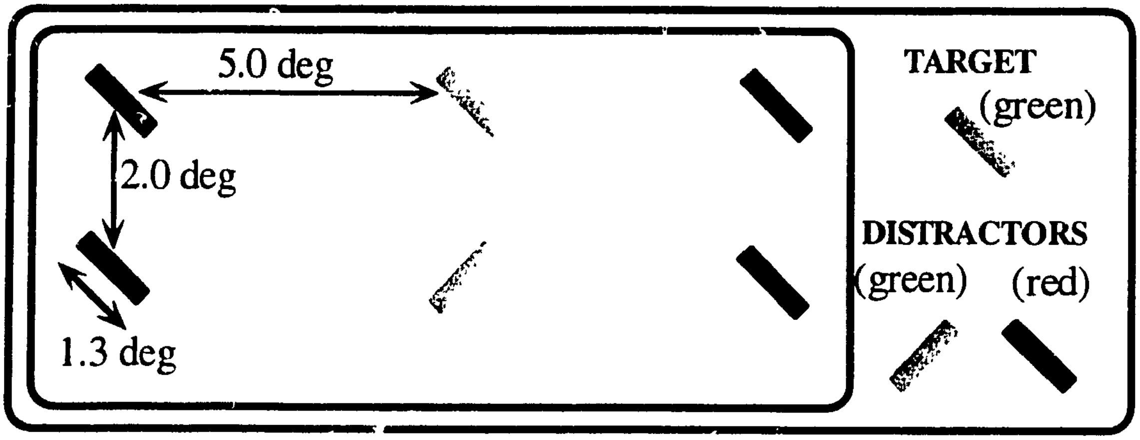


Figure 7. Display sample with a green left-oblique (-45°) target (Experiment 1).

In half of the conditions the target was defined as a +45° red bar and appeared together with two types of distractor items +45° green and -45° red bars, each sharing only one feature with the target - i.e. orientation *or* color, respectively (see Figure 6). The features defining the target were reversed for the rest of the conditions (i.e. -45° green, see Figure 7) whereas the two distractor types remained the same, each sharing one feature with the target.

Items were presented on a white background (86.9 cd/m^2). The red color(19.7 cd/m^2) and the green color(20.3 cd/m^2) were adjusted to have about the same luminance as physically measured by a photometer. Thus all items had a Michelson contrast of .63 relative to the background (i.e. were darker than the background).

Displays

The display area filled the whole screen, subtending 23.5 X 17.5 degrees of visual angle at 57 cm distance between eyes and screen. Two, four, eight, 16 or 24 items arranged in rows and columns were presented within the display area. The rectangular matrix formed by the search items was always centered at fixation which coincided with the geometrical center of the display. The spacing between items, as shown in Figure 6 and Figure 7, was maintained constant across display sizes. While display density remained the same, the number of rows and columns in the matrix of items changed from 1 to 7 and 2 to 4, respectively, depending on the number of items within a condition.

Mask

A high contrast black and white checkerboard mask filled the display area at the end of each trial. It consisted of black and white squares (.3 X.3 deg) and this particular spatial structure was designed to interfere optimally with the spatial extent of the horizontal bar and of the low contrast spot used in subsequent experiments.

Procedure

Subjects were tested individually in a quiet and darkened room. The procedure was explained by the experimenter prior to each session.

The combination of two target types (+45° red, -45° green), five display sizes (2, 4, 8, 16 and 28 items) and two trial types (target present, target absent) resulted in 20 experimental conditions (i.e. 10 conditions for each target type) which were administered to each subject in a random order. Each session (condition) lasted about 15 minutes. Sessions took place on the same or different days, depending on the subjects' availability.

Each session comprised three blocks of 60 trials. Within a block the target was present on half of the trials (i.e. 30 positive trials) and absent on the other half (30 negative trials). Thus for each display size and target type there were 90 positive and 90 negative trials, randomized within each block.

The sequence of events and their duration within a trial is illustrated on Figure 8. The target was described and shown to the subjects before each session. On each trial observers had the task to search for the target and report its presence or absence as quickly as possible by pressing two different keys on the computer keyboard. In the beginning of each session subjects positioned their right and left index fingers on the target present and the target absent key, respectively. Subjects were instructed to fixate at the onset of each trial and to maintain the fixated position as much as possible during search thus minimizing eye movements. After 400 ms the fixation cross was replaced by the matrix of search items which marked the beginning of search. On each trial the distractors and the target (if present) appeared at random locations. The number of distractors from each type was also randomly varied across trials. The number of possible item locations was limited by the number of rows and columns for a given display size. The mask was displayed as soon as a response was given, or after 2500 ms if a response was not made, remained on for 400 ms and was replaced by the next trial's fixation cross. All subjects in all experimental conditions responded within the response time limit.

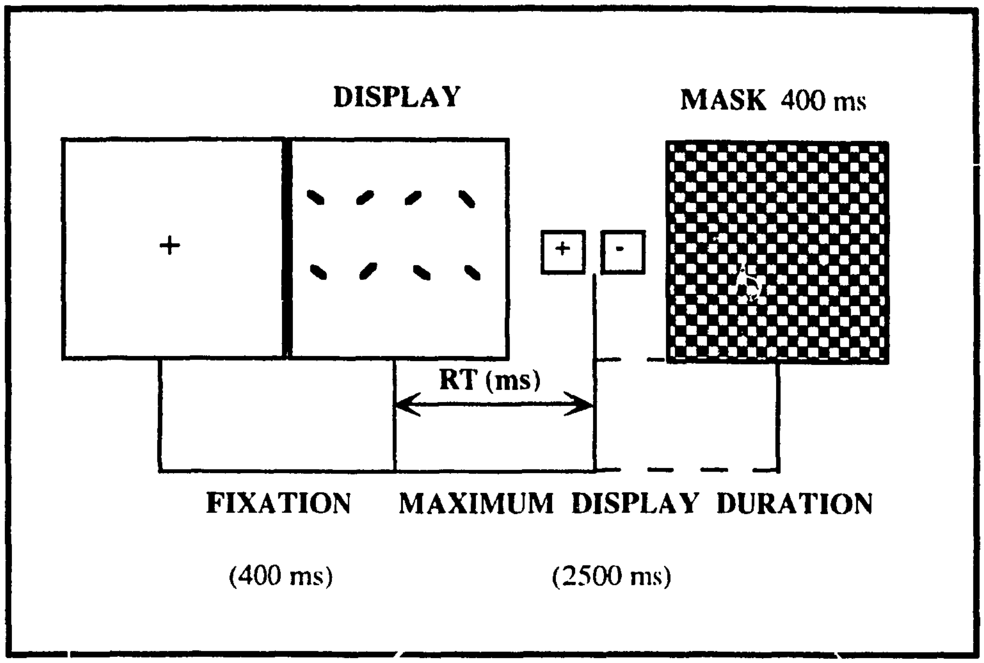


Figure 8. Sequence of events within a trial (Experiment 1).

The time from display onset to the key press indicated the duration of search and was recorded in milliseconds for each trial. The accuracy of the response was also recorded (correct-0 or wrong-1).

Results

The raw data consisted of each subject's mean search times for correct responses from the 90 positive and 90 negative trials in each experimental condition. Error data was not analyzed since response accuracy was higher than 96% for all subjects and there was no evidence for speed-accuracy trade-off across conditions. On average, error rate was not associated with faster response times and did not vary with display size. Mean error rates ranges across display size (smallest to largest) in each of the four experimental conditions were as follows: 98%-97%; 98%-99%, 97%-96%; 98%-98%.

Three types of analyses were performed. Linear regressions and analyses of trends examined the change response time (RT) as a function of display size. Regression statistics were then compared across target type to test whether search changed with reversal of the target features.

Linear Regression

Four linear regression equations of RT on display size were computed for each subject, for each of the four combinations of trial type (target present, target absent) and target type (+45° red, -45° green). Figure 9 and Figure 10 show the two least square regression lines fit through the average RTs for each target type.

As can be seen in Figure 9 and Figure 10, on average, RT increased linearly as more items were added to the display on both positive and negative trials for both target types. The regression lines fitted the data well, accounting for 91% and 99.8% of the variance in mean RT for a red right-oblique target, on target present and target absent trials, respectively, and for 94.2% and 98.8%, respectively, when the target features were reversed (i.e. green left-oblique).

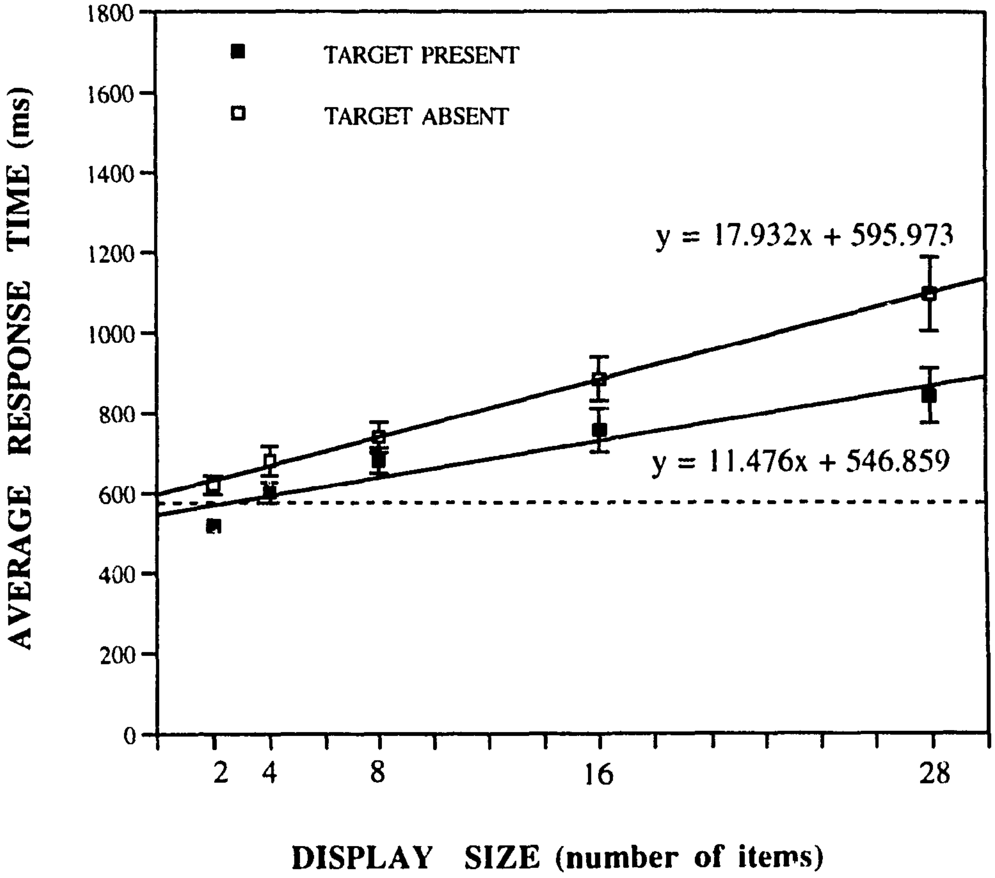


Figure 9. Search time for a red right-oblique (+45°) target as a function of display size.

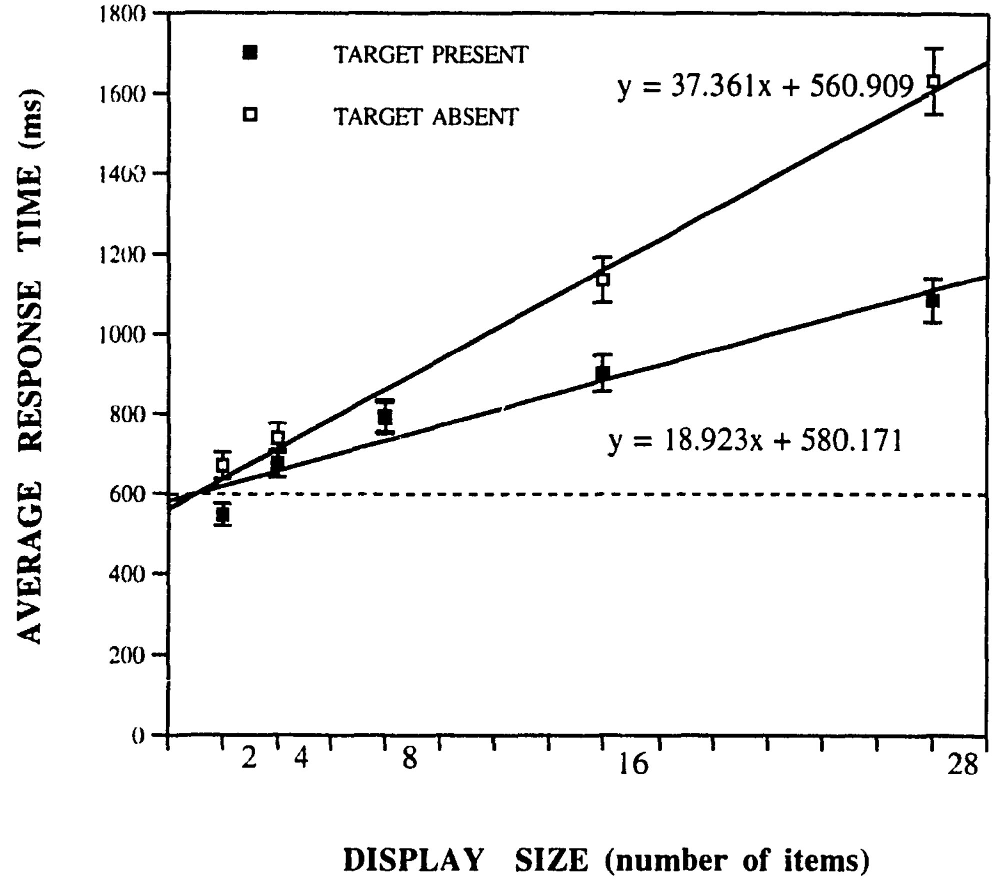


Figure 10. Search time for a green left-oblique (-45°) target as a function of display size.

Trend Analysis

Trend analyses (Appendix A, Tables 1, 2, 3 & 4) revealed a significant linear trend for both target present ($F(1,9)=30.09$, $p<.05$; $F(1,9)=43.02$, $p<.05$) and target absent trials ($F(1,9)=42.32$, $p<.05$; $F(1,9)=67.87$, $p<.05$), for the red and the green target, respectively. The linear trends accounted for the major portion of the variance within subjects - i.e. for 73% on target present trials and for 74% on target absent trials during search for a red target, and for 80% and 85%, respectively, when the target was green. These results are consistent with the linear regression analysis, but also indicate that the linear increase in search times with display size is more pronounced for the green left-oblique target.

Moreover, on target absent trials a significant quadratic trend ($F(1,9)=32.28$, $p<.05$; $F(1,9)=61.20$, $p<.05$) explained 6% and 15% of the within subject variance in RT above and beyond that explained by the linear component, for the red and the green target, respectively. Note, that because this nonlinear trend is weaker than the linear one and characterizes the variation within individual data it is not very obvious in Figures 9 and 10 where only the RT means are plotted. In contrast, there were no significant nonlinear trends in the data from the positive trials.

Comparison of Regression Statistics by Target Type

The search functions yielded by the two different target types were compared by t-tests and analyses of variance in respect to the most important regression statistics. The more stringent $\alpha=.01$ was adopted as protection against family-wise inflation of type I error. The four search statistics described below were obtained for each subject and their average values and standard errors appear in Table 1.

Table 1

Mean Scan Rate, Slope Ratio and Linear Regression Statistics of Search Time on Display Size (N=10, Experiment 1).

Target	Trial		Intercept (msec)	Slope (msec)	Positive/ Negative Slope Ratio	Scan rate (ms/item)
RED +45°	Positive	M	546.9	11.5	.64	19.6
		SEM	17.9	2.2	.06	3.1
	Negative	M	596.0	17.9		20.3
		SEM	22.8	2.8		3.9
GREEN -45°	Positive	M	580.2	18.9	.50	30.6
		SEM	20.8	2.9	.06	4.4
	Negative	M	560.9	37.4		33.0
		SEM	31.1	4.5		5.2

Y-axis intercepts

Conceptually, this value (also known as the least squares' base) indicates the motor response component of the reaction time to the target presence or absence (see dashed line in Figures 9 & 10). It can be thought of, therefore, as a constant , independent of display size. Consequently, any increment in RT beyond the value of the Y-intercept refers to the processing time of items on display, or in other words, to the "true" search time. Indeed, analysis of variance on the Y-intercepts (see Appendix B, Table 1) revealed no significant differences in the Y-intercept by trial type (target present, target absent) or target type (+45° red, -45° green). Thus across conditions, subjects took, on average, about 570 milliseconds to execute a motor response.

Slopes

The slope of the search function, as determined by the least square regression line fit through the data, indicates the rate at which search times increase as more items are added to the display. As can be seen in Figure 9 and Figure 10, the slopes of the "green target" search functions were steeper (18.9-target present, 37.4-target absent) than those for the "red target" functions (11.5-target present, 17.9-target absent) and this difference was significant (F(1,9)=44.962, p<.01) in an analysis of variance on slopes (target type X trial type, see Appendix B, Table 2). Also, slopes for target absent trials were significantly steeper (F(1,9)=65.347, p<.01) than those for target present trials and the absolute magnitude of this discrepancy was significantly larger (F(1,9)=15.643, p<.01) for the green than for the red target.

Ratios of Target Present to Target Absent Slopes

In the context of feature integration theory, a 1:2 ratio of target present to target absent slopes indicates a self-terminating search, meaning that items are searched one by one and at random and the target's presence is detected twice as fast as its absence because, on average, the target will be encountered after half of the items have been checked, whereas decision about its absence will require examination of all items. In the present experiment slope ratios for a red right-oblique (.64=1:1.5) and a green left-oblique target (.50=1:2) were both, on average, close to one half and a dependent samples' t-test (see Appendix B, Table 4) indicated no significant difference between them.

Scan Rate

The mean scan rate was obtained for each of the four combinations of trial and target type. It indicated the average increment in RT for each item added to the display and was calculated using the following formula, designed originally for experiments with three different display sizes (VSearch Color^{TM} User Manual):

$$\text{Scan Rate} = \frac{\left(\frac{RT_{hi} - RT_{med}}{NI_{hi} - NI_{med}}\right) + \left(\frac{RT_{med} - RT_{low}}{NI_{med} - NI_{low}}\right)}{2}$$

Where:

NI = number of items (low, medium, high)

RT = mean response time for a particular display size (low, medium, high)

The above formula was extended to accomodate the five display sizes used in the present experiment as follows:

$$\text{Scan Rate} = \frac{\left(\frac{RT_{28} - RT_{16}}{28 - 16}\right) + \left(\frac{RT_{16} - RT_{8}}{16 - 8}\right) + \left(\frac{(RT_{8} - RT_{4}}{8 - 4}\right) + \left(\frac{RT_{4} - RT_{2}}{4 - 2}\right)}{4}$$

It should be noted that this statistic is often referred to as "slope" or "average slope" which is not to be confused with the least square slope from the linear regression equation. To avoid misunderstanding the better term "average scan rate"(Treisman & Gelade, 1980) is consistently used in this text. Whenever used, the term "slope" refers to the least square regression slope.

Analysis of variance (target type X trial type) on scan rate (Appendix B, Table 3) indicated that, on average, search for a red right oblique target (19.94 msec/item) was significantly faster ($\underline{F}(1,9)=22.58$, $\underline{p}<.01$) than search for a green left-oblique target (31.82 msec/item). In contrast, search on positive and negative trials proceeded at about the same rate, regardless of target type.

Discussion

The Nature of the Present Search

Results from this experiment provide only partial support to the serial spotlight model of attentional allocation during search for conjunction of features. As expected, search was self-terminating in that the target's presence was detected twice as fast as the target's absence, and there was a linear increase in response time as more items were added to the display, suggesting that each item imposed additional demands for attention. On average, however, processing of individual items took only 20 to 30 milliseconds which is faster than the scanning rate of 50 milliseconds per item considered diagnostic for serial search (Treisman & Gelade, 1980). In addition, as suggested by the quadratic trend in the data for the negative trials, a parallel process might have been also at work to aid in determining the target's absence by simultaneously rejecting groups of irrelevant items. Subjects' accounts of their search strategy is in line with the above suggestion. When asked to describe their experiences during search, most observers reported that they simplified the task by attending to items with the target color while trying to ignore items with the irrelevant color across the whole display if items were few or across smaller regions if items were numerous.

Taken as a whole, these results do not support a strictly serial, sequential model of attentional allocation in search for conjunction of features, according to which attention is focused at random on individual items. In spite of the fact that the present search task relies on a limited capacity attentional process, this process is too fast to be strictly serial and is not confined to individual item locations but may also unfold over larger display areas and operate in parallel on groups of items. In other words, it is unlikely that attention scans the present displays by moving its rigid and narrow spatial window (i.e. the spotlight) but rather changes its spatial extent to meet optimally the processing demands at different stages during search.

Does Search Change With Reversal of Target Features?

In spite of the fact that red and green items had the same luminance contrast in respect to the background and the target was always embedded among the same distractors, search for a green left-oblique target required more effort and was slower than search for a red right-oblique target. Interestingly, this discrepancy persisted after extensive practice and may be due to some innate attentional bias, culturally based learning or a combination of these two factors. It is most likely, however, that this effect is an artifact of our stimulus construction since colors were equated on luminance but not on brightness. As reported by Kaptein et al. (1995) that red and green are perceived as equally salient if the green color is more luminant than the red one. Consistent with this observation, it is known that the spectral sensitivity changes as a function of wavelength (Zrenner, Abramov, Akita, Cowey, Livingstone & Valberg, 1990) and the wavelength compositions of the green and the red color used in the present experiment is not known. The issue of apparent color equiluminance should be more carefully considered in future studies involving attentional manipulations. Psychophysical methods such as the minimum-flicker technique (Wagner & Boynton, 1972) would be helpful in this respect.

Nevertheless, for the purpose of the present study it is important that although search for a red right-oblique target was more efficient than that for a green left-oblique target, both searches were carried out at a rate faster than that typical for serial search, were self-terminating and in both cases the relation between response time and display size had a major linear and a minor nonlinear component . Thus there is no reason to believe that target reversal changed the nature of search in a qualitative way.

A Working Model of Attentional Allocation

The presents experiment adds to the large body of evidence that search for conjunction of features relies in most cases, on both serial and parallel processes. Based on current accounts of conjunction search and on the reports of our observers, search in the present task may be thought of as recursive narrowing of attention to the target location which unfolds in a sequence of interdependent stages (Pashler, 1987; Grossberg et al., 1994). During each stage parallel operations of different spatial extent take place and their outcome guides subsequent stages. The following description of these stages is plausible but by no means conclusive from the visual search data which, as mentioned earlier, can provide only an overall index of search difficulty.

First, display presentation initiates simultaneous encoding of color and orientation at multiple locations in the visual field. Activity in the color module differentiates red from green items whereas activity in the orientation module differentiates left-oblique from right-oblique items. The target, however, cannot be located either by knowing its color or its orientation, but only combined information from both modules may mark the target location.

It appears that in the present search activity in the color module had more weight in guiding search than activity in the orientation module since the two values along the color dimension were optimally distinct, whereas the two orientations were not. The maximum orientation difference of 90^0 failed to produce optimal discrimination since items were similar in that they were all oblique. This is to be expected from the oblique effect in orientation discrimination which is also known to affect visual search performance (Wolfe et al., 1989) in that the same orientation difference of 90^0 is more salient when comparison is made between horizontal and vertical items than between oblique ones.

