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Visual Attention

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Abstract

A typical visual scene we encounter in everyday life is complex and filled with a huge amount of perceptual information. The term, "visual attention" describes a set of mechanisms that limit some processing to a subset of incoming stimuli. Attentional mechanisms shape what we see and what we can act upon. They allow for concurrent selection of some (preferably, relevant) information and inhibition of other information. This selection permits the reduction of complexity and informational overload. Selection can be determined both by the "bottom-up" saliency of information from the environment and by the "top-down" state and goals of the perceiver. Attentional effects can take the form of modulating or enhancing the selected information. A central role for selective attention is to enable the "binding" of selected information into unified and coherent representations of objects in the outside world.

In the overview on visual attention presented here we will review the mechanisms and consequences of selection and inhibition over space and time. We will examine theoretical, behavioral and neurophysiologic work done on visual attention. We also discuss the relations between attention and other cognitive processes such as automaticity and awareness.

We are all familiar with the act of paying attention to something in our visual world. A brilliantly colored flower draws a stroller's gaze as he walks in the park. A teacher looks at a toddler climbing a ladder while monitoring the movements of other toddlers in the playground. You search for a bundle of keys on your paper-strewn office desk. These examples illustrate different aspects of visual attention.

Rather than being a single entity, visual attention can best be defined as a family of processing resources or cognitive mechanisms that can modulate signals at almost every level of the visual system. The goal of this chapter is to introduce the reader to the most relevant aspects of visual attention and the research being done on this topic. We will address 6 questions:

1) What is visual attention used for?
2) How does attention select stimuli across space and over time?
3) What is the role of inhibition in attentional processes?
4) What happens when observers are asked to divide attention across several stimuli?
5) What is the relationship of visual attention to the processes of automaticity and awareness?
6) How is attention implemented at the neuronal level (see also COGSCI-141)?

What is visual attention for?

Attention serves at least four different purposes in the visual system, including data reduction / stimulus selection, stimulus enhancement, feature binding, and recognition.

Data reduction / stimulus selection: Systems controlling perception cognition and action all exhibit capacity limitations. The brain is unable to simultaneously process everything in the continuous influx of information from the environment. One of the most critical roles for visual attention is to filter visual information. Research shows that visual attention can perform this function by actively suppressing irrelevant stimuli (1) or by selecting potentially relevant stimuli. In either case, attention makes it possible to use limited resources for the processing of some stimuli rather than others.

Stimulus enhancement: The inputs to the visual system are noisy and ambiguous and attention can act to enhance the signal or the amplitude of neuronal activity in the sensory pathways at the initial stages of visual processing. It can enhance or alter the processing of the attended stimulus, allowing for ambiguity resolution and noise reduction. As we will discuss later, stimulus enhancement can be a consequence of allocating attention to a stimulus directly (e.g. space and object-based attention) or of directing attention to some attribute of the stimulus (e.g. color, "feature-based attention"). This allows the observer to be an active seeker and processor of information. Behaviorally, stimulus enhancement is observable in faster reaction times and higher accuracy. Physiologically, we see enhanced activity of neuronal populations that process the stimulus (1-3).

Binding: Early stages of visual processing appear to involve decomposition of the signal into separable dimensions like color and orientation, with these dimensions being processed to some degree in different neural areas (e.g., see (4, 5). This functional decomposition has raised the question of how we integrate this compartmentalized informSation into the perception of a unified world. This problem, or set of problems, is referred to as the "binding problem" (Treisman & Gelade, 1980). The role of visual attention in resolving the binding problem can be described in at least two ways: (1) Attention may permit the generation of stimulus representation (e.g. arbitrary conjunctions of features) that are not "hard-wired" in the visual system (6, 7) and (2) Attention may resolve ambiguities that arise when multiple stimuli fall into a single receptive field, perhaps by dynamically altering the selectivity or spatial extent of the receptive field of a neuron (8).

Recognition: Closely related to its role in binding is attention's role in object recognition. We define visual recognition here as the ability to identify the perceived stimulus not merely to be aware of the presence of a stimulus. Since object recognition mechanisms cannot simultaneously handle every object in the field, attention serves to deliver digestible subsets of the input for recognition. As a consequence of these acts of attention, representations of attended objects differ from those of unattended objects (9); (10).