At this first stage of search, knowledge of the target's attributes initiates a top-down selective process to reduce the number of locations worth scrutiny. Logically, this process would take advantage of the more salient color distinction already made. Thus attention is deliberately directed towards items with the target color (Kaptein, 1995). At the neuronal level attention modulates the activity in the color map by either enhancing responses of cells selective to red (Wolfe et al, 1989), inhibiting responses of cells selective to green (Treisman & Gelade, 1995) or both. Such top-down selection, however, requires effort and is limited in capacity in that it cannot be carried out over all item locations simultaneously. Attention is thus forced to zoom in and operate sequentially on smaller areas of the display when items are numerous. Occasionally, incidental groupings of spatially adjacent items of the same color allow attention to operate in parallel over larger display areas. The amount of effort and time required to select sets of items with the target color and ignore items with the irrelevant color determines to a large extent the overall efficiency of search. As discussed above, results indicate that selecting green items and ignoring red ones requires more attentional resources than the reverse.

Once attention has selected a subset of items with the target color search proceeds along the orientation dimension only and the target, if present, readily pops-out as the item with the odd orientation. Thus following selection of a subset of items with the relevant color containing the target attention is quickly summoned at the target location. Additional narrowing may take place to ensure that the designated item matches the internal representation of the target. Target identification then elicits a motor response upon which attention disengages from the target location.

It must be emphasized that the sequence of events outlined above is hypothetical, though consistent with the obtained search functions. Its only purpose is to guide interpretation of results from subsequent experiments concerned with the relation between selective attention during search and the motion induction effect.

EXPERIMENT 2

Using the stimuli and displays from Experiment 1 the present experiment examined whether motion induction occurs in the context of the visual search with deliberate attentional selection of a target defined by a conjunction of features. To address this question we combined the paradigms of visual search (Experiment 1), double motion induction and spatial precueing. This approach is based on the work of von Grünau et al. (in press) who demonstrated that motion induction occurs in multi-item displays where cueing takes place at multiple locations and, potentially, each item may induce illusory motion if the test bar is presented in its vicinity.

In the present experiment the bar was presented at different delays after display onset in the middle between two randomly chosen adjacent items. Since a target defined by a conjunction of features does not pop-out among the background items, selective deliberate allocation of attention is needed to single it out. Search is guided in a top-down manner by the internal representation of the target. Since all items are very similar in that they all share features with each other, if an item in a pair acts as a stronger inducer and triggers motion in the bar away from itself this could be due only to attention selectively allocated to this item. On the other hand, if both items flanking the bar are nonattended or equally attended the direction in which the bar appears to grow would be ambiguous.

Thus it was hypothesized that:

(i) optimal motion away from the target would be observed when the delay between the onset of the multiple cues and the presentation of the bar (SOA) approximates the average time needed for target detection when the probability of selective attention at target is highest. Motion induction at target would develop slowly since selection of the target is achieved through gradual deliberate narrowing of attention.

(ii) The SOA at which motion induction at target is optimal would be longer for displays comprising more items, where detection of the target takes longer, as shown in Experiment 1.

(iii) At earlier stages in search when the bar is presented between two different distractors motion induction would be observed away from distractors with the target color if they are selectively attended.

(iv) At all times during search, when the bar is presented between two identical distractors, motion would be seen equally often towards and away from a randomly chosen item in each pair.

(v) Finally, if the same pattern of results emerges, regardless of the particular combination of features defining the target (i.e. red-right oblique, green left-oblique) the effect could be unambiguously attributed to attentional selection and not to the particular characteristics of the stimulus.

Method

Subjects

Nine subjects, ages between 22 and 50, took part in all conditions of Experiment 2. They were all right-handed, with normal or corrected to normal visual acuity (Snellen 20/20). All but three of the observers were naive about the hypotheses tested.

Apparatus

The computer equipment described in Experiment 1 was also used for Experiment 2. The software program (Motion Cue) was developed in the Vision Lab at Concordia University. It combined the visual search task with the motion induction paradigm by presenting a horizontal bar at random locations across the multi-item displays, at different times after search onset. Thus it was possible to record both search times and directional responses (left/right) to the motion perceived within the bar.

Head position was fixed with a chin and forehead rest to maintain a constant distance of 57 cm between eye and screen.

Stimuli

Search items, display arrangements and the mask were identical to those in Experiment 1. Only two display sizes (i.e. with eight and 28 items) were used in Experiment 2.

The dimensions of the horizontal bar (in degrees of visual angle at 57 cm) and the way it appeared among the search items are illustrated in Figure 11. The width (i.e. shorter sides) of the bar and the search items was the same (.3 deg). Horizontally, the bar was presented exactly in the middle between the two flanking items (cues) and its vertical position was aligned with their centers. Thus both ends of the bar were separated by the same distance from the corresponding cue. The relative position of the test bar in respect to the two associated cues was always the same, since the horizontal spacing between items was kept constant, irrespective of the number of items on display.

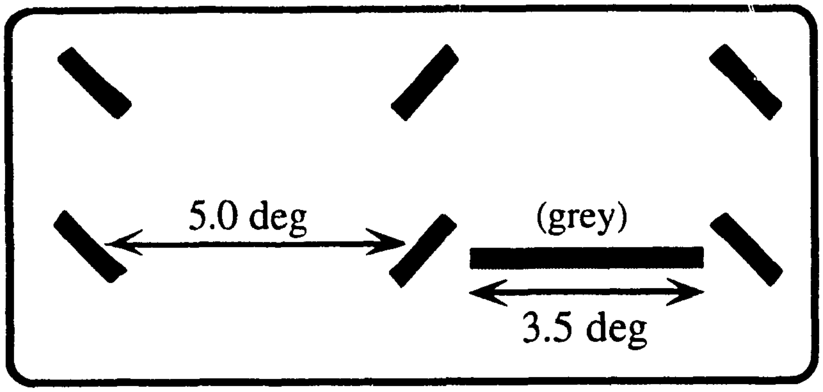


Figure 11. Dimensions and relative position of the test bar (Experiment 2).

The bar appeared gray, darker than the background and its luminance (20.6 cd/m^2) was approximately equal to that of the search items. Thus all stimuli had a Michelson contrast of .63 relative to the background.

Procedure

Preliminary Procedure

Prior to their participation in the experiment all subjects were exposed to the standard motion induction setting. A horizontal bar (above fixation and centered on the screen), was preceded and flanked on one or both sides by spots of the same luminance. Based on previous studies (Hikoska et al, 1993a) we used a 100 ms stimulus onset asynchrony (SOA) between the spots(s) and the bar which is known to produce optimal sensation of motion. Observers were simply asked to fixate and describe their experience. As expected, with a single cue, they all reported motion within the bar away from the cue (single motion induction). With two cues presented simultaneously observers reported ambiguous direction of motion, or motion away from both ends of the bar towards the center (split cueing). In the latter case, with asynchronous presentation of the spots, subjects tended to see motion away from the spot presented last. In this way it was assured that all subjects do experience the basic motion induction effect.

Experimental Procedure

Experiment 2 was carried out in four separate sessions which were administered to each subject in a randomly determined order. The type of target (red+45°, green -45°) and the number of search items (8, 28) was varied between sessions. Before running each session subjects were introduced to the search displays and the target item they had to search for. This was done by giving each observer a short practice (60 trials) with the regular visual search task from Experiment 1 for the relevant combination of target type and display size. Data from these practice trials was not analyzed.

Each of the four experimental sessions comprised 560 trials. The sequence and duration of events within a trial is illustrated in Figure 12.

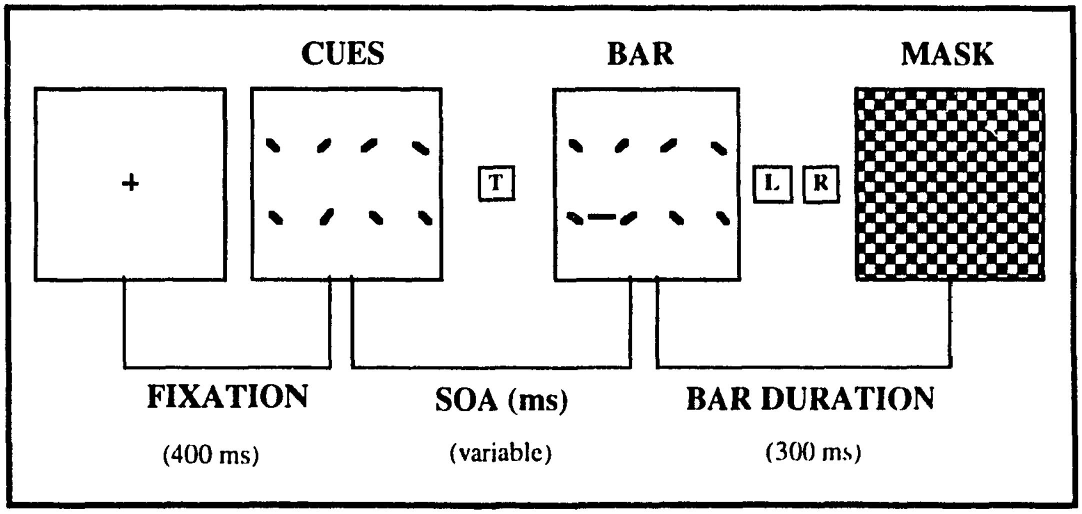


Figure 12. Sequence of events within a trial (Experiment 2).

After fixating at the cross, subjects were presented with the multi-item display which initiated the search. They were instructed to maintain the fixated position during search as much as possible. The bar came on some time after display onset at an unpredictable location in the middle between two items, and was quickly followed by the mask which replaced the display thus interrupting search. On each trial subjects had two tasks:

(i) to search for the target and report its presence as quickly as possible (a speeded RT task);

(ii) to report in a 2AFC manner the direction of motion (i.e. leftward / rightward) perceived within the test bar (a nonspeeded task).

Observers gave a speeded RT response to the target presence by pressing a key on the keyboard with their left index finger. The forced choice directional response was given with the right hand by pressing two adjacent keys for leftward and rightward motion, respectively. Response times for target detection given after bar presentation were not recorded. A new trial was initiated only after a directional response was made.

Within each of the four sessions, the horizontal bar was presented at a variable delay (SOA or cue lead time) following display onset. Since it was important that the temporal sampling was sensitive to the deployment of attention during search, and because search was found to be slower with more items (Experiment 1), the five SOAs for displays with 28 items were chosen to be longer (195, 495, 1005, 1755 and 1995 ms) than those for displays with 8 items (150, 405, 705, 1200 and 1995 ms).

Within a session, 112 randomized trials were run at each SOA and the target was present on half of them. To reduce the length of the experiment, when the target was present (i.e. on 56 trials per SOA) the bar was always presented at target (i.e. between the target and a distractor). When the target was absent, the bar was presented at random either between two identical distractors (on 28 trials approximately) or between two different distractors (on 28 trials approximately). The three presentation conditions with a red right-oblique (+45^o) target are schematically presented in Figure 13. The illustration also applies for a green left-oblique (-45^o) target since the two distractors are always the same.

It should be noted that although the bar was always presented exactly between two items, the program assigned the bar to only one of them. We will further refer to this item in a pair as the designated item (see Figure 13, items enclosed in dashed rectangles) which was the target on half of the trials (56 per SOA, Figure 13, left panel) and a distractor - on the other half (56 per SOA, Figure 13, right panel). When the designated item was a distractor, its type (red+45^o or green-45^o) was chosen at random. Since each of the two distractors had equal chance to be designated, the bar was assigned about equally often to each type of distractor. Technically, the bar was randomly presented to the left or to the right of the designated item. In addition, on each trial, items in the two vertical extreme columns of the item matrix were never designated so that the bar never appeared next to a single item in the display margins outside the matrix. It must be emphasized, that observers were never aware which one of the two items flanking the bar was the designated one. The designation procedure, however, determined the way in which data were recorded (i.e. whether motion was reported away from [coded as -1] or towards [coded as 0] the designated item, regardless of direction - i.e. left / right) which is important for understanding the analysis of the results.

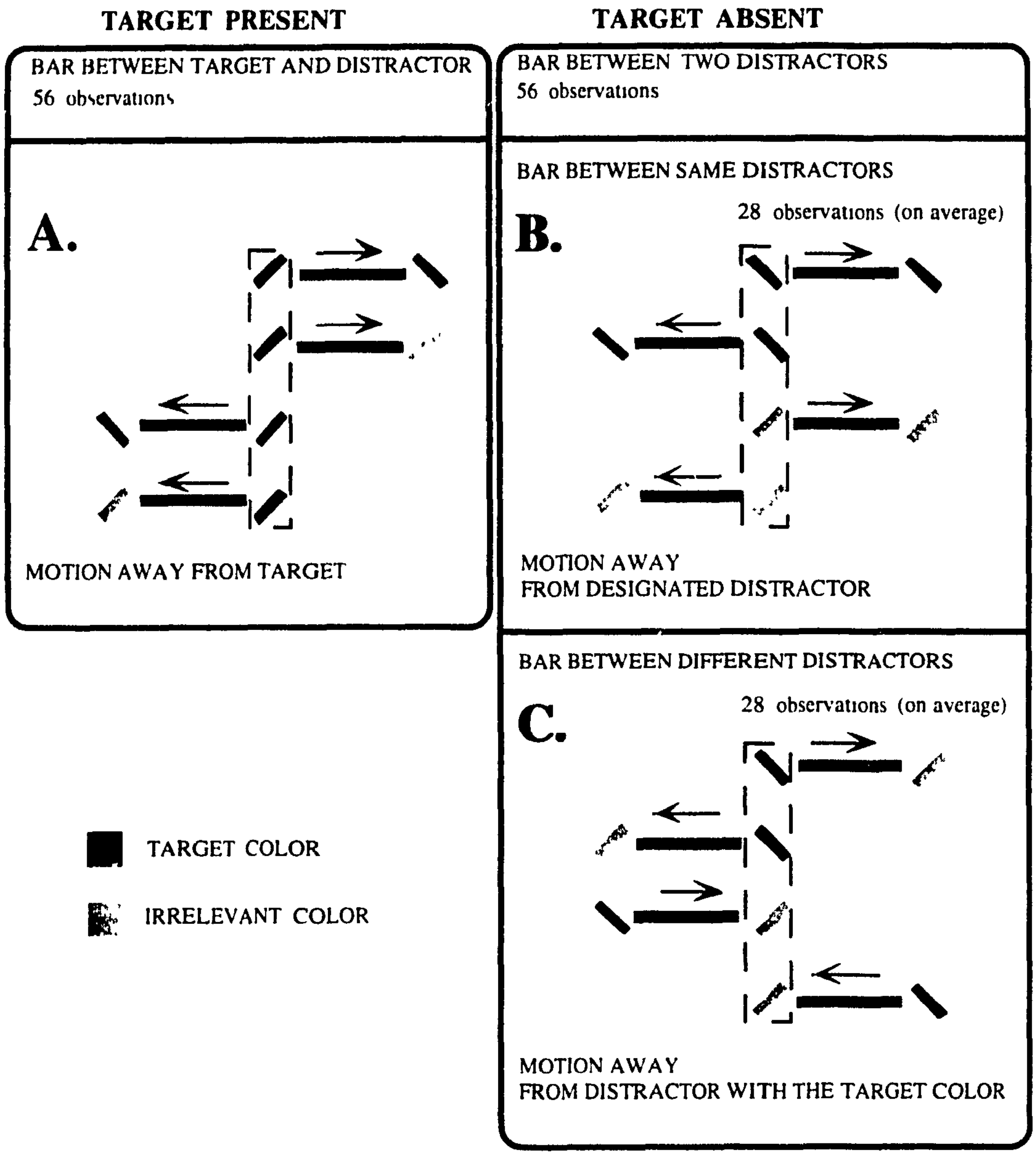


Figure 13. Cueing conditions in Experiment 2.

Motion induction was measured by the proportion responses in the direction of the arrows out of the total number of trials in each condition.

Results

For each of the four combinations of target type and display size, motion induction was measured at each of the 5 SOAs , for each of the three inducing conditions (Figure 13, A, B, C):

1. On target present trials (56 per SOA), the percentage of times when motion was reported away from the target (Figure 13-A, see arrows) indicated *motion induction at target.*

2. On target absent trials, when the bar was presented between two different distractors (about 28 times per SOA), the percentage of motion away from distractors with the target color (Figure 13-C, see arrows) indicated *motion induction at the target color.*

3. On target absent trials, when the bar was presented between the same distractors (about 28 times per SOA), the percentage of motion away from the designated distractor, regardless of type (Figure 13-B, see arrows) indicated the strength of motion induction expected by chance. Since the distractors flanking the bar were identical and neither one of them was expected to be more attended than the other, they were expected to act as equivalent inducers. In this situation the direction of motion within the bar is expected to be ambiguous - that is, motion would be reported equally often (50%) away and towards the designated item which was a distractor of one or the other type equally often, on average. Thus measures in this condition provided a *baseline* for evaluating the strength of the motion induction effect at target and at distractors with the target color.

For each subject, the percent motion induction was measured in each of the above conditions, at each SOA and for each of the four combinations of target type and display size. The individual mean response time for target detection in each of the four sessions was also computed.

Three ANOVAs were conducted on the data from this experiment. ANOVA on target present RTs compared the efficiency of visual search in Experiment 2 and

Experiment 1. Two separate ANOVAs examined the motion induction effect in the 8-item and 28-item conditions, respectively, since the levels of the SOA factor were specific for each display size.

ANOVA on Target Present RT-s from Experiments 1 and 2

Descriptive statistics on the RT data from the two experiments appear in Appendix C, Table 1. Results from the split-plot ANOVA on target present RTs with Target Type (red+45°, green -45°) and Display Size (8, 28 items) as repeated factors and Experiment (1,2) as a between-subject factor are summarized in Table 2, Appendix C. Since there were nine subjects in Experiment 2 (versus ten in Experiment 1), the missing data points in Experiment 2 were substituted with the mean from the corresponding condition.

Results indicate that, overall, search was faster (Mean Difference = 130 ms) in Experiment 2 than in Experiment 1 [main effect of Experiment, $F(1, 18)=4.548$, $p<.05$]. In both experiments, however, it took significantly longer, on average, to detect the target among 28 items than among 8 items [main effect of Display Size, $F(1, 18)=109.165$, $p<.05$]. Also, in both experiments, on average, search for a green left-oblique target was slower than search for a red-right oblique target [main effect of Target Type, $F(1, 18)=52.231$, $p<.05$]. The latter effect, however, was less pronounced in Experiment 2 than in Experiment 1 [Target Type X Experiment interaction, $F(1, 18)=13.244$, $p<.05$]. Also, there was a significant Experiment X Display Size X Target Type interaction [$F(1, 18)=11.165$, $p<.05$] in that in Experiment 1 the difference in RT for the two targets was significantly larger with 28 than with 8 items [Display Size X Target Type @ Experiment 1, $F(1, 9)=11.570$, $p<.05$], whereas it was the same across display size in Experiment 2. These two partial interactions could be examined in Appendix C, Table 3.

ANOVA on the Motion Induction Data (8 Search Items)

Summary results from the repeated measures' ANOVA on the motion induction data from search displays with 8-items with Target Type (red+45°, green -45°), Inducer Type (target, nontarget with target color, nontarget) and SOA (150, 405, 705, 1200 and 1995 ms) as within subjects' factors are presented in Appendix D, Table 1. The average percentages of motion induction with their standard errors are plotted in Figures 14 and 15, separately for each target type. The vertical dotted lines intersecting the figures indicate the mean RT for target detection.

Despite the fact that all subjects showed similar pattern of results, the individual variation in the data was considerable and in some instances inconsistent across conditions. The values of the Greenhouse-Geisser Epsilon correction factor ranged from .93 to .32 across within subjects' effects, indicating slight to severe violation of the sphericity assumption of ANOVA. Since this correction is known to be quite conservative the ANOVA effects and planned comparisons were evaluated against the more liberal α =.05 to compensate for the loss of power. The multiple post-hoc comparisons, however, were evaluated against α =.01 to protect against familywise inflation of Type I error.

The ANOVA results indicate a significant two-way interaction between the effects of Inducer and SOA [$\underline{F}(8,64)=14.536$, $\underline{p}<.05$], meaning that for both target types the difference in motion induction across inducers changed as a function of SOA. The main effect of Inducer [$\underline{F}(2,16) = 76.462$, $\underline{p}<.05$] and SOA [$\underline{F}(4,32)=8.739$, $\underline{p}<.05$] were also significant but of little interest on their own, since they were subsumed under the Inducer X SOA interaction.

Since no other effects were significant and the pattern of results was similar for both target types (no three-way interaction) the subsequent analysis examines the effects of Inducer across SOA (i.e. the Inducer X SOA interaction), averaged across target type.

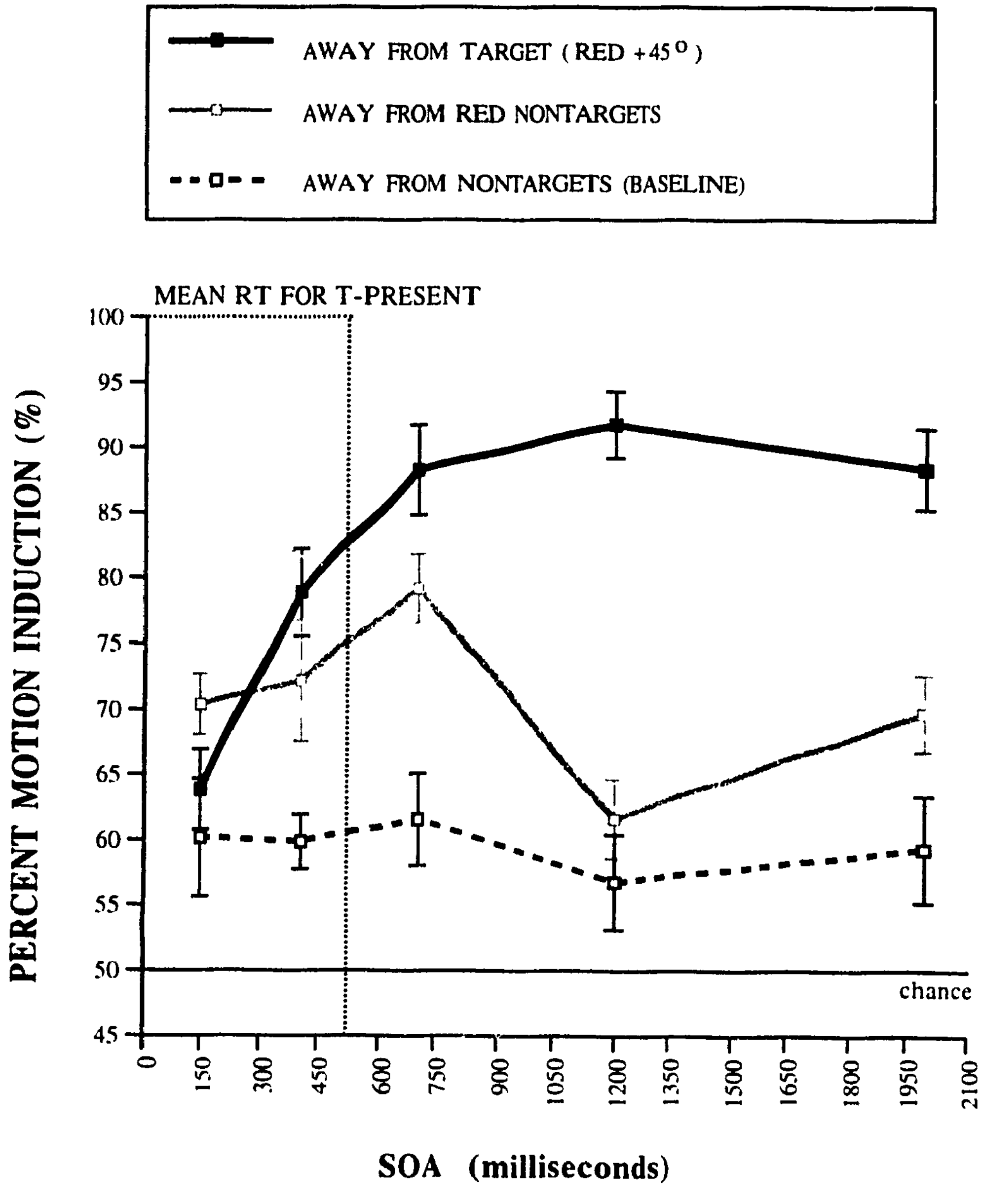


Figure 14. Motion induction as a function of SOA and type of inducer in search for a red right-oblique (+45°) target (display size = 8).

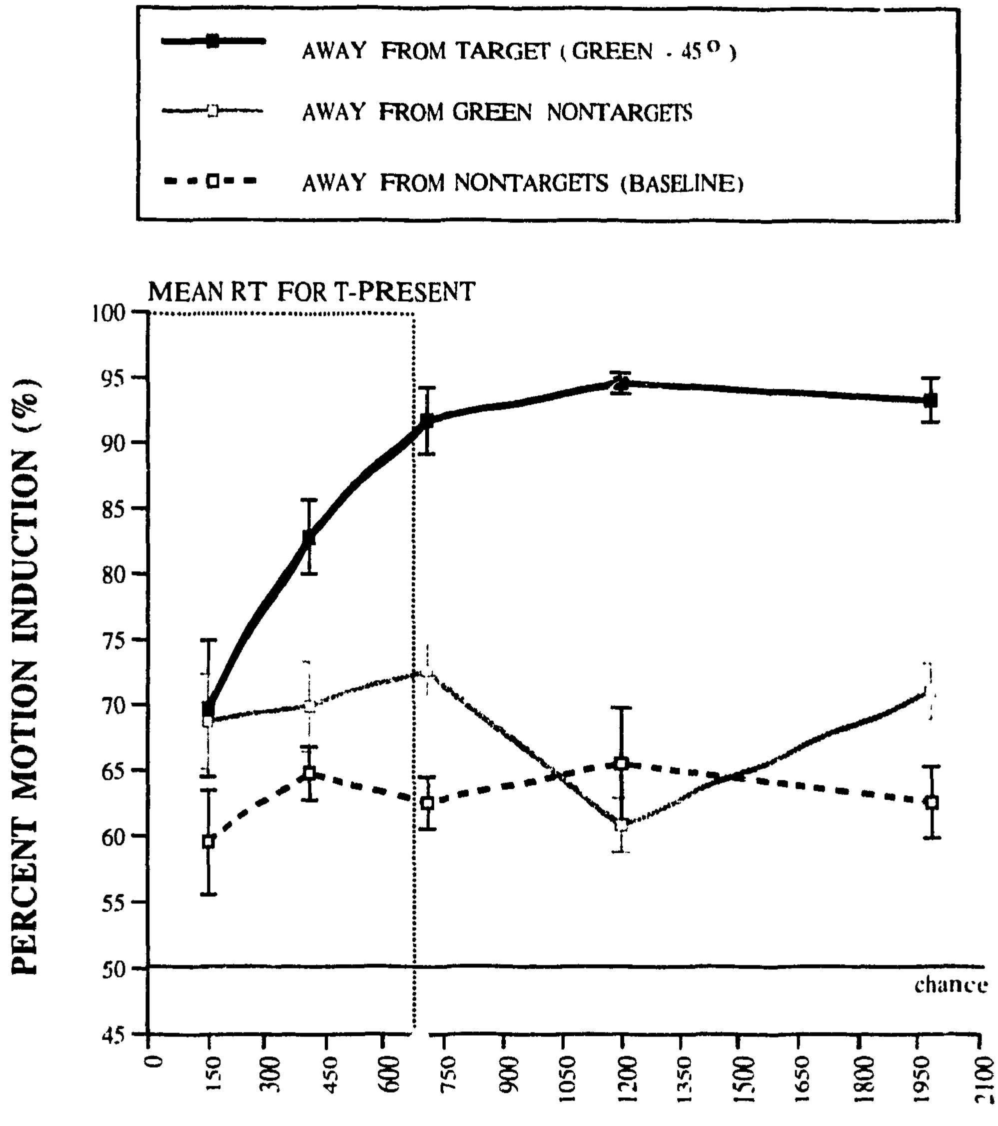


Figure 15. Motion induction as a function of SOA and type of inducer in search for a green left-oblique (-45°) target (display size = 8).

Analysis of simple effects (Appendix D, Table 2) revealed that the Type of Inducer at which the bar was presented had a significant overall effect at all SOA-s, although, as can be seen on Figures 14 and 15, the vertical separation between curves was smaller at shorter SOA-s.

Components of the overall effect of Inducer across SOA levels were further analyzed in detail by comparisons of means and trend analysis of the difference between pairs of inducing conditions.

Strength of Motion Induction at Target

This effect was measured by the difference between motion induction at target and at baseline. A planned comparison of means (Appendix D, Table 3) averaged for both target types and across SOAs indicated that motion induction at target was significantly above baseline [Mean Difference = 23.06%, $F(1,8)=150.006$, $p<.05$]. Pairwise comparisons between means at each SOA (Appendix D, Table 4) revealed that for both target types motion induction at target was significantly ($p<.01$) above baseline at all SOA-s except at the shortest one (150 ms). Trend analysis of this difference (Appendix D, Table 5) indicated that the contrast between motion induction at target and baseline increased linearly [$F(1,8)=33.667$, $p<.01$] with SOA. There was also a significant, albeit weaker, quadratic trend [$F(1,8)=12.791$, $p<.01$] in that, as can be seen in Figures 14 and 15, the separation between motion induction at target (upper curve) and that at baseline (bottom curve) increased up to 1200 ms and then decreased slightly at the longest SOA (1995 ms). On average, for both target types, this effect was significant at the SOA=705 ms which was the closest value to the mean RT for target detection (607 ms) but reached optimal strength much later (i.e. at 1200 ms).

Strength of Motion Induction at Target Color

This effect was measured by the difference between motion induction at nontargets with the target color and that at baseline. A planned comparison of means averaged for both target types and across SOAs (Appendix D, Table 3) indicated that motion induction at nontargets with the target color was significantly above baseline [Mean Difference = 8.36%, F(1,8)=15.836, p<.05]. Pairwise comparisons between means at each SOA (Appendix D, Table 6) revealed that motion induction at the target color was present (i.e. significantly above baseline) only at the three shortest SOAs, that is up to 700 ms after search onset. No trend accounted significantly for the temporal dynamics of this effect (Appendix D, Table 7). As can be seen in Figure 14 and Figure 15, however motion induction at the target color (in contrast to baseline) showed the same pattern across SOA for both target types: it was present at 150 ms, increased slightly reaching optimum at 705 ms, and dropped to baseline by 1200 ms. Motion induction at the target color peaked around the average time for target detection (607) and decreased steeply afterwards.

Although the overall effect of inducer did not differ across Target Type (Target X Inducer interaction was not significant) a planned interaction contrast (Appendix D, Table 10) revealed that motion induction at distractors with the target color compared to baseline was more pronounced [Mean Difference = 5.65 %, F(1,8)=6.124, p<.05] in search for a red-oblique target (Figure 14) than for a green left-oblique target (Figure 15).

Strength of Motion Induction at Target Beyond that at Target Color

This effect was measured by contrasting motion induction at target with that at nontargets with the target color. A planned comparison between means averaged for both target types and across SOAs (Appendix D, Table 3) indicated that motion induction at target was significantly stronger than that triggered by the target color [Mean Difference = 14.71 %, F(1.8)=78.936, p<.05]. Pairwise comparisons between means at each SOA (Appendix D, Table 8) revealed that motion induction at target was significantly stronger than that at the target color at the three longest SOAs only, that is beyond 705 ms. Thus at shorter SOAs the motion induction effect at target could be fully accounted for by motion induction at distractors with the target color. The effect increased linearly with SOA [F(1,8)=145.21, p<.01] but also showed a significant quadratic trend [F(1,8)=29.273, p<.01, see Appendix E, Table 9], reaching optimal strength at SOA = 1200 ms and decreasing for the longest SOA (1995 ms). This effect was barely emerging and was weakest at SOAs closest to the mean detection time, attaining optimal strength 500 ms later (i.e. at 1200 ms).

In addition, a planned interaction contrast (Appendix D, Table 10) indicated that the motion induction effect at target that could not be attributed to the target color is stronger [Mean Difference = 6.16 %, F(1,8)=7.347, p<.05] in search for a green left-oblique target (Figure 15, separation between two upper curves) than for a red right-oblique target (Figure 14, separation between two upper curves).

ANOVA on the Motion Induction Data (28 Search Items)

This analysis follows the same logic as the one for the smaller display size. The average percentages of motion induction with their standard errors and mean RT for target detection are shown on Figures 16 and 17, separately for each target type. The ANOVA summary table appears in Appendix E, Table 1. The values of the Greenhouse-Geisser Epsilon correction factor ranged from .79 to .36 across within subjects' effects, indicating moderate to severe violation of the sphericity assumption of ANOVA . Critical α values were set again at .05 for the overall ANOVA and for planned contrasts and at .01 for unplanned follow-ups.

The overall ANOVA results are similar to those for the smaller display size. Again, the only effect of interest was the significant Inducer X SOA interaction [F(8,64)=16.921, p<.05], with main effect of Inducer [F(2,16) = 84.689, p<.05] and SOA [F(4,32)=28.723, p<.05] also significant.

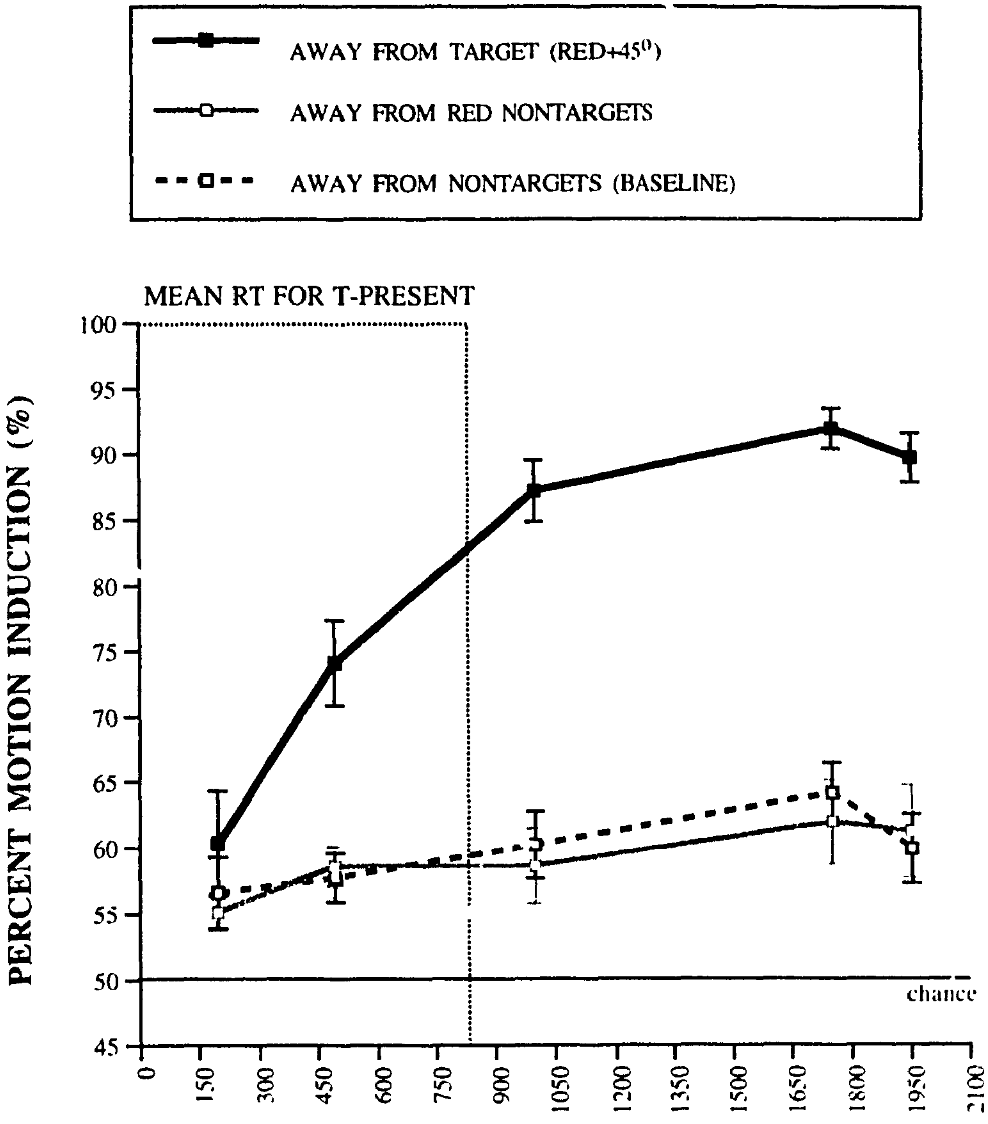


Figure 16. Motion induction as a function of SOA and type of inducer in search for a red right-oblique (+45°) target (display size = 28).

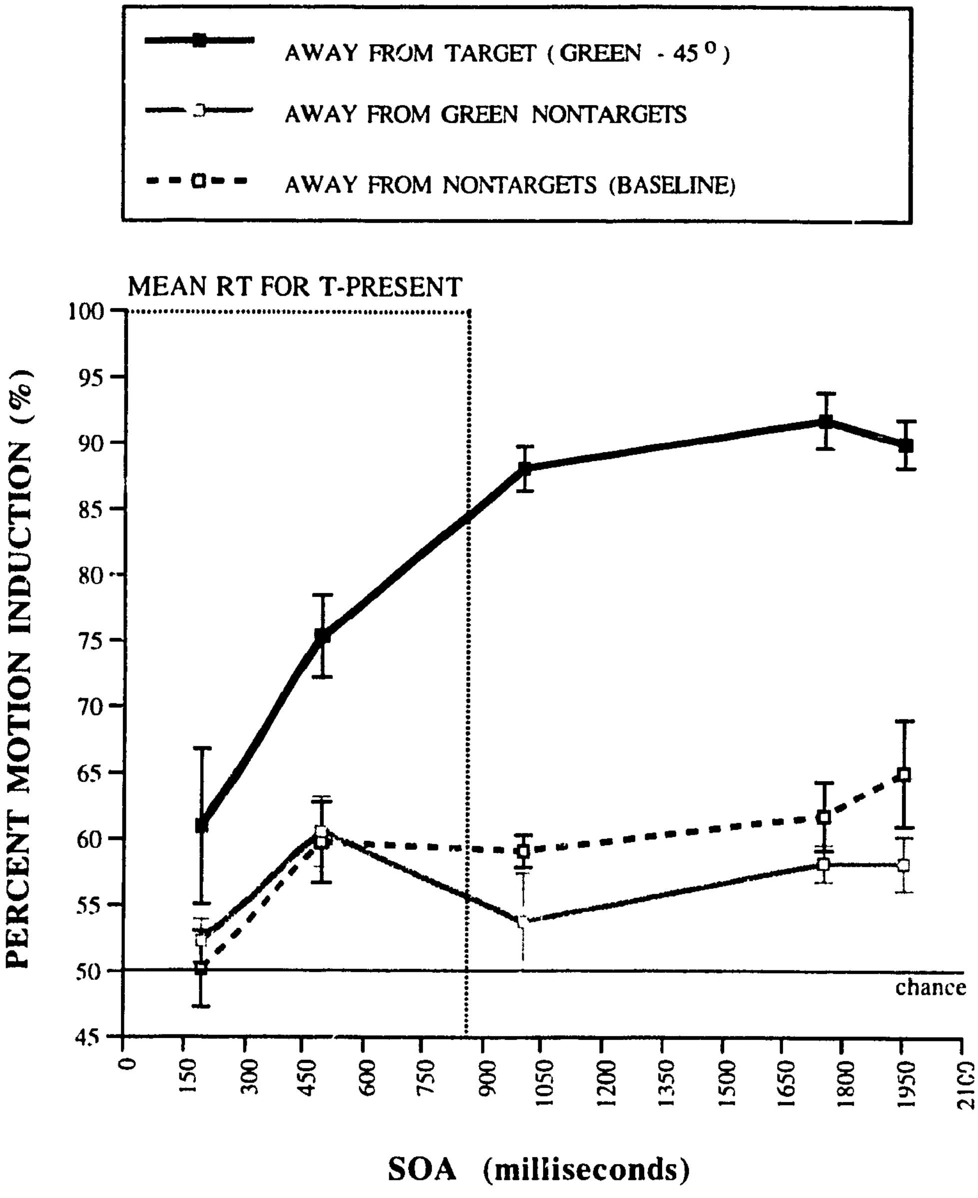


Figure 17. Motion induction as a function of SOA and type of inducer in search for a green left-oblique (-45°) target (display size = 28).

Analysis of simple effects within the Inducer X SOA interaction (Appendix E, Table 2) revealed that the type of Inducer had a significant overall effect at all SOA-s, except at the shortest one (195 ms). Planned comparison of means (Appendix E, Table 3) indicated that overall, for both target types and averaged across SOA-s, motion induction at target was significantly above baseline [Mean Difference = 21.5%, $F(1,8)=402.82$, $p<.05$], whereas motion induction at nontargets with the target color was not different from baseline. Thus there was no evidence for motion induction at the target color as measured by the contrast between motion induction at distractors with the target color and baseline. As shown in Figures 16 and 17 the two bottom curves overlap almost completely at all SOAs and for both target types. In other words, the simple effects of Inducer reflect primarily the difference between motion induction at target and the baseline. The change of this difference as a function of SOA was examined next.

Strength of Motion Induction at Target

This effect was measured by the difference between motion induction at target and the baseline. Trend analysis of this difference (Appendix E, Table 4), averaged for both target types, indicated that the contrast between motion induction at target and baseline increased linearly [$F(1,8)=24.322$, $p<.01$] with SOA. A significant quadratic trend [$F(1,8)=27.74$, $p<.01$] was also present in that, as is more obvious in Figure 17 (green target), the separation between motion induction at target (upper curve) and that at baseline (bottom curve) increased up to 1755 ms and then decreased slightly at the longest SOA (1995 ms). For both target types, the effect was present at the SOA=1005 ms which is closest to the average RT for target detection (832 ms) but peaked about 800 ms later (i.e. at SOA=1755 ms).

Discussion

Can Deliberate Selection of a Cue Trigger Motion Induction ?

Results clearly demonstrate that in the context of visual search, a target defined by a conjunction of color and orientation can trigger illusory motion away from itself. As discussed earlier, detecting the presence of such target among distractors sharing its features requires effort and would take quite some time if the target combination of features is not known in advance. In such displays all items are expected to have the same effect on the bar unless one of them is deliberately singled out. Most importantly, motion induction at target was equally strong and showed the same pattern regardless of the particular combination of color and orientation defining the target. Therefore, the observed motion induction effect can be unambiguously attributed to deliberate attentional selection of the target and is not due to its particular stimulus properties. In the conjunction search situation target selection is the outcome of a relatively slow, gradual process and the probability of target detection increases as search progresses. Consistently, results indicate that motion induction at target developed gradually as the time between search onset and bar presentation increased. Also, with more items on display, when the deployment of attention is slower and search takes longer, the motion induction at target reached optimal strength at longer times after search onset than in displays with fewer items.

Components of the Motion Induction Effect at Target

For displays with eight items and regardless of target type a weaker motion induction effect was also observed at nontargets with the target color. This effect was present shortly after display onset (i.e. at 150 ms), lasted only until target detection (up to 700 ms) and could be attributed to selective attention distributed across all items with the target color. As discussed in respect to Experiment 1, attention may have been preferentially allocated to the target color rather than to the target orientation because with the present stimuli the color distinction may have been more salient to begin with. Also, consistent with results from Experiment 1 showing that search for a green target is more difficult than search for a red target, the motion induction effect at the target color was weaker during search for a green target, suggesting that selection of the green color may be more difficult than selection of the red color.

If, as hypothesized earlier, simultaneous selection of items with the target color facilitates target detection, then motion induction at items with the target color could be thought of as part of the effect at target. The other component of the effect at target, beyond that due to the target color, is likely to reflect attentional resources allocated exclusively to the target orientation.

Results support the above interpretation. First, prior to target detection the effect at target is almost fully accounted for by the effect at the target color, suggesting that attentional resources are almost entirely engaged in selecting items with the target color and ignoring those with the irrelevant color. This process may involve all items if they are fewer or groups of items if they are numerous which may partially explain the fact that motion induction at the target color was well pronounced in displays with eight items and not different from baseline with 28 items. As the time of target detection approaches, the motion induction effect increased beyond that at the target color, suggesting that at the time of target detection some attentional resources are already concentrated at the target location. The unique effect at target, however, takes over the effect at color only later in search, as attention narrows at target.

Why Does Motion Induction at Target Persist Long After Target Detection?

It follows from the above that after the target identity is confirmed, maintaining focused attention at target would no longer be necessary. Indeed the quadratic trends in the data provide evidence for some decline in motion induction at target at the longest SOA (i.e. at about 2000 ms after display onset). This decline, however, was very slight (up to 5%) and occurred quite late. Because when the target was present the bar was always presented next to it, it is possible that subjects had learned to anticipate the appearance of the bar, thus maintaining attention at target.

It is also possible that the speeded RT task may have interfered with the process of attentional narrowing, thus delaying its effects on the bar. The fact that, on average, RT-s in this experiment were faster than those during regular visual search (Experiment 1) suggests that subjects may have been overly concerned with the detection response, since almost half of the display exposures were too short to allow target detection.

Is Motion Induction at the Target Color Confined to Smaller Displays?

As mentioned above, the present results indicate that motion induction at the target color does not differ from baseline in displays with 28 items. One reason for this may be that color selection is more difficult with numerous items when attention has to operate on more locations and therefore at a given time it may not be strong enough at a given item to trigger motion induction. On the other hand, the result may be due to the fact that the baseline in all conditions of the present experiment was inflated to 60% (i.e. above the expected 50%) thus possibly underestimating all effects.

This baseline inflation is most likely due to imbalance in the randomization of bar presentation combined with a possible bias in the experience of motion induction across the display. As explained earlier, the baseline percent motion induction was computed from trials when the target was absent and the bar was presented between two identical distractors one of which was chosen at random to be the designated item and determined the relative bar location on a given trial (see Figure 13 B). Items in the left and right extreme columns of the item matrix, however, were never designated (see Procedure for reasons for the restriction). Thus on trials when the bar was presented between the two left-extreme or right-extreme columns, the designated item was always in the column closer to the center of the display. In addition, many subjects reported that when not able to locate the target they tended to see illusory motion away from the central vertical axis which is not surprising assuming a center-surround organization of the attentional field (Steinman et al., 1995), narrowed by default at fixation prior to each trial. Putting these two facts togethter means that in these cases motion away from the center also meant motion away from the designated item, thus increasing the baseline probability of motion induction.

Another possibility is the influence of eye movements executed away from fixation. Such bias would then result in motion reported consistently away from the designated item when it was located in the second extreme columns thus inflating the baseline beyond 50%. The baseline, however, served its main purpose in removing any systematic influences from the effects of interest.

To summarize, Experiment 2 showed that motion induction can occur with active attentional selection, independent of the stimulus properties of the inducer. In addition, the observed temporal dynamics of motion induction support the hypothetical model of attentional allocation during search, outlined in Experiment 1. Experiment 3 deals with some of the methodological shortcomings of Experiment 2 and attempts to rule out alternative hypotheses.

EXPERIMENT 3

This experiment addressed methodological issues raised by Experiment 2 and tested the stability of its results. In essence, this was a partial replication of Experiment 2, using the same general method and stimuli. Motion induction was measured at different inducers, as search for a red + 45^0 target unfolded. Here, however, only the first 920 ms of search were of interest during which target detection was found to take place for all subjects (i.e. at 560 +/- 40 ms, on average). The dynamics of motion induction were examined more precisely within this time frame by presenting the bar at denser and equally spaced delays.

To control for expectancy effects, on positive trials in this experiment the bar did not always appear next to the target but was presented with the same probability at target, between distractors when the target was present, or between distractors when the target was absent. Thus in contrast to Experiment 2, the number of trials in the baseline condition (bar between distractors, target absent) was now equal to that in the test condition (bar at target). These changes made it impossible to anticipate the position of the bar on a given trial which was meant to discourage subjects from maintaining attention at target long after detection. Moreover, the new sample included observers with no previous experience in psychophysical experiments.

The possibility that the speeded detection response in Experiment 2 interrupted search and interfered with the subsequent development of the motion induction effect was also of concern. In the present experiment there was no RT task and observers had to report the presence or absence of the target only in the end of the trial, after having indicated the direction of motion within the bar.

Method

Subjects

Eleven subjects, ages between 21 and 50, participated in this experiment. Only two of them were familiar with the purpose of testing. Four observers had no previous experience with psychophysical tasks. All subjects were right-handed with normal or corrected to normal visual acuity.

Apparatus

The same equipment as in Experiment 1 and 2 was used. A new version of the software program used in Experiment 2 (Motion Cue) allowed for modifications in the experimental procedure. Viewing distance was maintained at 57 cm.

Stimuli

Stimuli, displays and the relative position of the bar between items were identical to those in Experiment 1 and 2. In the present experiment there was a single target (red $+45^{\circ}$) and displays comprised eight items.

Procedure

Preliminary Procedure

Before taking part in the experiment subjects were exposed to the motion induction phenomenon in the way described for Experiment 2. All observers reported experiencing single and double motion induction.

In addition, prior to the experiment, each subject was familiarized with the target and the search aspect of the task by running 60 regular visual search trials.

Experimental Procedure

Experiment 3 consisted of 960 trials, run in two identical blocks of 480 trials each which were administered on separate sessions.

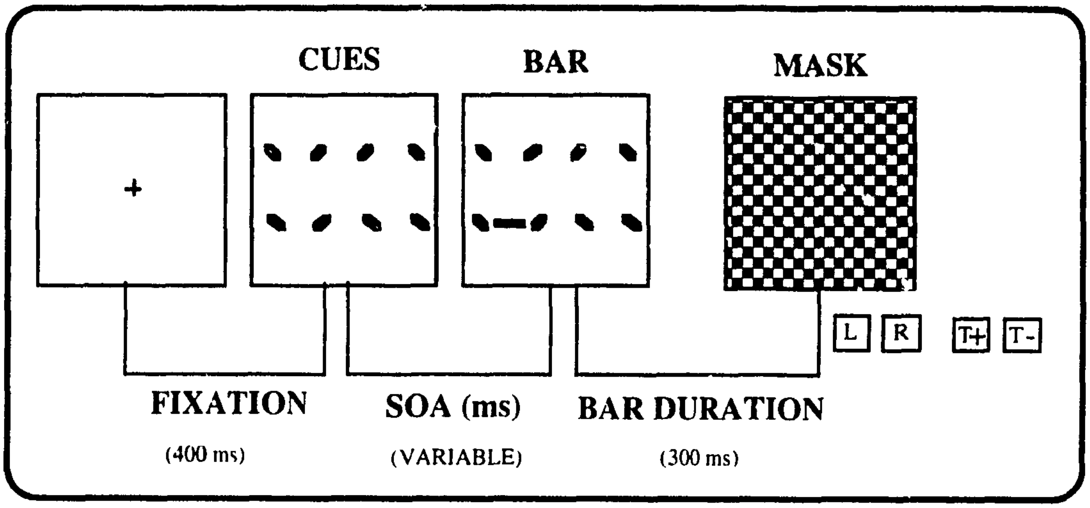


Figure 18. Sequence of events within a trial (Experiment 3).

The sequence and duration of events within a trial were the same as in Experiment 2 except that no speeded response to the target presence was required during search (Figure 18). Observers were simply asked to search for the target and this was emphasized as their main task. Following bar presentation and while being exposed to the mask subjects had unlimited time to give their directional response first and then indicate the target's presence or absence. A new trial was initiated only after the outcome of the search task was reported.

The bar was presented at eight different SOAs after display onset (120, 240, 360, 480, 600, 720, 840 and 960 msec), sampling search at equally spaced intervals of 120 ms. The SOA for a given trial was randomly determined.

There were 120 trials per SOA. The target was present on 80 of them and absent on 40. The bar was presented at target on half of the target present trials (i.e. 40) and between two randomly chosen distractors - on the other half (i.e. 40).

Percent motion induction was recorded for each subject and at each of the eight SOAs in each of the three conditions, illustrated on Figure 19:

1. Out of the 40 target present trials, when the bar was presented at target the percent motion reported away from target indicated *motion induction at target* (Figure 19 - A1, see arrows).

2. Out of the 40 target present trials, when the bar was presented between two randomly chosen distractors the percent motion reported away from the designated distractor (regardless of type) indicated *motion induction expected by chance* (Figure 19 - A2, see arrows).

3. Out of the 40 target absent trials, when the bar was presented between two randomly chosen distractors the percent motion reported away from the designated distractor (regardless of type) also indicated motion induction expected by chance (Figure 19 - B, see arrows) which was taken as *baseline*.

It should be noted, however, that the baseline condition (3) was expected to yield similar results to condition (2) where the inducing items flanking the bar were exactly the same. In both cases distractors are expected to act as equivalent inducers but for different reasons. Conceptually, the target absent situation (condition 3) is more appropriate for baseline since no item on display would be singled out from the rest and attention would be equally likely to engage or withdraw from any randomly chosen item. In the target present situation (condition 2) at some point in search attention would narrow at target thus withdrawing processing resources to an equal extent from all distractors.

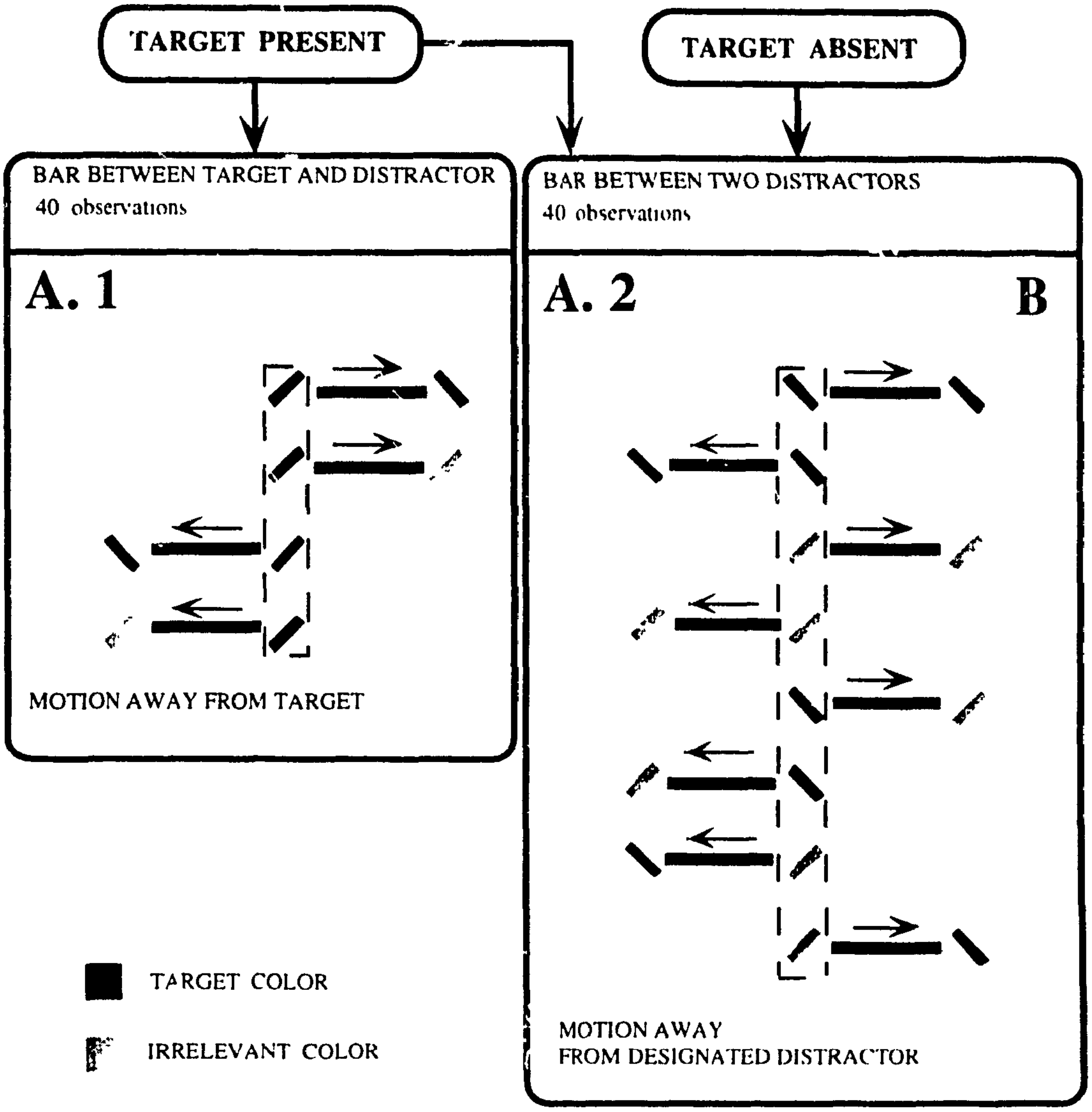


Figure 19. Cueing conditions in Experiment 3.

Motion induction was measured by the proportion responses in the direction of the arrows out of the total number of trials in each condition. Condition B (target absent) provided the baseline.

Results and Discussion

The mean percent motion induction in each of the three inducing conditions and at each SOA are presented in Figure 20. As expected, motion induction was at the same level when the bar was presented between distractors, regardless of whether the target was present or absent (see overlap between the two bottom curves). A planned contrast indicates no significant difference between the means in these two conditions, averaged across SOAs (see Appendix F, Table 1). Therefore, motion induction at distractors in the target present condition was not considered in the subsequent analysis which focused on evaluating the effect at target in respect to the baseline.

Summary results from the ANOVA on percent motion induction with Inducer (target, baseline=nontargets/target absent) and SOA (120, 240, 360, 480, 600, 720, 840 and 960 ms) as within subjects' factors appear in Appendix F, Table 2. The values of the Greenhouse-Geisser correction factor ranged form .34 to .66 indicating severe to moderate violations of the sphericity assumption. All effects were evaluated against α=.05.

Analogous to Experiment 2, results indicate a significant two-way interaction between Inducer and SOA [$F(7, 70) = 5.326$, $p<.05$] meaning that the difference between motion induction at target from baseline changes as a function of SOA. The main effects of Inducer and SOA were also significant but of little interest on their own.

Analysis of simple effects (Appendix F, Table 3) revealed that the motion induction at target was significantly above baseline at all SOAs except at the shortest one (120 ms). Trend analysis of this difference (Appendix F, Table 4) indicated significant linear [$F(1, 10) = 11.272$, $p<.05$] and quadratic [$F(1, 10) = 8.169$, $p<.05$] components in the development of the effect over time.

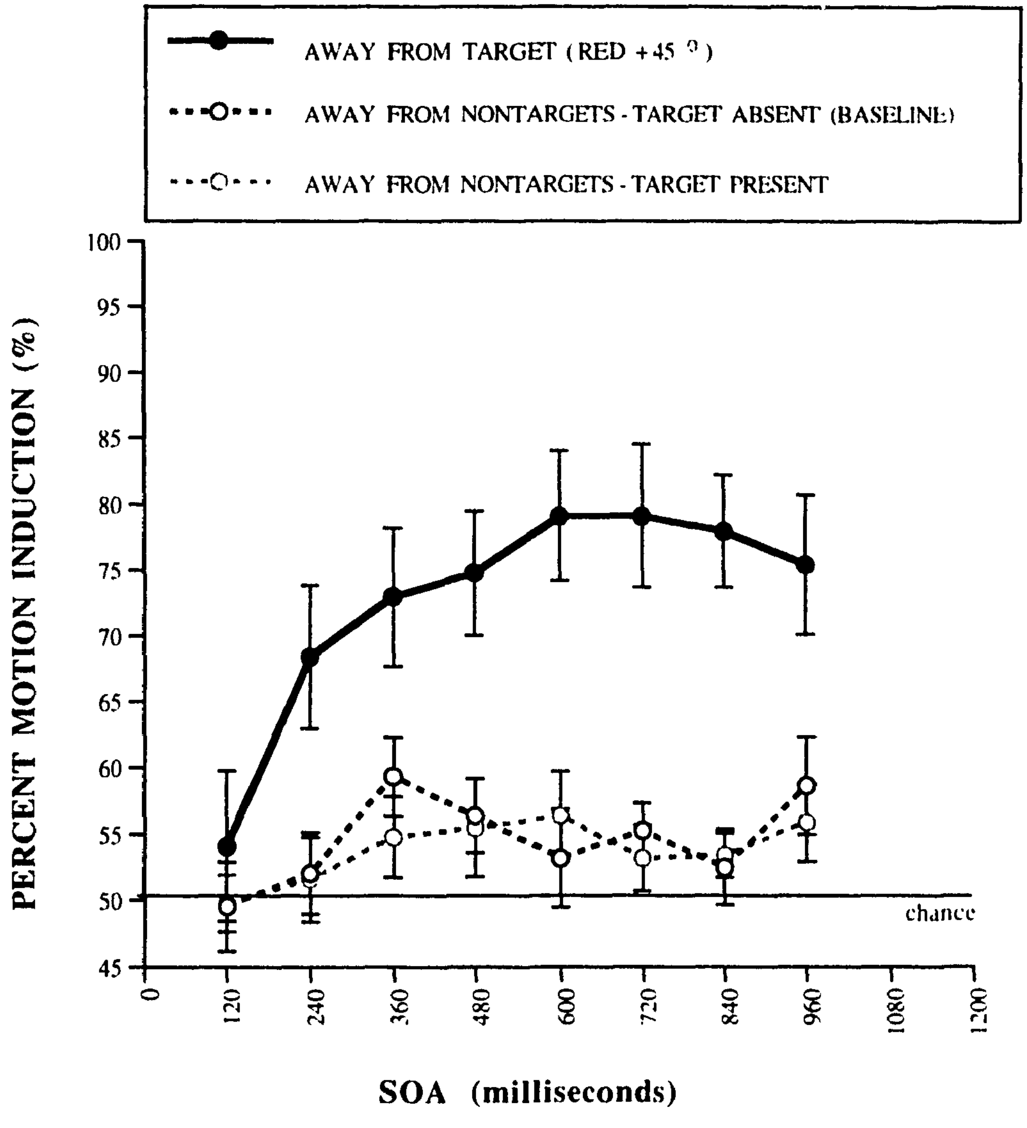


Figure 20. Motion induction at target and at distractors compared to baseline as a function of SOA (display size = 8)

So far, results replicate the pattern observed in the corresponding condition of Experiment 2. Generally, the motion induction effect at target gained strength as search progressed with a relative decline observed at the longest SOAs when attention starts disengaging from the target location.

There were, however, important differences between the dynamics of the effect in the two experiments. Results from Experiment 2 and 3 can be compared in Figure 21 where they are plotted together for SOAs up to 1200 msec. Although within these time limits the overall strength of the effect was comparable, it reached an optimal level twice as early in Experiment 3 (600 ms) than in Experiment 2 (1200 ms). Also, in the present experiment the peak in motion induction at target was followed immediately by a visible decline, while the effect observed in Experiment 2 was still gaining strength.

It should be noted, however, that there was more variability between subjects in Experiment 3 which was probably due to the increased experimental uncertainty, as well as to the inclusion of more inexperienced observers in the sample. Representative individual results can be examined in Appendix G, Figure 1 and Figure 2. One can see that both experienced and unexperienced observers showed considerable differences in the strength of perceived illusory motion (upper vs. bottom graphs on each figure), as well as in their tendency to maintain the effect at longer delays (Figure 1 vs. Figure 2). Since the pattern of results from subjects showing stronger effects have more weight in the average data, the percent motion induction for each subject was standardized in respect to this subject's mean and standard deviation across all conditions. The standardized difference in motion induction at target from baseline was then averaged across subjects at each SOA and presented in Figure 22, bottom. The same was done for the corresponding data from Experiment 2 (see Figure 22, top).

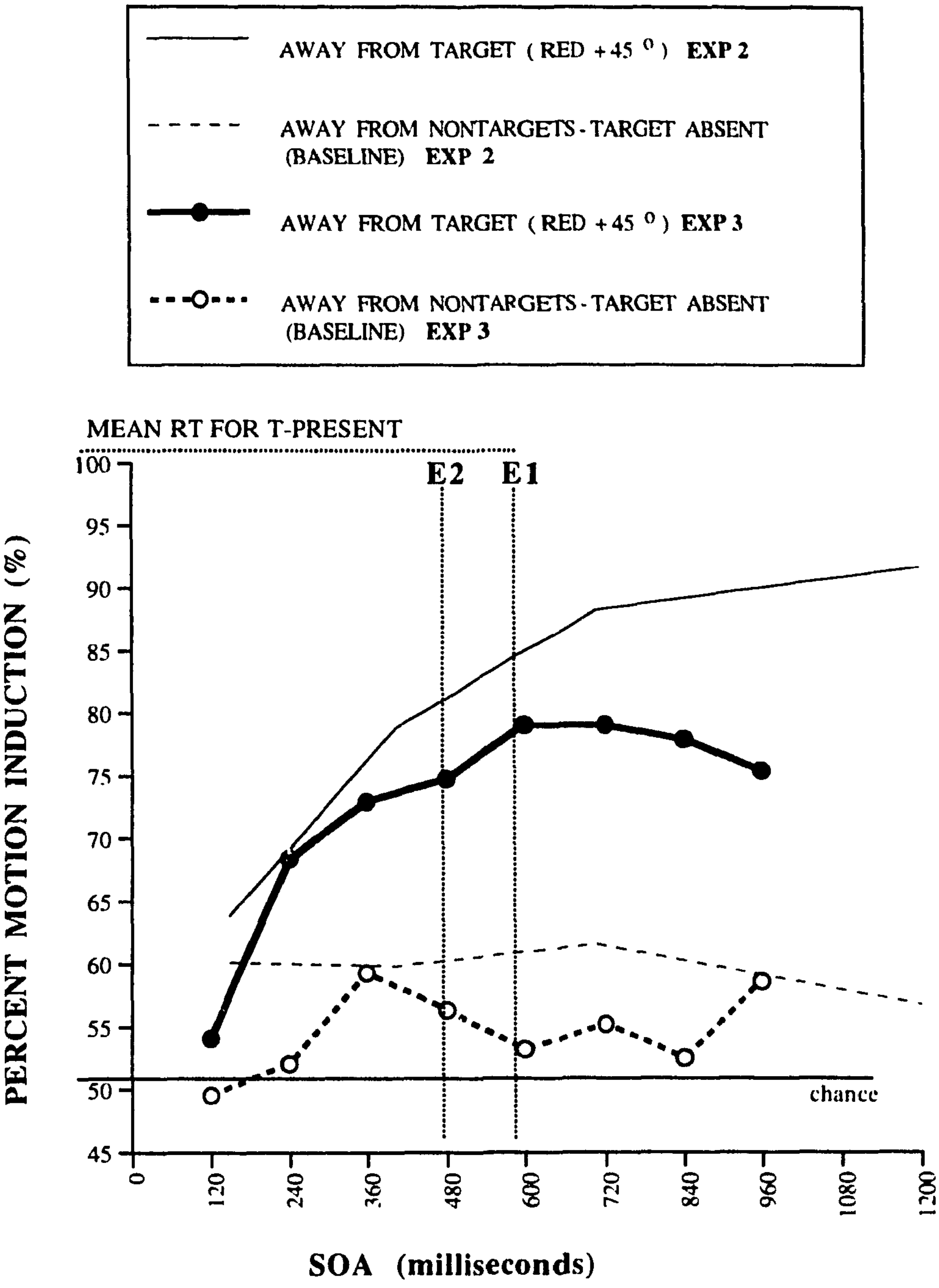


Figure 21. Motion induction at target compared to baseline as a function of SOA in Experiments 2 and 3 (display size = 8).

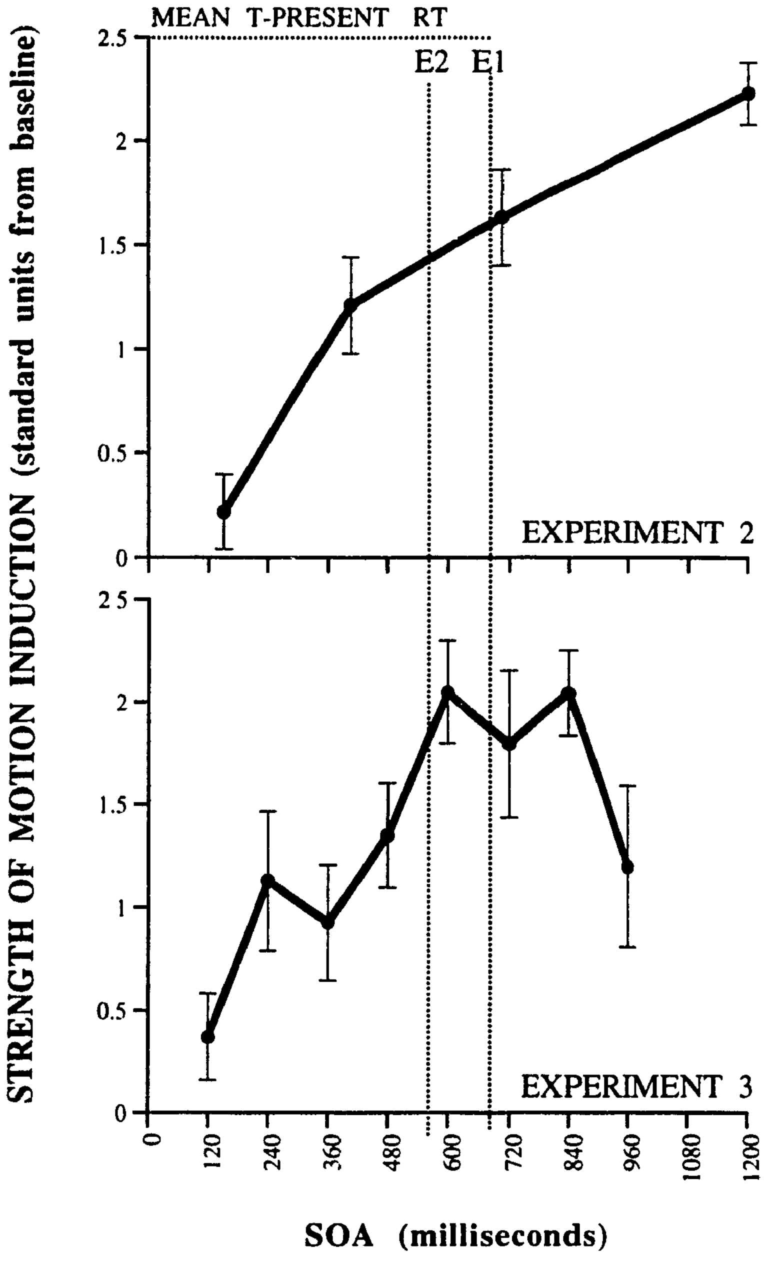


Figure 22. Time course of motion induction at target in Experiments 2 and 3 (display size = 8).

Taking individual variation into account accentuated the difference in the dynamics of motion induction between experiments. Figure 22 shows that in Experiment 3 the peak in the effect clearly coincides with the average time for target detection recorded in Experiments 1 and 2 when the probability of attention being at target is highest. In contrast, in Experiment 2 at the time of target detection motion induction is experienced at only half of its optimal strength. These results strongly suggest that the motor execution of a detection response in Experiment 2 might have indeed interfered with perception by absorbing attentional resources and delaying the optimal experience of motion induction at target.

In addition, whereas in the present experiment motion induction at target remained at full strength for no more than 200 ms after it peaked, dropping sharply thereafter, in Experiment 2 the effect remained optimal up to 800 ms after its peak. Indeed, results indicate that the quadratic trend was more pronounced in Experiment 3 than in Experiment 2 accounting for 34% of the variance due to the SOA X Inducer interaction compared to 48% explained by the linear component. In contrast, in Experiment 2 the quadratic trend was much weaker (21%) relative to the linear one (76%). Thus, as hypothesized, the persistence of the effect at extremely long delays in Experiment 2 could be explained with expectancy of the bar at the target location since, as presently shown, when this factor is controlled motion induction at target decreases shortly after target detection.

In summary, with a new sample of observers and more precise temporal sampling Experiment 3 confirmed that motion induction occurs with deliberate attentional selection of the inducer. In addition, it demonstrated that the illusion is extremely sensitive to task demands and top-down influences such as expectancy and cognitive strategy. It is also susceptible to interference from a preceding or concurrent task. It should be pointed out that these factors are attentional in nature in that they determine the distribution of processing resources between tasks and across space and time.

EXPERIMENT 4

This last experiment assessed independently the perceptual effects of attention at the same times during search and at the same locations at which the motion induction effect was measured in Experiment 3. This made it possible to relate directly the time course of attentional alocation with the dynamics of motion induction.

A reaction time paradigm (Posner, 1980) was used to measure the strength of attention at target, at nontargets when the target was present and at nontargets when the target was absent (baseline). While searching for the same target as in Experiment 3 observers now had to detect a low contrast small spot presented at different SOAs next to a randomly chosen item or separated by 2.5 degrees of visual angle from it. It was expected that attention at target would speed up detection of probes presented at the target while possibly slowing down detection of probes at nontargets. Thus the reduction in detection times below baseline at and around the target location measured attentional facilitation at target whereas the increase in detection times above baseline at nontargets when the target was present measured attentional inhibition.

Hikosaka et al. (1993a) attributed the motion induction effect to attentional facilitation of visual processing which would be strongest at the attended location and progressively weaker at more distant locations. Based on this, one would expect that the attentional facilitation at target (as measured in the present experiment) and the motion induction effect at target (Experiment 3) would develop in a similar way over time. Moreover, when attention is optimally narrowed at target facilitation was expected to be stronger for probes next to the target than for more distant ones, reflecting the spatial gradient of attention.

Method

Subjects

The eleven observers who took part in this experiment were the same ones as in Experiment 3.

Apparatus

The computer equipment and the software program were identical to those used in Experiment 3. Again, viewing distance was 57 cm.

Stimuli

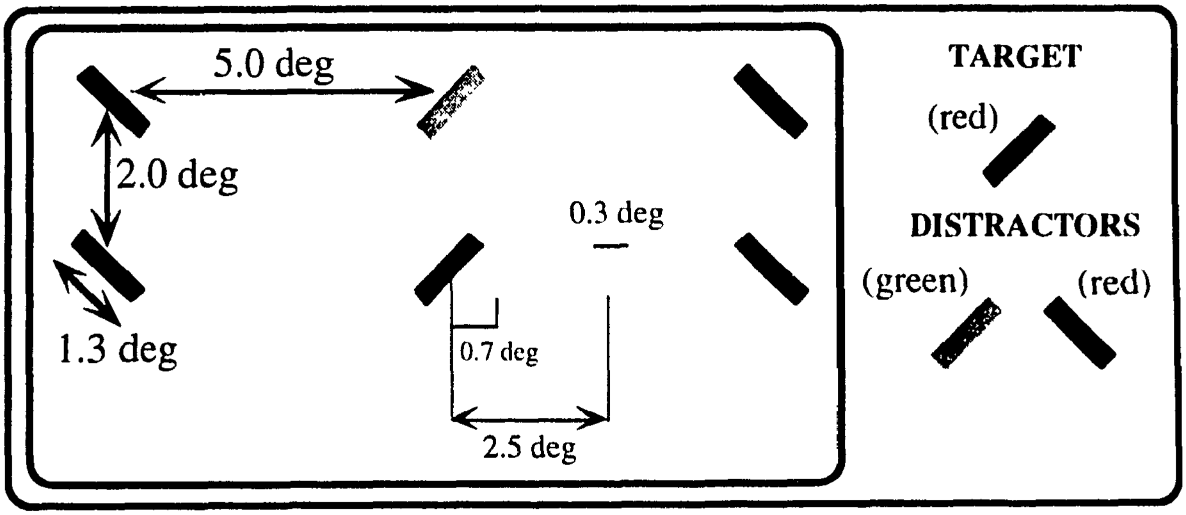


Figure 23. Dimensions and positions of the low contrast probe between items (display sample from Experiment 4)

Search items and their arrangement were the same as in Experiment 3. Again, the target was a +45° red item and there were always eight items on display. Instead of a horizontal bar, however, a low contrast (.08) gray square spot (72.9 cd/m^2) was presented in the space between items, at the level of their centers. The two positions at which the probe appeared between items, its separation from them and its dimensions are shown on Figure 23. At the largest separation (2.5 deg) the probe appeared exactly in the middle between two items.

Procedure

The experiment consisted of 1024 trials. To avoid the effects of fatigue or boredom the 1024 trials were administered in two identical blocks of 512 trials each, which were run in two separate sessions. Completion of each session took about 40 minutes, on average.

For each combination of SOA and probe separation there were 64 trials. Sixteen of them (8-target present, 8-target absent) were catch trials on which the probe was not presented. On the remaining 48 trials the probe appeared either at a nontarget when the target was absent (16 trials), at a nontarget when the target was present (16 trials) or at the target (16 trials). With this distribution of trials, the probability of the spot being presented in each of the three conditions or not being presented at all was the same.

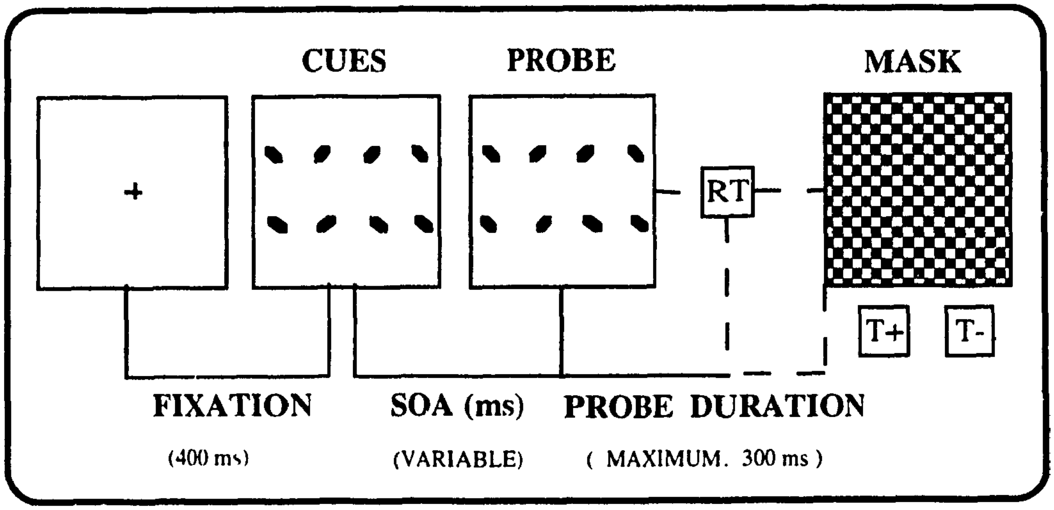


Figure 24. Sequence of events within a trial in Experiment 4

The sequence and duration of events within a trial are illustrated in Figure 24 and could be compared to those in Experiment 3 (Figure 18). First, observers fixated at the cross in the middle of the screen for the same amount of time (400 ms) as in Experiment 3. They were asked to keep their eyes on the fixated position as much as possible throughout the whole trial. Again, upon display presentation observers had to search for a red right-oblique ($+45^o$) target among red left-oblique (-45^o) and green right-oblique ($+45^o$) distractors. Reporting the target's absence or presence was again delayed until the end of the trial (i.e. upon presentation of the mask). Instead of a horizontal bar, however, a low luminance probe appeared at randomly chosen variable delays following display onset, at either .7 deg or 2.5 deg separation, on the left or right side of a randomly chosen item. The eight SOA-s (120, 240, 360, 480, 600, 720, 840 and 960 ms) were the same as in Experiment 3. Observers had the task to report the low contrast probe as soon as they noticed it but were explicitly instructed not to look for it. They were asked to concentrate fully on the search task and carry it out as usual. The probe remained available for detection for a maximum of 300 msec and was then replaced by the mask if by this time a detection response was not made. In this case a RT of 300 msec was recorded. If subjects responded to the probe before the maximum 300 msec had elapsed, their actual response time was recorded and the mask followed immediately. The mask remained on until the target's presence or absence was reported. A new trial was initiated only after the outcome of the search task was registered.

Results

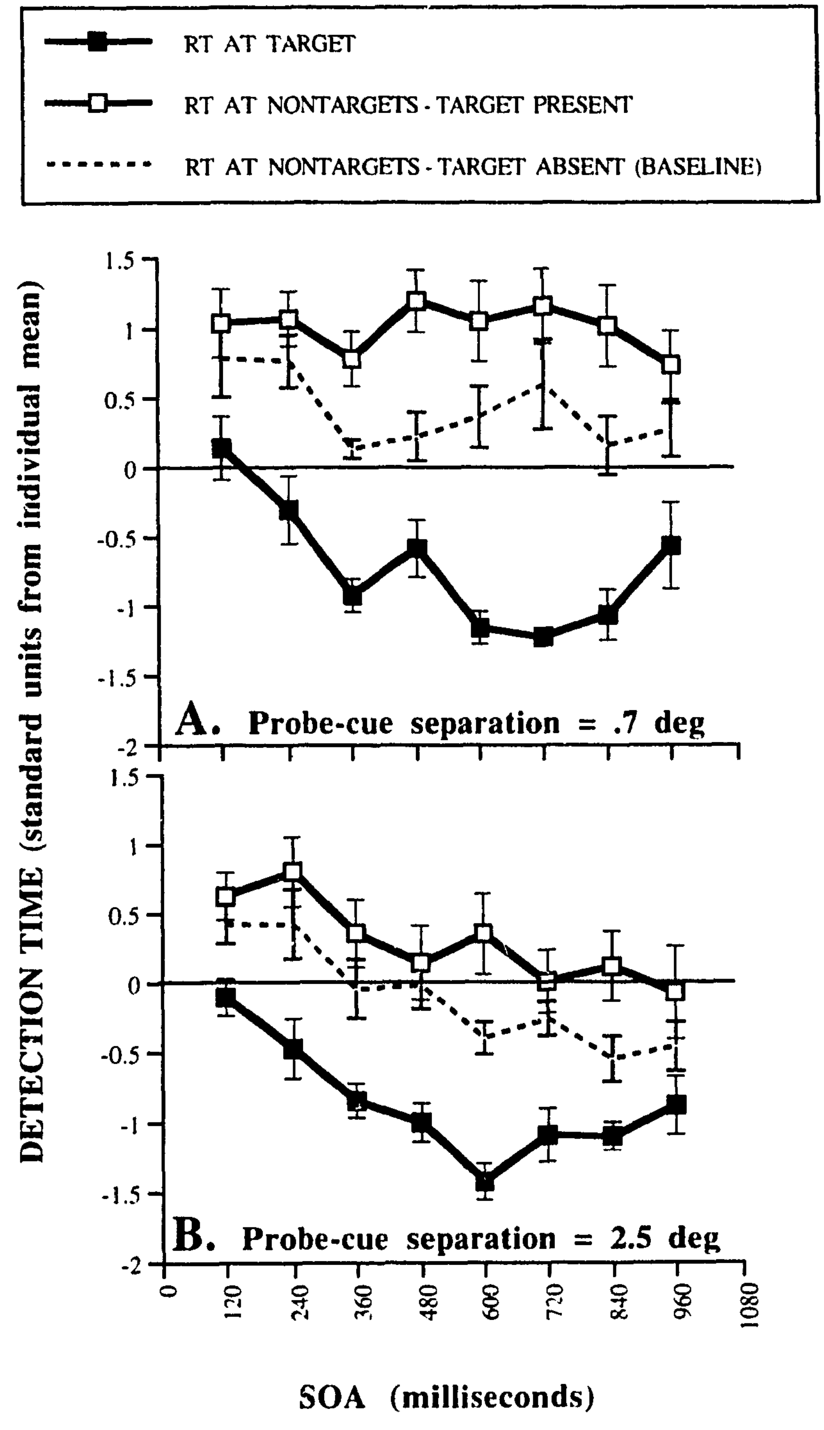
The raw data consisted of individual mean RT from the 16 trials run at each SOA and for each of the two probe positions in each of the three cuing conditions listed below:

1) Probe at target
2) Probe at nontarget - target present
3) Probe at nontarget - target absent

The last condition provided the *baseline RT.*

Analysis of Variance

Since overall, individual average response times ranged from 200 to 700 ms with standard deviations of 50 to 150 ms the RT data was standardized in respect to each observer's mean and standard deviation across conditions. Thus the analysis was carried out on the RT data expressed in standard units, that is, in number of standard deviations above (+) or below (-) the overall individual mean (i.e. 0). A three-way ANOVA examined the separate and combined effects of Probe Separation (.7 deg, 2.5 deg) and SOA (120, 240, 360, 480, 600, 720, 840 and 960 ms) on standardized detection times across the three Cueing Conditions (at target, at nontarget, baseline). Violations of the sphericity assumption of within-subjects' ANOVA were moderate to severe (Greenhouse-Geisser correction factors ranging from .86 to .26). Since this is known to reduce statistical power, all effects were evaluated against the more liberal α=.05. The summary ANOVA table is presented in Appendix H, Table 1. Means and their standard errors for each of the two probe separations appear in Figure 25, A and B.



A. Probe-cue separation = .7 deg

B. Probe-cue separation = 2.5 deg

Figure 25. Detection times in the three cueing conditions as a function of SOA and distance from the cue.

As can be seen in these figures, for both probe separations and across SOAs, cuing condition had a significant overall effect on detection times [F(2,20)=35.221, p<.05]: on average, detection of the probe when the target was present was about 1.5 SD faster at the target than at nontargets (Mean Difference=1.45). A significant Cuing X Separation interaction [F(2,20)=30.052, p<.05] indicated that this overall attentional advantage at the target relative to nontargets was more pronounced at the smaller separation (.7 deg) than at 2.5 deg. Also, regardless of probe separation, the overall effect of cuing changed as a function of time [significant Cuing X SOA interaction, F(14,140)=2.913, p<.05], in that it was weakest at the shortest and longest SOAs and strongest at the intermediate ones. Although the overall three-way interaction was not significant, analysis of simple effects, planned contrasts and trend analyses were conducted within this interaction to isolate the effects of interest and to examine their time course.

Overall Attentional Effect: RT at Target vs. RT at Nontargets

The difference between RT at nontarget minus RT at target indicated the overall detection advantage at the target location relative to search irrelevant locations and was therefore taken as an index of the overal attentional effect at target. This effect (in absolute standard units) is plotted on Figure 26 as a function of SOA for the two Probe-Cue separations. As discussed above, overall, detection of the probe was faster at the target than at any of the surrounding nontargets and this effect changed over time. Analysis of simple effects (Appendix H, Table 2) revealed, however, that the effect changed across SOA only for probes presented next to the cue [F(7,70)=2.93, p<.05] and remained relatively constant for more distant ones. This change was both linear [F(1,10)=2.93, p=.05] and quadratic [F(1,10)=11.69, p<.05] in nature (Appendix H, Table 3).

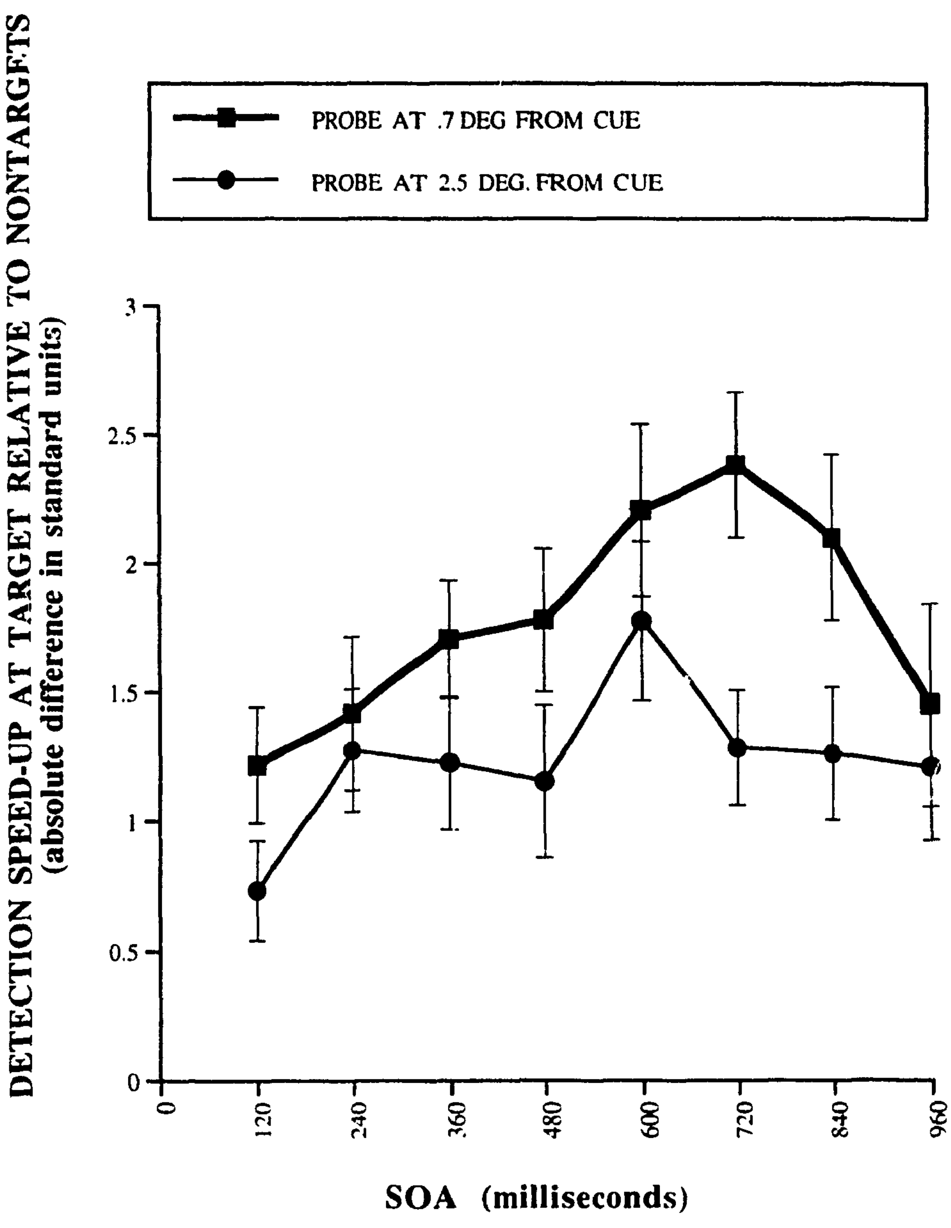


Figure 26. Time course of the overall attentional effect at .7 deg and at 2.5 deg from the target.

Also, as the ANOVA results indicated, the overall attentional effect was significantly stronger immediately next to the target than at some distance away from it at the four intermediate SOAs, before (360 ms and 480 ms) and after (720 ms and 840 ms) the mean time for target detection recorded in previous experiments (see simple effects, Appendix H, Table 2). There was no such difference for the shortest and longest SOAs.

Facilitation Effect: RT at Target vs. Baseline

The mean difference between RT at target and the baseline RT is plotted at each SOA for the two item-probe separations on Figure 27, top. The horizontal line (i.e. 0 difference) indicates baseline.

First, contrasts within the Cuing X Separation interaction (Appendix H, Table 4) examined the significance of the overall reduction of RT at targets (facilitation effect), relative to baseline at each of the two item-probe separations. The overall facilitation effect (RT decrement from baseline at target , Figure 27, top), averaged across SOA-s, was significant at both .7 deg [Mean Difference=1.1 SD, F(1,10)=120.252, p<.05] and 2.5 deg. from the cue [Mean Difference=.8 SD, F(1,10)=76.835, p<.05] but was significantly stronger at the smaller separation [F(1,10)=44.806, p<.05]. Furthermore, simple effects (Appendix H, Table 5) indicated that the facilitation effect changed as a function of SOA for probes at .7 deg separation only [F(7,70)=2.583, p<.05], being present to some extent immediately after display onset, remaining relatively constant for up to 480 msec, increasing and reaching optimal strength at 720 msec (about 2 SD below baseline) and then dropping back to its initial level. No regular trend accounted significantly for this change (Appendix H, Table 6). In addition, at the three SOA-s (600, 720 and 840 ms) at and after the average time for target detection facilitation was significantly stronger at the target location than at 2.5 deg away from it (see simple effects, Appendix H, Table 5)

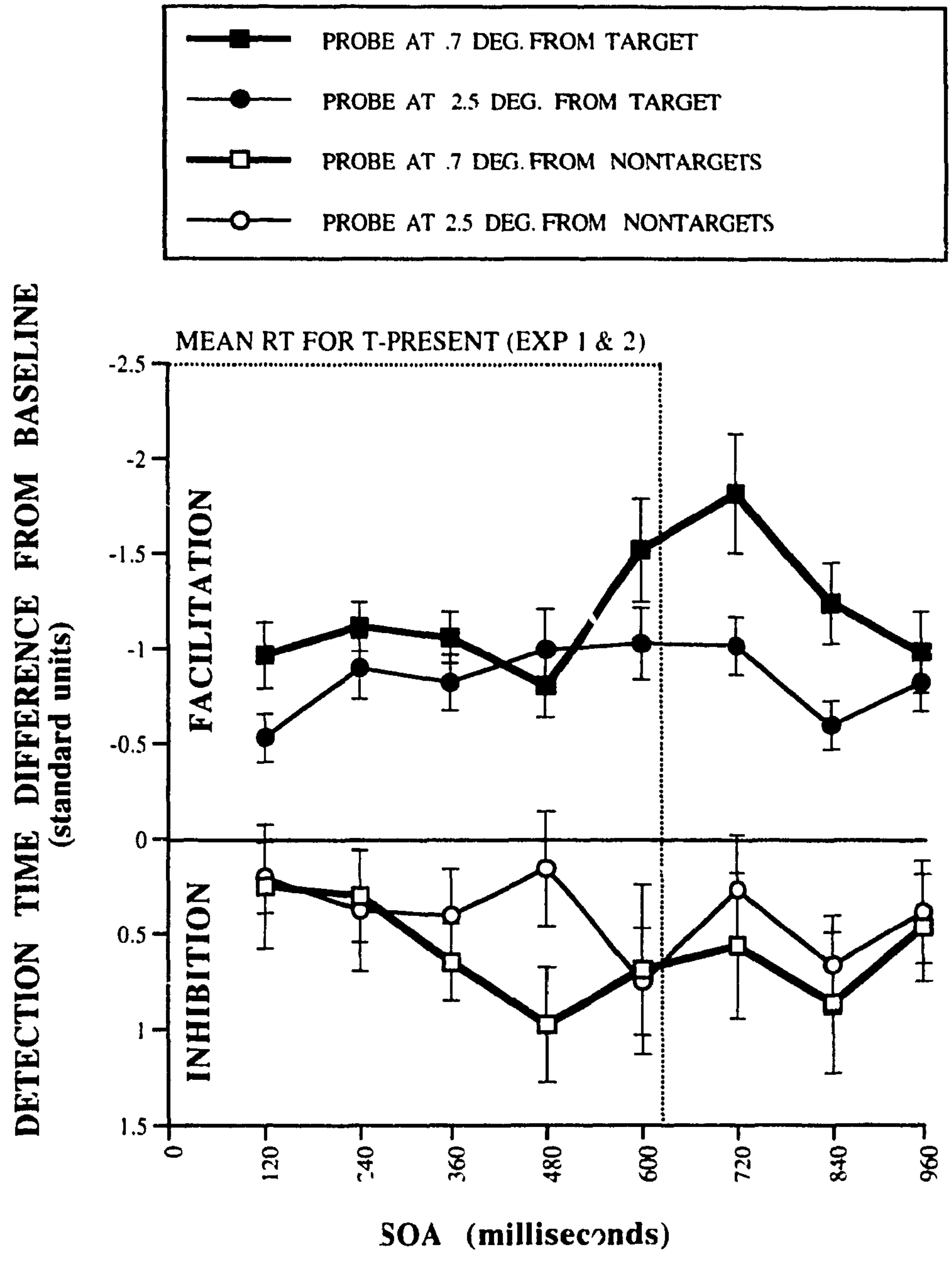


Figure 27. Time courses of facilitation at target (top) and inhibition at nontargets (bottom) at the two probe-cue separations.

Inhibition Effect: RT at Nontargets vs. Baseline

The average increments in RT at nontargets relative to baseline indicate attentional inhibition and are plotted at each SOA for the two item-probe separations on Figure 27, bottom part.

In contrast to the facilitation effect which was present at both probe-item separations, planned contrasts within the Cuing X Separation interaction (Appendix H, Table 4) indicated that the overall inhibition effect at nontargets was significant only for probes presented next (i.e. at .7 deg) to the nontarget cue [Mean Difference=.6 SD, $F(1,10)=8.591$, $p<.05$] and was significantly weaker than the facilitation effect at the same separation [$F(1,10)=6.008$, $p<.05$]. Analysis of simple effects (Appendix H, Table 7) revealed that inhibition did not change significantly as a function of time. A complex comparison of means, however, indicated that at 480 msec inhibition was significantly stronger [$F(1,10)=5.041$, $p<.05$] than in the beginning (120 ms) and in the end (960 ms) of search. Also, at 480 ms inhibition was confined to the nontarget location being significantly stronger at .7 deg than at 2.5 deg separation [$F(1,10)=6.775$, $p<.05$, see simple effects, Appendix H, Table 7].

Attentional Effects (Experiment 4) and Motion Induction at Target (Experiment 3) as a Function of SOA

First, it should be noted that the overall detection speed-up at target relative to nontargets represents both facilitation at target and inhibition at nontargets added together, as illustrated in Figure 28. Results indicate that the development of this overall attentional effect at target matches better that of motion induction than either facilitation or inhibition taken on their own. Comparing facilitation alone with motion induction at target reveals that the two have a different time course for up to 480 ms with the former staying constant and the latter steadily increasing.

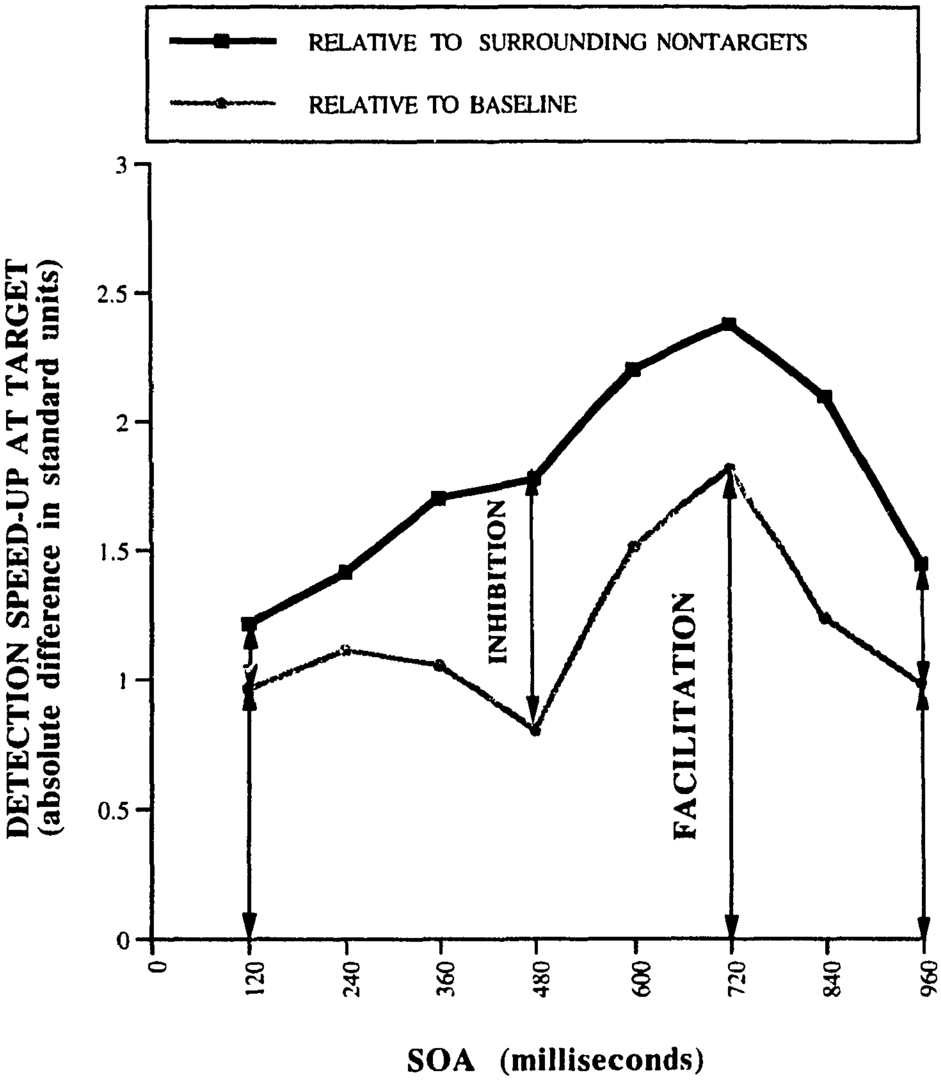


Figure 28. Relative contributions of facilitation at target and inhibition at nontargets to the overall effect of attention at target.

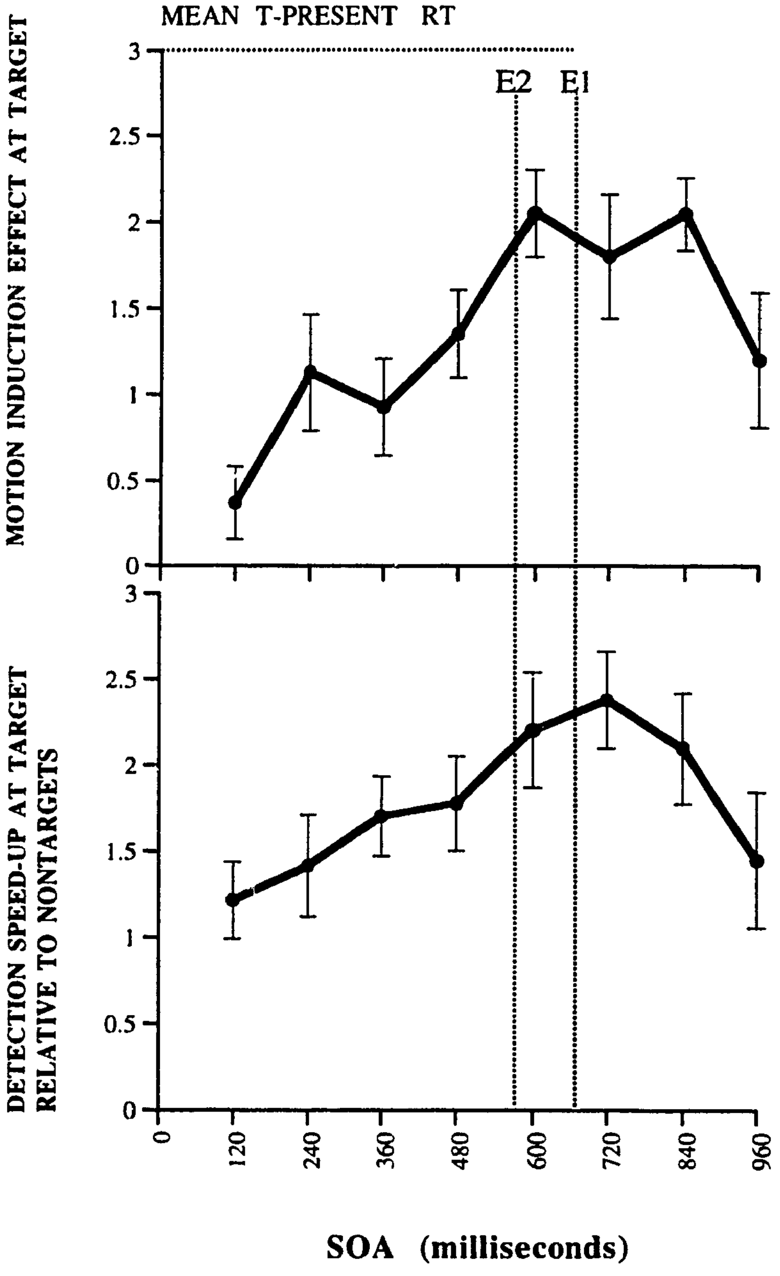


Figure 29. Time courses of the overall attentional effect at target (Experiment 4) and the motion induction effect at target (Experiment 3)

Figure 29 shows the correspondence between the time course of the overall attentional effect at target relative to nontargets (bottom) and that of the motion induction effect at target (top), expressed in standard units. Both effects gained strength gradually and became optimal slightly after 600 msec when target detection was most likely to occur. Also, on average, both effects remained optimal for about 200 ms after detection and dropped off sharply thereafter. In spite of the considerable individual variation, the correspondence in the development of the two effects was obvious in the individual data, as well (see Appendix I, Figures 1 & 2).

In addition, the combination of a linear and a quadratic trend, accounted for most of the variance in the development of both the attentional and the motion induction effect (76% and 82%, respectively). The quadratic trend, however, was stronger in the RT data (49%) than in the motion induction data (34%), whereas the converse was true for the linear trend (27% vs. 48%).

Discussion

Is Motion Induction Due To Attentional Facilitation at Target?

Taken together, results provide evidence for the attentional origin of the motion induction effect at target observed in Experiments 2 and 3. It was demonstrated that the detection speed-up at the target relative to nontargets and the motion induction effect change similarly over time peaking at the time optimal for target detection. This suggests that both effects, measured independently, reflect the deployment of attention during search. Moreover, consistent with the literature (Posner et al., 1978, Posner, 1980), it was found that the overall detection advantage at the target location was the result of two independent attentional processes - facilitation at target and inhibition at nontargets (see Figure 28). Interestingly, although facilitation was the dominant component, it determined the course of the overall effect only for times longer than 480 msec, that is after target selection. In contrast, the initial increase in both attention and motion induction could be attributed to increased inhibition at nontargets which developed early and reached optimum at 480 ms after which time facilitation took over. This suggests that the motion induction effect reflects not only facilitation of processing at the target-inducer, as hypothesized, but also inhibition of processing at the other search-irrelevant item flanking the bar (i.e. at the distractor). In other words, illusory motion in the same direction (i.e. away from the inducer) may be triggered either when the inducer is actively attended and its processing is made more efficient, or when the other item is "actively nonattended" and its processing suppressed. Thus double motion induction seems to be sensitive to the relative distribution of attention between inducers rather than to facilitation or inhibition per se.

The fact that with the present search task optimal inhibition at nontargets preceded optimal facilitation at the target is noteworthy. This seems to support the hypothesis, that search for conjunction of features unfolds in successive stages (Grossberg et al., 1994) with rejection of irrelevant items preceding target selection. The fact that the inhibition observed at nontargets was smaller in magnitude than the facilitation at the target suggests that rejection of irrelevant items was relatively difficult. This is consistent with some evidence (Posner et al., 1980) that larger signal-to-noise ratios reduce attentional inhibition at irrelevant cues. On the other hand, it has been also reported (Posner, 1980) that when stimulus input controls attentional allocation reaction time benefits (i.e. facilitation) precede reaction time costs (i.e. inhibition) because attention is immediately and involuntarily driven to the stimulus location. In contrast, the results from the present experiment suggest that when attention is under internal, central control the temporal sequence of inhibition and facilitation may be reversed. With respect to motion induction, this means that one has to carefully consider both the source of attentional control and the temporal delay at which the illusion occurs before attributing the effect exclusively to attentional facilitation.

Evidence for Spatial Gradient of Attention

Generally, results indicate that both attentional inhibition and facilitation were operating primarily at the items' locations, rather than over the space between items. Facilitation was weaker and there was no inhibition when the probe was presented in the middle between items, rather than next to one of them. Moreover, the spatial gradient of attention was strongest at times when facilitation at the target and inhibition at nontargets were strongest which was consistent with the relative increase in the incidence of motion induction. In contrast, the attentional effects were not location specific in the beginning and in the end of search suggesting that before and after its commitment to particular locations attention was spread homogeneously over larger display areas. These findings are consistent with the hypothesis that a spatial gradient of attention, strongest at the target center and weakening away from it may underlie motion induction. This experiment, although not sensitive enough to capture adequately the development of the spatial gradient over time, recorded its presence and at the points in time when it was strongest motion induction was optimal as well.

Did Foveating the Target Reduce Detection Times?

Since there was no control on eye-movements in the present experiment it is possible that on some of the trials foveating the target and attending to it were inseparable. Naturally, eye movements correlate with attentional movements and the extent to which subjects maintained initial fixation during search is unknown, depending on their experience, commitment to the task and level of fatigue. Thus the reduction of detection times at target relative to other display locations may be at least partially due to the higher contrast sensitivity at the fovea. For spatial frequencies of 1 to 2 cpd (roughly corresponding to the .3 deg probe) contrast sensitivity is known to decrease by about 30% from 0^o to 4^o eccentricity (Rovamo, Virsu & Näsänen, 1978). Consequently, one would expect that at SOAs beyond 200 ms when the target may be brought on the fovea reaction times to the probe at .7 deg from the target would be faster than those at 2.5 deg eccentricity. This, however, was not the case in the present experiment (see Figure 25-A,B, compare bottom curves). In fact, there was slight advantage in the opposite direction with RT being somewhat faster for probes separated by 2.5 deg from the target. It should be emphasized that the effects of interest represent RT differences from baseline and there is no reason to expect any systematic effect of eccentricity on RT to nontargets when the target was absent (baseline). In addition, foveating the target cannot explain the larger RT costs at irrelevant items at the smaller separation. One must also consider the fact that extended practice in visual search tends to reduce eye-movements. Moreover, other studies combining spatial precueing with visual search (Nakayama & Mackeben, 1989) have found that the pattern of results obtained without control on eye-movements remains unchanged after exclusion of trials on which the eyes had moved. For the above reasons, we may regard the present results as genuinely attentional in nature. Eye-movements, however, may have increased performance variability within and between subjects, thus masking the effects of interest and decreasing experimental power.

GENERAL DISCUSSION

Taken together, results from the present study indicate that the motion induction effect is sensitive to the deployment of voluntary attention during visual search. These findings have important implications in the context of several lines of research. First, they support the attentional account of motion induction and add to the growing body of evidence for attentional contributions to motion perception. Second, they suggest new ways of delineating the voluntary and bottom-up components of attention. Third, since results are consistent with reports in the visual search literature, the method employed in this study may be useful in discriminating between current models of search for conjunctions of features. The main findings from the present study will be discussed with these perspectives in mind. Some methodological issues will be addressed as well.

Motion Induction With Selective Narrowing of Attention

Results from this study support the finding of Hikosaka et al.(1993b) that motion induction can be triggered by voluntary attention narrowed at a cue with predefined attributes. In the present experiments, however, attentional narrowing was the outcome of a dynamic search process during which attention was "distracted" by multiple irrelevant items defined along the same stimulus dimensions as the target. Both Experiment 2 and Experiment 3 showed that the motion induction illusion occurs at a target defined by conjunction of features regardless of the particular combination of features. In addition, Experiments 3 and 4 demonstrated that the development of motion induction at target parallels the raise and decay of the overall attentional effects at target as measured independently with a reaction time method. Moreover, results were stable in that they were replicated across different samples of observers and with different temporal sampling.

As expected, in the present experiments optimal motion induction due to voluntary attention at target was observed at cue lead times longer than the 400 milliseconds, reported by Hikosaka et al., (1993b) who conducted their experiments with two cues at fixed positions and differing in color only. The present study showed that with more items present in the display, longer delays were needed for optimal motion induction. Whereas with eight items the effect at target was observed by about 600-700 milliseconds on 90% of the trials, with 28 items the effect needed almost 2 seconds to reach the same probability level. The slower development of motion induction was consistent with the longer response latencies needed for target detection in displays with more items. It is thus possible that the result reported by Hikosaka et al. (1993) indicates only the minimum time necessary for optimal engagement of voluntary attention, which does not generalize to more complex situations with more alternatives.

It must be noted, however, that the present set up differed in more than one respect from the one of Hikosaka et al.(1993b). Using displays with multiple items had two consequences which acted together in determining the results. First, there was uncertainty in respect to the positions of both the target and the bar, whereas in the study by Hikosaka et al. (1993b) the two possible stimulus positions were fixed Second, the overall perceptual load was greater. In addition, stimuli were defined along two instead of along only one dimension. Thus it is not clear to what extent each of these factors hindered the allocation of voluntary attention in the present experiments. In future studies it would be interesting to examine the role of each of these components separately.

It may be worthy, for example, to replicate the experiment of Hikosaka et al. (1993b) with two items, differing in color only but appearing at various locations in the visual field with the bar always presented in between. In this way the role of positional uncertainty in respect to the cues will be isolated. Subsequently, uncertainty as to the bar position may be introduced (i.e. the bar would not always appear between the two cues). Similarly, a conjunction search with two items may be conducted without change in the spatial positions of the cues and the bar. Such approach would be useful in delineating components in voluntary attention such as selection of spatial location or selection of one or more features which may contribute differently to the temporal course of motion induction.

How Sustained is "Sustained Motion Induction"?

The results clearly indicate that whether a sustained or a transient effect will be observed at longer delays depends on whether subjects have some incentive to maintain attention at the selected location. In Experiment 2 motion induction at target remained optimal long after target detection and up to two seconds. It was found, however, that this is due to expectancy of the bar which appeared always at the target location. Interference caused by the motor response required during search might have also contributed to the shift of the effect towards longer delays. With these two factors removed in Experiment 3, the average probability of reported motion induction declined after target selection. Knowledge of the hypotheses or a spontaneously developed strategy to maintain attention at target may have similar consequences. It is thus clear that the allocation of voluntary attention and, as a result, the incidence of motion induction are extremely sensitive to minor modifications in the structure of the experiment which should be taken into account in designing future studies.

In addition, there were considerable individual differences in the magnitude and temporal course of motion induction. Individual results in Experiment 3 fell roughly into either a "sustained" or a "transient" category with the transient one being better represented. Some individual differences could also be noticed in the data presented by von Grünau et al. (in press) with the "sustained category" being more prominent in their sample. Similarly, in their initial experiments on motion induction Hikosaka et al. (1993a) reported that although the performance "for most subjects" was sustained until the longest cue lead times "subjectively (...) the sensation was strongest at the cue lead times between 100 and 200 msec, as suggested typically by the data of SS". These individual differences are interesting, since they seem stable and resistant to practice effects, possibly reflecting innate differences in the flexibility of attentional disengagement. Thus it would be interesting to explore whether individual effects would preserve their characteristic time course when attentional strength is measured with different methods. The fact that most observers in the present study performed similarly in the motion induction and reaction time experiments is encouraging.

Related to the above observations is a finding by Nakayama and Mackeben (1989) who used a somewhat reversed paradigm and examined the effects of transient and sustained spatial cues on the accuracy for target detection in conjunction search displays. Results indicated that even with transient cueing the down-turn in performance was not always present especially when the test stimuli on which the cue acted were displayed for a longer time (i.e. for 117 msec; Nakayama & Mackeben, 1989). The authors failed to provide explanation for this observation and placed it under the rubric "unresolved questions". Extrapolating this finding to the present experiments, one may wonder whether the effects of attentional cueing on motion induction depend on the duration of the test bar. In other words, it is possible that the time course of the effects observed is contingent not only on the strength of attentional engagement at the cue but also on the time during which attention is allowed to act on the test stimulus. In the present experiments the fixed bar duration of 300 msec was chosen more or less arbitrary after pilot trials on which we attempted to determine the shortest bar duration at which illusory motion is still clearly seen so that the following mask would not interfere with the motion percept. Interestingly, during these trials it was noticed that at short bar durations the direction of illusory motion becomes difficult to judge. The variation in motion induction as function of bar duration, is a question which has not been addressed by previous studies and deserves systematic investigation. It is possible that with the same type of attentional cueing motion induction exhibits different time courses depending on the amount of time during which the bar remains available for processing.

Relation Between Voluntary and Stimulus Driven Motion Induction

The fact that motion induction occurs in the context of deliberate visual search at a target-cue defined by a conjunction of features opens new possibilities for exploring the interaction between voluntary and stimulus driven attention. So far, cueing experiments have examined only the relation between the dynamics of voluntary attention and that of attention captured by visual transients (Nakayama & Mackeben, 1989; Müller & Rabbit, 1989). The general finding is that the temporal course of voluntary attention can be easily and immediately disrupted by abrupt visual onsets, whereas transient attention is unaffected by task demands or voluntary effort. This has been also demonstrated in respect to motion induction when active and passive attentional cueing were brought into conflict (Hikosaka et al.,1993b). In a double motion induction setup prior to bar presentation one cue was flashed whereas the other was not. Observers were asked to direct and maintain their attention to the non-flashed cue, that is, to the side opposite to the stimulus change. It was found that illusory motion away from the flashed cue dominated completely at shorter cue lead times (<200 msec) regardless of the amount of voluntary effort, whereas the "anti-stimulus" voluntary effect (i.e. away from the non-flashed side) took over much later (>400 msec).

As discussed earlier, however, attention can also be passively drawn to a conspicuous stimulus other than an abrupt luminance onset which may also trigger illusory motion. Von Grünau et al. (1996a), for example, have demonstrated motion induction driven by a feature contrast along one dimension - i.e. a stimulus "pop-out". At the present time the status of this effect in respect to the reflexive-voluntary dichotomy of attention is not clear. It may be useful, therefore, to juxtapose "pop-out" motion induction with the "abrupt onset" effects as well as with the effect observed in the present study. The present paradigm combines visual search, spatial precueing and motion induction which makes it possible to examine the development of these effects as they occur together and influence one another in a single experiment. So far, as mentioned earlier, isolated studies in this direction had been conducted with the standard visual search method. Interference effects were reported between two "pop-outs" (Theeuwes, 1992) and an unexpected "pop-out" was shown to slow down conjunction search (Todd & Kramer, 1994). In visual search, however, observers must have an explicit search task - which already introduces the voluntary aspect of attention, as well as a secondary motor response requirement. Also, in visual search, interference is measured only by the overall costs in detection efficiency. In contrast, with motion induction as the dependent measure the present paradigm (von Grünau et al., 1996a) could reveal the temporal course of the interaction between different types of attentional cueing in visual search displays, without the need of search instructions or motor response.

Motion Induction With Parallel Attentional Selection?

One of the most interesting findings in the present study is that the increase in motion induction at target in the initial stages of search could be almost fully accounted for by the increase in motion induction at distractors with the target color. This effect was observed only before the optimal time for target detection and conforms to reports form the visual search literature (Egeth et al., 1984; Kaptein et al., 1995). The motion induction effect thus revealed that color based selection guided subsequent target selection. Moreover, since the test bar sampled distractor locations at random, it could be inferred that attention operated concurrently on a subset of distractor locations. In other words, instead of examining items one by one, observers had limited their search to the subset of items with the relevant color. This result, therefore, provides evidence for parallel processes during search for conjunction of features (Pashler, 1987; Wolfe et al., 1989; Treisman & Sato, 1990; Grossberg et al., 1994) which is also consistent with the presence of a significant nonlinear trend in the functions relating search times to the number of items on display (Experiment 2), as well as with subjective reports.

Was Color Selection Due to Stimulus Differences?

The present search displays were designed to minimize bottom-up factors which may facilitate target selection. With widely spaced elements arranged in a regular matrix grouping may have played a role only occasionally, when items with the same color (or orientation) happened to fall in one part of the display. This unsystematic factor, however, cannot explain the robust color based effect observed. Another possibility is that the target color was in some way more salient, possibly drawing attention to itself in a bottom-up manner. Indeed, the search functions for the two target types (i.e. red $+45^0$, green -45^0) differed in their steepness (Experiment 1) which was interpreted as evidence that in spite of the fact that the red and green colors were equated in luminance, the red color was stronger perceptually (e.g. with respect to brightness) than the green one since there was no reason to believe that the $+45^0$ orientation was more salient than the -45^0 orientation. If color based selection was based on stimulus salience (Wolfe et al., 1989), one may expect that it would occur for the red color only. Illusory motion away from distractors with the target color, however, was observed regardless of whether the target was green or red. It may be concluded, therefore, that color selection was guided in a top-down manner by knowledge of the target color. In search for a green target deliberate attention to the green color subsets was shown to override the stimulus advantage of red items.

These results are in close agreement with the findings of Kaptein et al. (1995) who examined explicitly the role of stimulus salience in color based selection during search for a conjunction of color and orientation. These authors used differently oriented red and green bars quite similar to the ones employed in the present study. They took special care in equating the red and green color in brightness. Also, to prevent selection by orientation a very small orientation difference was used. By varying the number of distractors in each color subset while keeping the total number of items constant these authors found that search times are affected only by changes in the number of distractors with the target relevant color. Based on previous findings (Egeth et al., 1984) they concluded that search was limited to the subset of items with the target color. Furthermore, the same results were obtained after introducing brightness and luminance differences between the two colors. As in the present study, switching the target color led to selection of the relevant color subset. Interestingly, results were the same with and without instruction for color based selection, suggesting that this is a likely strategy which develops spontaneously in search for conjunctions.

Why Selection Was Based on Color and Not on Orientation?

Since color differences are not a priori dominant over orientation differences the fact that in the present study attentional selection was based on color and not on orientation deserves explanation. As suggested earlier, in the present displays the orientation difference was most likely subject to the oblique effect and may have not been optimal. Both orientations used were oblique and similar in that they mirrored each other. Based on empirical evidence, it has been argued that in visual search context orientation differences are most salient when vertical and horizontal items are used (Wolfe et al., 1989). If one accepts such explanation, this would suggest that attention relies on the most salient feature difference to divide the display into subsets.

It is also possible, however, that color has innate attentional priority over other stimulus dimensions. In fact deliberate selection of subsets of items in conjunction search has been reported so far only for color and shape, with selection by shape being less efficient (Egeth et al., 1984). This is consistent with the fact that the most robust effects of voluntary attention on neuronal responses have been found in areas of the cortex specialized for the encoding of color (V4) and shape (IT).

The present results provide evidence for top-down parallel processing during search for conjunction. This goes against the common assumption that only preattentive processes can be parallel. It appears, however, that parallel deliberate selection is spatially limited since in the present experiments motion induction away from distractors with the target color was observed only in displays with eight items and not in larger displays (i.e. 28 items). This is consistent with Pashler's (1987) suggestion that parallel attention has a maximum limit of eight objects or eight spatial locations. According to this model, when displays contain more than eight items, subsets of about eight items are searched in series. The idea that small clumps of the display are searched in parallel, but global search (among clumps) is serial is also advanced by most recent conceptualizations of conjunction search (Grossberg et al., 1994). However, only few models emphasize the possibility that parallel stages may be selective and not necessarily "preattentive" (Pashler, 1987; Treisman & Sato, 1990).

Implications For the Attentional Account of Motion Induction

Overall, the present results are in line with the attentional account of motion induction (Hikosaka et al., 1993a). Experiment 3 and 4 showed that in the same visual search context illusory motion and detection efficiency at the target location rise and decay over time in a similar way. This indicates that there is an increase in processing efficiency at the attended location which affects different aspects of perception similarly. Thus results are thus consistent with the proposal that attentional modulation of processing underlies motion induction (Hikosaka et al., 1993a). As discussed earlier, however, increased processing efficiency may involve both signal amplification and faster signal transmission and the two possibilities cannot be separated at the present time.

The attentional account of motion induction attributes motion induction exclusively to attentional facilitation at the attended location. Selected signals, however, may attain processing priority by means of both facilitation at the attended location and inhibition at nonattended locations (Posner, 1980). The inhibitory mechanisms of attention and their role in motion induction have been so far largely ignored. This might have happened for two reasons. First, as shown by the present study (Experiment 4), motion induction seems to reflect the overall advantage of attended signals over nonattended ones at any given moment in time, regardless of the underlying processes that have brought about this contrast in processing efficiency. Second, motion induction has been studied mainly with one or two cues which summon attention reflexively. It has been shown (Posner, 1980) that in such situations facilitation develops first, followed by inhibition at the same location (i.e. inhibition of return). Inhibition of return, however, has not been observed with motion induction (Hikosaka et al., 1993a) which has suggested that motion induction is insensitive to attentional inhibition. On the other hand, in the absence of irrelevant signals, inhibition at irrelevant locations may simply be absent. Nevertheless, some studies have reported an inhibitory zone at large distances from the cue (Steinman et al., 1995). At any rate, in these studies the illusory motion away from the cue has been attributed again to the spatial gradient of attentional facilitation. Thus the inhibitory surround has been thought of as an intrinsic characteristic of the attentional field and simply as an extension of the decay in facilitation towards the periphery.

In contrast, results from the present study suggest that increase in active inhibition at nontarget locations underlies the initial increase in motion induction prior to target selection since over the same period of time facilitation remained at a steady level and peaked only later confining itself to the target location. This suggests that the motion induction observed early in search at nontargets with the target color was supported by both facilitation in processing of the selected subset and inhibition of distractors with the irrelevant color. The importance of selective inhibition at nontargets in conjunction search has been also discussed by Treisman & Sato (1990), who, however, hypothesized that all distractors with the irrelevant attribute are inhibited to the same extent. The present study suggests that the inhibitory process is not spread evenly over areas of the display, but operates locally. When inhibition was optimal, it was stronger at the actively suppressed location than at some distance away from it. Thus one may speculate, that voluntary attention creates not only facilitatory but also inhibitory spatial gradients, with inhibition preceding facilitation. Although this hypothesis needs to be tested explicitly, it is obvious from the data that attentional facilitation is not sufficient to account for the motion induction effects observed in the context of voluntary search. It is reasonable to expect that inhibition of irrelevant information is a fundamental characteristic of voluntary attention distinct from the inhibition observed with stimulus-induced attention.

The allocation of attention in the present experiments was controlled by a search plan internal to the organism rather than by characteristics of the stimulus. Motion induction, however, was experienced in much the same way as with exogenous cueing of attention. Although voluntary and stimulus induced attention develop differently in time it was demonstrated once again that motion induction occurs regardless of the source of attentional control (Hikosaka et al., 1993b). This supports the premise of the attentional hypothesis that both voluntary and stimulus induced attention may bias the inputs to the motion detector in a similar way. The neural level of this attentional modulation, however, may differ depending on the nature of the cueing event. The present results indicate that the color based attentional effect and the one developing later at the conjunction target have distinct time courses and are characterized by different balances between facilitation and inhibition. It is thus tempting to speculate that the color based motion induction originates from attentional modulation in V4, whereas higher level attentional processes, possibly in IT, may be responsible for the effect at the conjunction target. Such speculation may not be farstreched since cells in the inferotemporal cortex are known to encode global object characteristics such as shape which is in fact a conjunction of features (Desimone & Duncan, 1995). The present results thus suggest that signals from extrastriate areas beyond MT may as well have access to motion detecting mechanisms at lower levels (possibly in MT) mediating motion induction. In other words, strictly speaking, attentional modulation may not always act *before* MT, as originally proposed (Hikosaka et al., 1993a). This is compatible with recent proposals that motion can be extracted from input signals that had undergone different amounts of preprocessing and may have been attentionally selected or suppressed by means of stimulus context or voluntary effort (Cavanagh & Mather, 1989; Lu & Sperling, 1995).

To conclude, this study categorizes motion induction as a "high-level" phenomenon which reflects the spatial distribution of voluntary attention at any given moment in time during search. Which leaves one pondering over the deceitful simplicity of the shooting line percept. The line shoots again and again slowly finding its way throughout the network of our brains, triggering new questions each time.

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Appendix A

Summary Tables of Trend Analyses on Response Time as a Function of Display Size for Each of the Four Combinations of Trial Type and Target Type in Experiment 1.

Table 1

Summary Table for Trend Analysis on Response Time as a Function of Display Size (Red Right-obliqueTarget Present)

Source	df	SS	MS	F
Within Subjects				
Display Size	4	653253	163313	24.73**
Error	36	237745	6604	
Linear Trend	1	653026	653026	30.09**
Error	9	195295	21699	
Quadratic Trend	1	3	3	0.001
Error	9	28887	3210	
Cubic Trend	1	204	204	0.292
Error	9	6299	700	

**$p < .01$

Table 2

<u>**Summary Table for Trend Analysis on Response Time as a Function of Display Size (Red Right-obliqueTarget Absent)**</u>

Source	**df**	**SS**	**MS**	***F***
Within Subjects				
Display Size	4	1454072	363518	36.29**
Error	36	360610	10017	
Linear Trend	1	1340038	1340038	42.32**
Error	9	285004	31667	
Quadratic Trend	1	107531	107531	32.28**
Error	9	29983	3331	
Cubic Trend	1	4802	4802	1.84
Error	9	23457	2606	

**$p < .01$

Table 3

Summary Table for Trend Analysis on Response Time as a Function of Display Size (Green Left-obliqueTarget Present)

Source	**df**	**SS**	**MS**	**F**
Within Subjects				
Display Size	4	1714623	428656	36.84**
Error	36	418944	11637	
Linear Trend	1	1698591	1698591	43.02**
Error	9	355327	39481	
Quadratic Trend	1	8011	8011	2.81
Error	9	25668	2852	
Cubic Trend	1	7465	7465	2.84
Error	9	23644	2627	

**$p < .01$

Table 4

Summary Table for Trend Analysis on Response Time as a Function of Display Size (Green Left-obliqueTarget Absent)

Source	**df**	**SS**	**MS**	F
Within Subjects				
Display Size	4	6372005	1593001	57.77**
Error	36	992716	27575	
Linear Trend	1	5386577	5386577	67.87**
Error	9	714312	79368	
Quadratic Trend	1	931709	931709	61.20**
Error	9	137027	15225	
Cubic Trend	1	28460	28460	2.11
Error	9	121428	13492	

**$p < .01$

Appendix B

ANOVA Summary Tables (Target Type X Trial Type) on Intercepts, Slopes and Scan Rate and a Dependent T-test Comparison of Slope Ratios by Target Type (Experiment 1).

Table 1

ANOVA Summary Table on Intercepts Compared Across Target Type and Trial Type

Source	**df**	**SS**	**MS**	**F**
Within Subjects				
Target Type	1	8	8	0.002
Error	9	34769	3863	
Trial Type	1	2228	2228	0.50
Error	9	39877	4431	
TType X TrType	1	11688	11688	5.10
Error	9	20615	2291	

$^{**}p < .01$

Table 2

ANOVA Summary Table on Slopes Compared Across Target Type and Trial Type

Source	**df**	**SS**	**MS**	**F**
Within Subjects				
Target Type	1	1806	1806	44.96**
Error	9	361	40	
Trial Type	1	1549	1549	65.35**
Error	9	213	24	
TType X TrType	1	359	359	15.64**
Error	9	206	23	

**$p < .01$

Table 3

ANOVA Summary Table on Scan Rate Compared Across Target Type and Trial Type

Source	**df**	**SS**	**MS**	**F**
Within Subjects				
Target Type	1	1408	1408	22.58**
Error	9	561	62	
Trial Type	1	23	23	0.74
Error	9	284	32	
TType X TrType	1	8	8	0.16
Error	9	455	51	

**$p < .01$

Table 4

Dependent Samples' T-test on Positive to Negative Slope Ratio Compared Across Target Type

Independent Variable	**Mean Difference**	**df**	**t**
Target Type	.14	9	1.59

**p < .01

Appendix C

Descriptive Statistics, ANOVA Summary Table and Follow-up Analyses on Target Present Response Times as a Function of Display Size(2, 28) and Target Type in Experiments 1 and 2

Table 1

Mean Target Present Response Times (in Milliseconds) for the Two Target Types, With Eight and 28 Items in Experiment 1 and 2

Experiment	**Target Type**	**Display Size**	**RT(ms)**	
1	Red $+45^0$	N=8	M	680.7
			SEM	30.9
		N=28	M	843.5
			SEM	68.2
1	Green -45^0	N=8	M	789.9
			SEM	40.2
		N=28	M	1085.0
			SEM	77.7
2	Red $+45^0$	N=8	M	560.2
			SEM	45.6
		N=28	M	822.0
			SEM	33.5
2	Green -45^0	N=8	M	654.1
			SEM	43.2
		N=28	M	843.8
			SEM	40.8

Table 2

ANOVA Summary Table for RT (in milliseconds) as a Function of Target Type and Display Size in Experiments 1 and 2

Source	**df**	**SS**	**MS**	**F**
Between Subjects				
Experiment	1	336751.2	336751.2	4.548*
Error	18	1332787.1	74043.7	
Within Subjects				
Display Size	1	1033793.4	1033793.4	109.165**
Display Size X Experiment	1	50.9	50.9	.005
Error	18	170460.6	9470.0	
Target	1	272020.0	272020.0	52.231**
Target X Experiment	1	68976.4	68976.4	13.244**
Error	18	93744.7	5208.0	
Display Size X Target	1	4536.5	4536.5	.999
Display Size X Target X Experiment	1	52202.4	52202.4	11.492**
Error	18	81763.1	4542.4	

*$p < .05$
**$p < .01$

Table 3

Partial Interactions of Display Size and Target Type on RT in Experiments 1 and 2

Source	**df**	**SS**	**MS**	**F**
Display Size X Target @ Experiment 1	1	43758.3	43758.3	11.57**
Error	9	34039.5	3782.2	
Display Size X Target @ Experiment 2	1	12980.6	12980.6	2.228
Error	9	277723.6	5302.6	

*$p < .05$
**$p < .01$

Appendix D

ANOVA Summary Table and Follow-up Analyses on Percentage Motion Induction as a Function of Target Type, Inducer Type and SOA for Search Displays With Eight Items (Experiment 2)

Table 1

ANOVA Summary Table for Percent Motion Induction as a Function of Target Type, Inducer Type and SOA (Display Size = 8 items)

Source	**df**	**SS**	**MS**	**F**
Within Subjects				
Target	1	253.44	253.44	.532
Error	8	3810.23	476.28	
Inducer	2	24548.82	12274.41	76.462**
Error	16	2568.46	160.53	
SOA	4	3447.10	861.77	8.739**
Error	32	3155.45	98.61	
Target X Inducer	2	509.07	254.53	2.953
Error	16	1376.18	86.20	
Target X SOA	4	161.75	40.44	.978
Error	32	1323.23	41.35	
Inducer X SOA	8	7170.93	896.37	14.536**
Error	64	3946.54	61.67	
Target X Inducer X SOA	8	254.99	31.87	.776
Error	64	2628.62	41.07	

*$p < .05$
**$p < .01$

Table 2

Simple Effects of Inducer Type on Percent Motion Induction at Each SOA, Averaged for Both Target Types
(Display Size = 8 items)

Source	df	SS	MS	F
@SOA=150 ms				
Inducer	2	900.84	450.42	7.64**
Error	16	942.40	58.90	
@SOA=405 ms				
Inducer	2	3091.62	1545.81	19.88**
Error	16	1244.16	77.76	
@SOA=705 ms				
Inducer	2	7020.88	3510.44	49.22**
Error	16	1141.12	71.32	
@SOA=1200 ms				
Inducer	2	12288.90	6144.45	51.81**
Error	16	1876.60	118.60	
@SOA=1995 ms				
Inducer	2	8417.50	4208.75	52.22**
Error	16	1289.44	80.59	

*p < .05
**p < .01

Table 3

Planned Comparisons of Means Averaged for Both Target Types and Across SOA (Display Size = 8 items)

Source	**Mean Difference (%)**	**df**	**MS**	**F**
T vs. NoT(baseline)	23.07	1	23945.05	150.006**
Error		8	159.62	
NoT(color) vs. NoT(baseline)	8.36	1	3146.20	15.836**
Error		8	198.67	
T vs. NoT(color)	14.71	1	9731.99	78.936**
Error		8	123.29	

*p < .05
**p < .01

Table 4

Pairwise Comparisons of Mean Percents Motion Induction at Target vs. Baseline (at Nontargets) Across SOA, Averaged for Both Target Types (Display Size = 8 items)

Source	Mean Difference (%)	df	MS	F
@ SOA=150 ms				
T vs. NoT(baseline)	6.93	1	432.71	9.697*
Error		8	44.62	
@ SOA=405 ms				
T vs. NoT(baseline)	18.52	1	3088.03	50.704**
Error		8	60.90	
@ SOA=705 ms				
T vs. NoT(baseline)	27.93	1	7020.76	83.382**
Error		8	84.20	
@ SOA=1200 ms				
T vs. NoT(baseline)	32.04	1	9238.09	74.373**
Error		8	124.21	
@ SOA=1995 ms				
T vs. NoT(baseline)	29.91	1	8052.67	60.623**
Error		8	132.83	

*$p < .05$;
**$p < .01$

Table 5

Trend Analysis of the Interaction Contrast Between Percent Motion Induction at Target vs. Baseline (at Nontargets) Across SOA, Averaged for Both Target Types
(Display Size = 8 items)

Source	df	SS	MS	F
Linear	1	3183.19	3183.19	33.667**
Error	8	756.40	94.55	
Quadratic	1	688.64	688.64	12.791**
Error	8	430.72	53.84	
Cubic	1	14.77	14.77	.392
Error	8	301.8 3	7.73	

*p < .05;
**p < .01

Table 6

Pairwise Comparisons of Mean Percents Motion Induction at Nontargets with Target Color vs. Baseline (at Nontargets) Across SOA, Averaged for Both Target Types
(Display Size = 8 items)

Source	Mean Difference (%)	df	MS	F
@ SOA=150 ms				
NoT(color) vs. NoT(baseline)	6.93	1	432.71	9.697*
Error		8	44.62	
@ SOA=405 ms				
NoT(color) vs. NoT(baseline)	18.52	1	3088.03	50.704**
Error		8	60.90	
@ SOA=705 ms				
T vs. NoT(baseline)	27.93	1	7020.76	83.382**
Error		8	84.20	
@ SOA=1200 ms				
T vs. NoT(baseline)	32.04	1	9238.09	74.373**
Error		8	124.21	
@ SOA=1995 ms				
T vs. NoT(baseline)	29.91	1	8052.67	60.623**
Error		8	132.83	

*$p < .05$; **$p < .01$

Table 7

Trend Analysis of the Interaction Contrast Between Percent Motion Induction at Nontargets with Target Color vs. Baseline (at Nontargets) Across SOA, Averaged for Both Target Types (Display Size = 8 items)

Source	**df**	**SS**	**MS**	**F**
Linear	1	75.85	75.85	.479
Error	8	1266.72	158.34	
Quadratic	1	2.07	2.07	.031
Error	8	533.84	66.73	
Cubic	1	260.36	260.36	3.188
Error	8	653.56	81.67	

*$p < .05$; **$p < .01$

Table 8

Pairwise Comparisons of Mean Percents Motion Induction at Target vs. Nontargets with Target Color Across SOA, Averaged for Both Target Types (Display Size = 8 items)

Source	Mean Difference (%)	df	MS	F
@ SOA=150 ms				
NoT(color) vs. NoT(baseline)	6.93	1	432.71	9.697*
Error		8	44.62	
@ SOA=405 ms				
NoT(color) vs. NoT(baseline)	18.52	1	3088.03	50.704**
Error		8	60.90	
@ SOA=705 ms				
T vs. NoT(baseline)	27.93	1	7020.76	83.382**
Error		8	84.20	
@ SOA=1200 ms				
T vs. NoT(baseline)	32.04	1	9238.09	74.373**
Error		8	124.21	
@ SOA=1995 ms				
T vs. NoT(baseline)	29.91	1	8052.67	60.623**
Error		8	132.83	

*p < .05; **p < .01

Table 9

Trend Analysis of the Interaction Contrast Between Percent Motion Induction at Target vs. at Target Color Across SOA, Averaged for Both Target Types (Display Size = 8 items)

Source	df	SS	MS	F
Linear	1	4241.82	4241.82	145.210**
Error	8	233.68	29.21	
Quadratic	1	766.15	766.15	29.273**
Error	8	209.36	26.17	
Cubic	1	399.17	399.17	3.897
Error	8	819.52	102.44	

*p < .05; **p < .01

Table 10

Interaction Contrasts of the Effect of Inducer Across Taget Type Averaged for all SOA-s (Display Size = 8 items)

Source	**Mean Difference (%)**	**df**	**MS**	**F**
Inducer Effect: T vs. Base				
@ Red Target VS. @ Green Target	5.65	1	330.48	6.124*
Error		8	53.97	
Inducer Effect: NoT(color) vs. Base				
@ Red Target VS. @ Green Target	5.65	1	330.48	6.124*
Error		8	53.97	
Inducer Effect: T vs. NoT(color)				
@ Red Target VS. @ Green Target	- 6.16	1	426.95	7.347*
Error		8	58.11	

*$p < .05$; **$p < .01$

Appendix E

ANOVA Summary Table and Follow-up Analyses on Percentage Motion Induction as a Function of Target Type, Inducer Type and SOA for Search Displays With 28 Items (Experiment 2)

Table 1

ANOVA Summary Table for Percent Motion Induction as a Function of Target Type, Inducer Type and SOA (Display Size = 28 items)

Source	**df**	**SS**	**MS**	**F**
Within Subjects				
Target	1	47.17	47.17	.374
Error	8	1007.68	125.96	
Inducer	2	29937.60	14968.80	84.689**
Error	16	2828.01	176.75	
SOA	4	8721.16	2180.29	28.723**
Error	32	2429.03	75.91	
Target X Inducer	2	108.37	54.19	1.950
Error	16	444.57	27.786	
Target X SOA	4	212.55	53.14	1.674
Error	32	1015.65	31.74	
Inducer X SOA	8	5401.34	675.17	16.921**
Error	64	2553.67	39.90	
Target X Inducer X SOA	8	262.327	32.79	.567
Error	64	2484.08	38.81	

*$p < .05$
**$p < .01$

Table 2

Simple Effects of Inducer Type on Percent Motion Induction at Each SOA, Averaged for Both Target Types
(Display Size = 28 items)

Source	df	SS	MS	F
@SOA=195 ms				
Inducer	2	604.20	302.10	3.27
Error	16	1480.00	92.50	
@SOA=495 ms				
Inducer	2	2915.12	1457.56	21.81**
Error	16	1069.44	66.84	
@SOA=1005 ms				
Inducer	2	10695.18	5347.59	69.60**
Error	16	1229.44	76.84	
@SOA=1755 ms				
Inducer	2	11122.86	5561.43	135.41**
Error	16	657.12	41.07	
@SOA=1995 ms				
Inducer	2	10001.62	5000.81	84.60**
Error	16	945.76	59.11	

*$p < .05$
**$p < .01$

Table 3

Planned Comparisons of Means Averaged for Both Target Types and Across SOA (Display Size = 28 items)

Source	**Mean Difference (%)**	**df**	**MS**	**_F_**
T vs. NoT(baseline)	21.50	1	20801.25	402.82**
Error		8	51.64	
NoT(color) vs. NoT(baseline)	- 1.59	1	113.75	.482
Error		8	236.01	

*$p < .05$
**$p < .01$

Table 4

Trend Analysis of the Interaction Contrast Between Percent Motion Induction at Target vs. Baseline (at Nontargets) Across SOA, Averaged for Both Target Types
(Display Size = 28 items)

Source	df	SS	MS	F
Linear	1	2542.80	2542.80	24.322**
Error	8	836.40	104.55	
Quadratic	1	639.92	639.92	23.068**
Error	8	221.92	27.74	
Cubic	1	29.38	29.38	3.729
Error	8	63.04	7.88	

*$p < .05$; **$p < .01$

Appendix F

Planned Comparison of Means, ANOVA Summary Table and Follow-up Analyses on Percentage Motion Induction as a Function of Inducer and SOA (Experiment 3)

Table 1

Planned Comparison of Mean Percent Motion Induction at Nontargets (Target Absent vs. Target Present Condition), Averaged Across SOA (Experiment 3)

Source	**Mean Difference (%)**	**df**	**MS**	**F**
NoT-absent (baseline) vs. NoT-present	.795	1	27.84	.656
Error		10	42.45	

$^{*}p < .05$
$^{**}p < .01$

Table 2

ANOVA Summary Table for Percent Motion Induction as a Function of Inducer Type and SOA (Experiment 3)

Source	**df**	**SS**	**MS**	**F**
Within Subjects				
Inducer	1	14454.69	14454.69	41.006**
Error	10	3525.00	352.50	
SOA	7	4269.74	609.96	8.555**
Error	70	4991.19	71.30	
Inducer X SOA	7	1961.79	280.26	5.326**
Error	70	3683.52	52.62	

*$p < .05$
**$p < .01$

Table 3

Simple Effects of Inducer Type (Target vs Baseline) on Percent Motion Induction at Each SOA (Experiment 3)

Source	df	SS	MS	F
@SOA=120 ms				
Inducer	1	113.64	113.64	1.718
Error	10	661.40	66.14	
@SOA=240 ms				
Inducer	1	1472.73	1472.73	12.378**
Error	10	1189.80	118.98	
@SOA=360 ms				
Inducer	1	7020.88	1022.73	11.104**
Error	10	921.00	92.10	
@SOA=480 ms				
Inducer	1	12288.90	1863.92	23.618**
Error	10	789.20	78.92	
@SOA=600 ms				
Inducer	1	8417.50	3692.05	49.527**
Error	10	745.50	74.55	
@SOA=720 ms				
Inducer	1	8417.50	3132.10	27.330**
Error	10	1146.00	114.60	

*p < .05
**p < .01

Table 3 (continued)

Source	**df**	**SS**	**MS**	**F**
@SOA=840 ms				
Inducer	1	900.84	3563.64	62.099**
Error	10	573.90	57.39	
@SOA=960 ms				
Inducer	1	3091.62	1555.68	13.163**
Error	10	1181.80	118.18	

*$p < .05$
**$p < .01$

Table 4

Trend Analysis of the Interaction Contrast Between Percent Motion Induction at Target vs. Baseline Across SOA (Experiment 3)

Source	**df**	**SS**	**MS**	**F**
Inducer X SOA	7	1961.79	280.56	5.326**
Error	70	3683.52	52.62	
Linear	1	941.08	941.08	11.272**
Error	10	834.89	83.49	
Quadratic	1	666.91	666.91	8.169**
Error	10	816.35	81.64	
Cubic	1	59.94	59.94	1.245
Error	10	481.40	48.14	

*p < .05;
**p < .01

Appendix G

Representative Individual Data (Experiment 3)

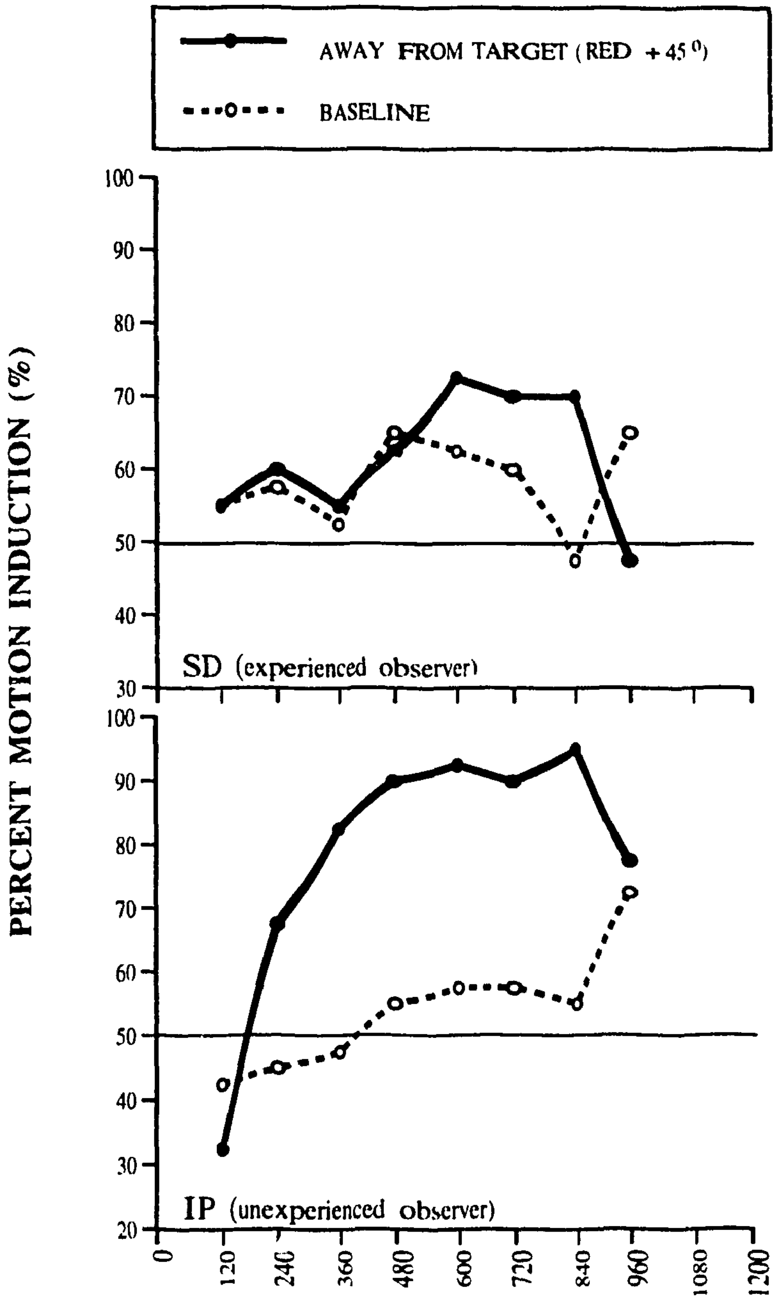

Figure 1. Motion induction at target compared to baseline as a function of SOA (display size = 8)

Transient effects.

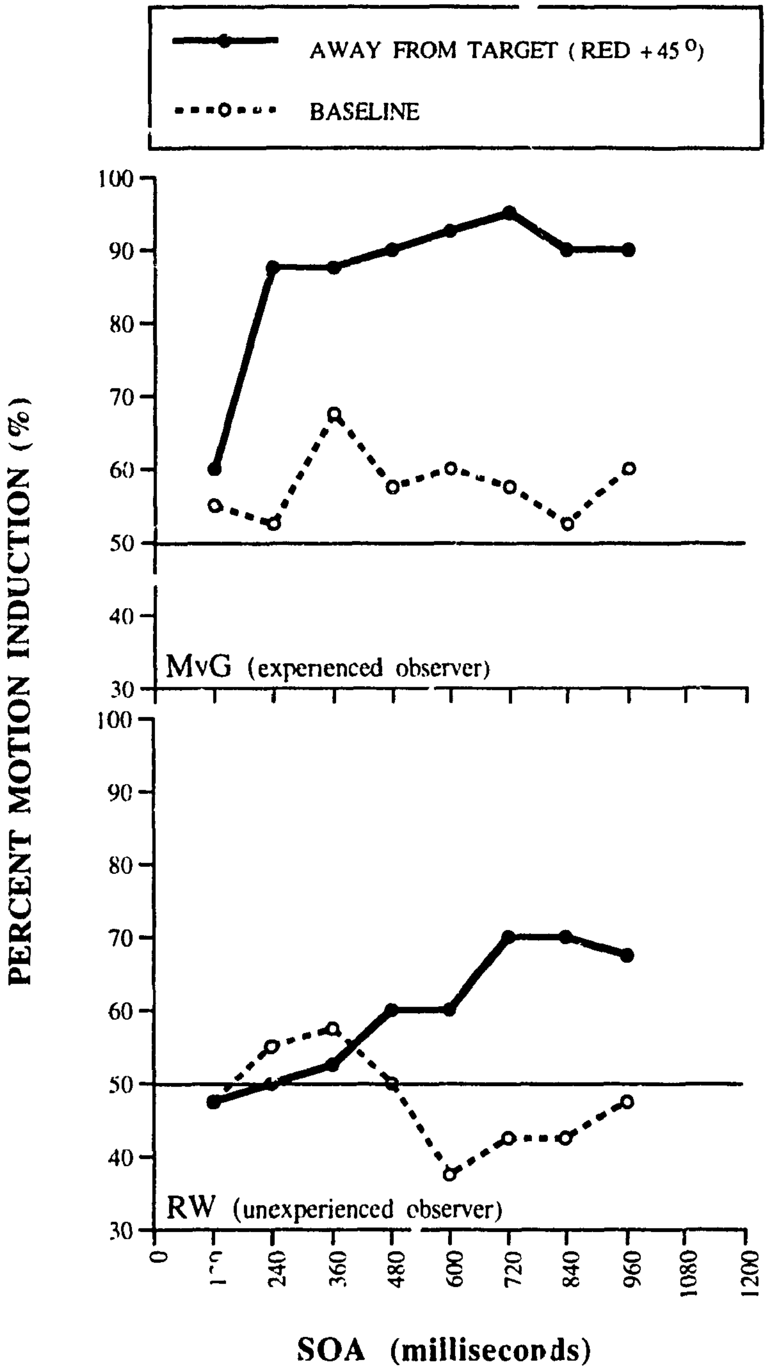

Figure 2. Motion induction at target compared to baseline as a function of SOA (display size = 8)

Sustained effects.

Appendix H

ANOVA Summary Table and Follow-up Analyses on Probe Detection Time as a Function of Item-Probe Separation, Cuing Condition and SOA
(Experiment 4)

Table 1

ANOVA Summary Table for Probe Detection Times (Standardized) as a Function of Probe-Item Separation, Cuing Condition and SOA

Source	df	SS	MS	F
Cuing	2	186.91	93.45	35.221**
Error	20	53.07	2.65	
Separation	1	28.11	28.11	14.798**
Error	10	19.00	1.90	
SOA	7	34.81	4.97	5.678**
Error	70	61.30	.88	
Cuing X Separation	2	7.10	3.55	30.052**
Error	20	2.36	.12	
Cuing X SOA	14	12.60	.90	2.913**
Error	140	43.26	.31	
Separation X SOA	7	3.63	.52	1.853
Error	70	19.61	.28	
Cuing X Separation X SOA	14	4.57	.33	1.220
Error	140	37.44	.27	

*$p < .05$
**$p < .01$

Table 2

Simple Effects of SOA and Probe-Item Separation on the RT Difference at Target vs.at Nontargets

Source	**df**	**SS**	**MS**	**F**
@Separation = .7 deg.				
SOA	7	13.31	1.90	2.930*
Error	70	45.43	.65	
@Separation = 2.5 deg.				
SOA	7	6.09	.87	1.993
Error	70	30.80	.44	
@SOA=120 ms				
Separation	1	1.29	1.29	2.558
Error	10	5.00	.50	
@SOA=240 ms				
Separation	1	.11	.11	.756
Error	10	1.50	.15	
@SOA=360 ms				
Separation	1	1.27	1.27	12.298**
Error	10	1.00	.10	
@SOA=480 ms				
Separation	1	2.15	2.15	11.705**
Error	10	1.80	.18	

*$p < .05$
**$p < .01$

Table 2 (continued)

Source	df	SS	MS	F
@SOA=600 ms				
Separation	1	1.02	1.02	1.029
Error	10	9.90	.99	
@SOA=720 ms				
Separation	1	6.63	6.63	9.761*
Error	10	6.80	.68	
@SOA=840 ms				
Separation	1	3.88	3.88	5.582*
Error	10	7.00	.70	
@SOA=960 ms				
Separation	1	.32	.32	.644
Error	10	4.90	.49	

*p < .05
**p < .01

Table 3

Trend Analysis of the RT Difference at Target vs. at Nontargets Across SOA at Probe-Item Separation = .7 deg

Source	**df**	**SS**	**MS**	**F**
Overall Partial Interaction	7	13.30	1.90	2.930*
Error	70	45.41	.65	
Linear	1	3.70	3.70	3.735*
Error	10	9.90	.99	
Quadratic	1	6.55	6.55	11.686**
Error	10	5.60	.56	
Cubic	1	2.53	2.53	2.501
Error	10	10.10	1.10	

*$p < .05$;
**$p < .01$

Table 4

Contrasts of Means and Interaction Contrasts Within the Cuing X Separation Interaction Averaged Across SOA

Source	**Absolute Mean Difference (SD)**	**df**	**MS**	**F**
FACILITATION				
RT @ Target vs. Baseline RT				
Separation = .7 deg	1.2	1	55.25	120.641**
Error		10	.458	
Separation = 2.5 deg	.8	1	25.05	76.835**
Error		10	.326	
RT Difference (@Target vs. @Baseline)				
@ .7 deg vs. @ 2.5 deg	.4	1	2.947	44.806**
Error		10	.066	
INHIBITION				
RT @ Nontargets vs. Baseline RT				
Separation = .7 deg	.6	1	15.53	8.591*
Error		10	1.81	
Separation = 2.5 deg	.3	1	7.07	4.023
Error		10	1.76	

*$p < .05$;
**$p < .01$

Table 4 (continued)

Source	**Absolute Mean Difference (SD)**	**df**	**MS**	***F***
FACILITATION VS. INHIBITION AT .7 DEG				
(RT@Target-RT@ Baseline) vs. (RT@ Nontargets-RT@ Baseline)	.6	1	15.51	6.008*
Error	10		2.58	

*$p < .05$;
**$p < .01$

Table 5

Simple Effects of SOA and Probe-Item Separation on the RT Difference at Target vs.Baseline

Source	**df**	**SS**	**MS**	**F**
@Separation = .7 deg.				
SOA	7	8.47	1.21	2.583*
Error	70	32.90	.47	
@Separation = 2.5 deg.				
SOA	7	2.73	.39	1.649
Error	70	16.80	.24	
@SOA=120 ms				
Separation	1	1.04	1.04	4.036
Error	10	2.60	.26	
@SOA=240 ms				
Separation	1	.26	.26	1.273
Error	10	2.10	.21	
@SOA=360 ms				
Separation	1	.31	.31	5.997
Error	10	.50	.05	
@SOA=480 ms				
Separation	1	.20	.20	.588
Error	10	3.40	.34	

*$p < .05$
**$p < .01$

Table 5 (continued)

Source	**df**	**SS**	**MS**	**F**
@SOA=600 ms				
Separation	1	1.33	1.33	7.469*
Error	10	1.80	.18	
@SOA=720 ms				
Separation	1	3.55	3.55	7.242*
Error	10	4.90	.49	
@SOA=840 ms				
Separation	1	2.26	2.26	10.633**
Error	10	2.10	.21	
@SOA=960 ms				
Separation	1	.14	.14	.569
Error	10	2.50	.25	

*$p < .05$
**$p < .01$

Table 6

Trend Analysis of the RT Difference at Target vs. Baseline Across SOA at Probe-Item Separation = .7 deg

Source	**df**	**SS**	**MS**	**F**
Linear	1	.92	.92	1.965
Error	10	4.70	.47	
Quadratic	1	1.18	1.18	1.893
Error	10	6.20	.62	
Cubic	1	2.63	2.63	4.359
Error	10	6.10	.60	

*p < .05;
**p < .01

Table 7

Simple Effects of SOA and Probe-Item Separation on the RT Difference at Nontarget vs.Baseline

Source	**df**	**SS**	**MS**	**F**
@Separation = .7 deg.				
SOA	7	4.97	.71	.857
Error	70	57.40	.82	
@SOA=120 ms				
Separation	1	.01	.01	.012
Error	10	10.80	1.08	
@SOA=240 ms				
Separation	1	.03	.03	.098
Error	10	3.20	.32	
@SOA=360 ms				
Separation	1	.33	.33	2.367
Error	10	1.40	.14	
@SOA=480 ms				
Separation	1	3.66	3.66	6.775*
Error	10	5.40	.54	
@SOA=600 ms				
Separation	1	.02	.02	.015
Error	10	14.00	1.40	

*$p < .05$
**$p < .01$

Table 7 (continued)

Source	**df**	**SS**	**MS**	***F***
@SOA=720 ms				
Separation	1	.48	.48	.756
Error	10	6.30	.63	
@SOA=840 ms				
Separation	1	.22	.22	.403
Error	10	5.40	.54	
@SOA=960 ms				
Separation	1	.04	.04	.080
Error	10	4.50	.45	

*$p < .05$
**$p < .01$

Appendix I

Relation Between the Attentional Effect at Target (Experiment 4) and Motion Induction (Experiment 3) Representative Individual Data

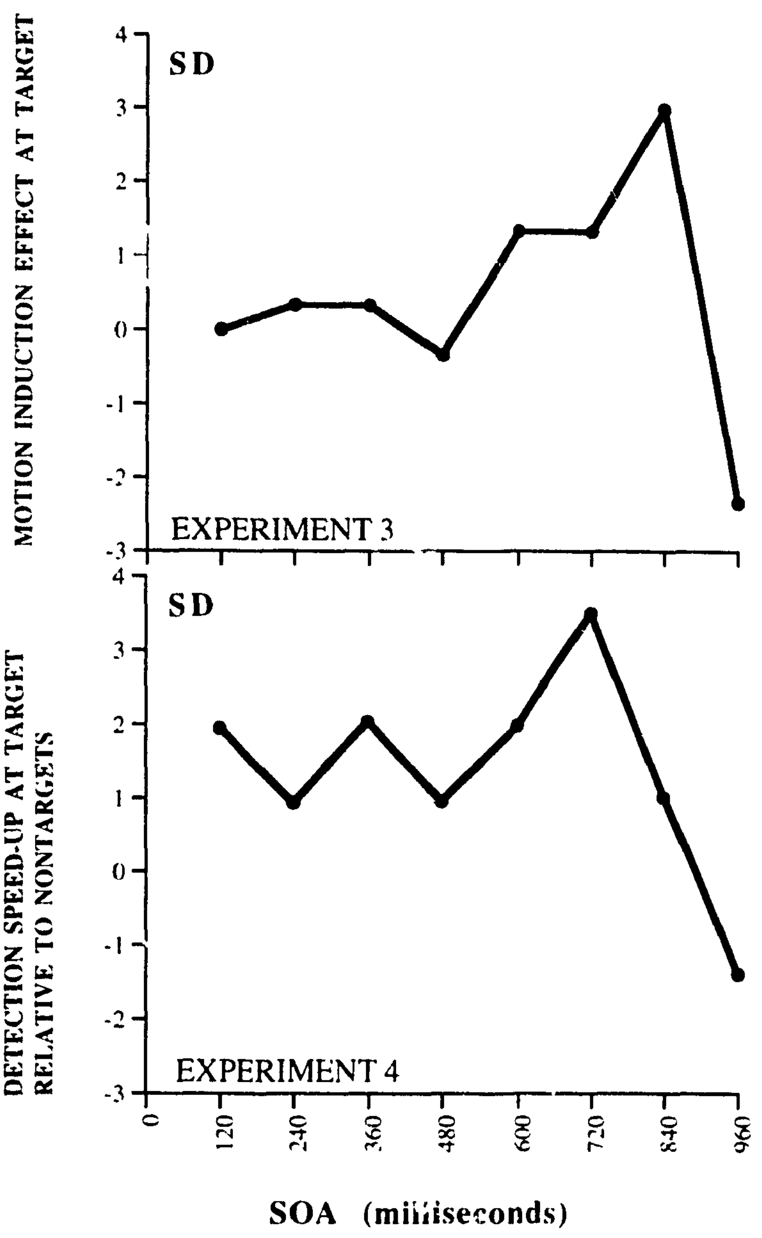

Figure 1. Time courses of the overall attentional effect at target (Experiment 4) and the motion induction effect at target (Experiment 3). Experienced observer.

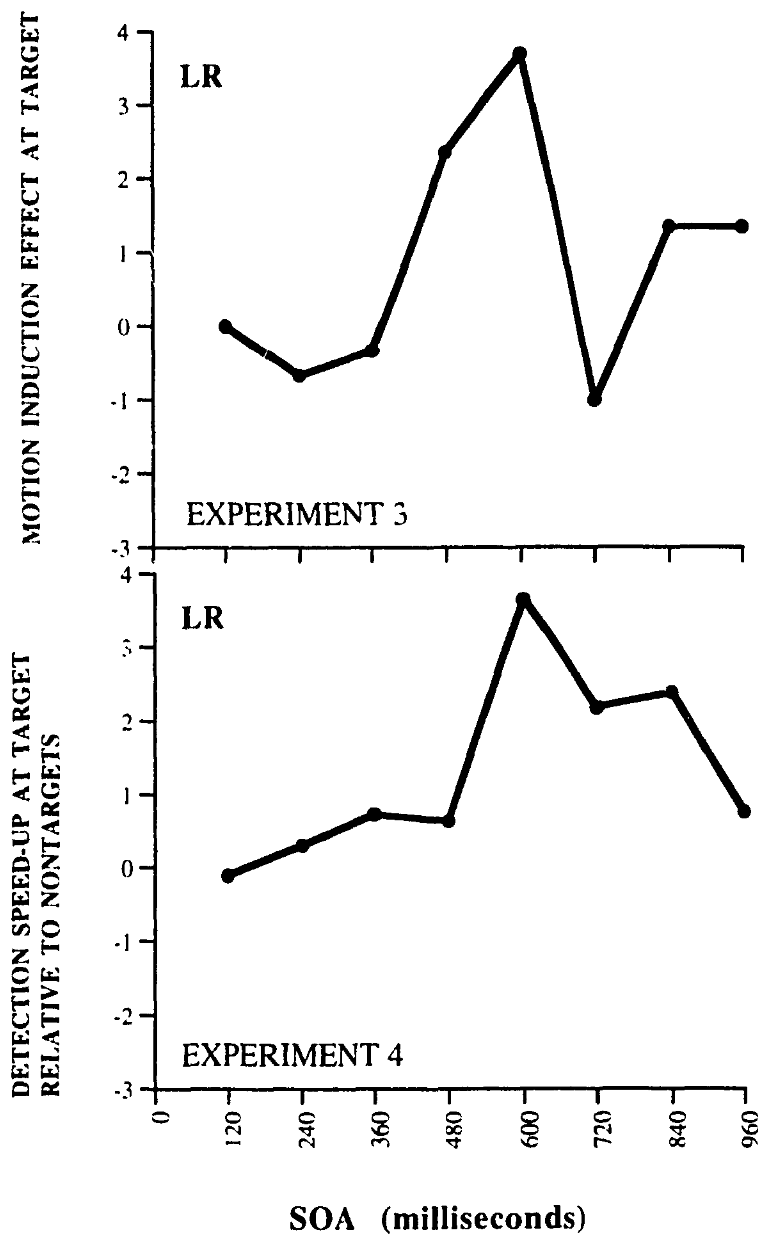

Figure 2. Time courses of the overall attentional effect at target (Experiment 4) and the motion induction effect at target (Experiment 3). Unexperienced observer.