Note that the functions described above are predominantly concerned with spatial visual processing, but attention plays similar roles in temporal processing (e.g. avoiding confusions between stimuli that appear in rapid succession) and in the management of different visual tasks (e.g. allowing the system to switching between searching for a target at one moment and perhaps tracking several objects at the next moment).

How does attention select stimuli across space and time?

As noted, an important function of visual attention is to avoid information overload by attempting to select the most relevant information. For example, object recognition processes can only operate on a small number of objects (perhaps 1-4) at any one time. Thus, you cannot read two streams of prose at the same time, even if the print is big enough to avoid acuity limits. Selective attention mechanisms serve to deliver a limited subset of the visual input to subsequent, limited-capacity processes.

Visual selective attention is a spatio-temporal phenomenon. You attend to one stimulus and then you attend to something else. Here we will discuss the spatial aspects of selection, while the next section will discuss the temporal aspects.

Spatial selective attention

Broadly speaking, the allocation of attention is controlled by "bottom-up" stimulus-based factors and "top-down" user-driven factors. The interplay of these factors has been studied extensively using visual search tasks in which observers look for a target item among some number of distractor items. When the display is visible until response, reaction time (RT) is the measure of greatest interest. If the display is flashed briefly, accuracy is the critical measure. In either case, the slope function relating the response measure to set size is the index of search efficiency. When RT is independent of set size (e.g., slope ≈ 0) we term the search "efficient", and infer that whatever property distinguishes targets from distractors can be processed in parallel across the visual field. Steep slopes (e.g., > 20 ms/item) suggest "inefficient" search, and we infer that processing of the target property is subject to an attentional bottleneck. There is a long-standing debate as to whether items are selected one at a time (serial processing) or if all items are processed simultaneously (parallel processing). The answer need not be exclusively one or the other. For example, items could be selected one after another, in series, while; at any one moment, several of those items might be undergoing processing in parallel.

Bottom-up *salience* can be thought of as the tendency of a stimulus to attract attention without regard to the observer's desires. A limited set of stimulus attributes computed in parallel across the visual field can drive bottom-up selection. These "preattentive" attributes include obvious early vision properties such as color and motion, as well as more complex attributes (e.g., various cues to depth). For a review, see Wolfe and Horowitz (11). The bottom-up salience of an item will be determined by its difference from neighboring items and by the heterogeneity of other items in the field. Thus, a vertical line will be very salient in a homogeneous field of lines tilted 45° to the left. It will be less salient if presented in a mix of horizontal, 45° left and 45° right lines and still less salient if 30° left and right lines are added to the mix (see Figure 1). Many computational models of search embody these rules in calculating a "salience map" (12).

The observer can also exert top-down control over selection. Thus, it is possible to select the green items in a heterogeneous array of colors that give no bottom-up advantage to green. In models such as Guided Search (13), the deployment of attention is determined by some weighted combination of bottom-up and top-down signals. “Attentional capture” is a popular paradigm for studying the interaction of the observer’s top-down desires with attention-grabbing demands of salient stimuli. Typically, observers will be asked to do a task in the presence of an irrelevant but salient distractor. Under some circumstances, this singleton will attract attention against the goals of the observer (14). Under other circumstances, top-down control is adequate to block the influence of the singleton. A full assessment of when a stimulus will and will not capture attention is beyond our scope but it is hard to do better than Sully (15) who wrote: “One would like to know the fortunate (or unfortunate) man who could receive a box on the ear and not attend to it”.

Top-down and bottom-up guidance operate essentially automatically. Once you establish your goals (e.g. look for things that are red and vertical), your “search engine” does the rest, at a rate of approximately 25 to 50 ms per item. It is also possible to select items volitionally (e.g. moving attention from item to item around a circle of letters). This is much slower with rates on the order of 3-5 Hz (16). This is similar to the speed of response to an “endogenous” attention cue (e.g. the word “left” telling the observer to move attention to the left) and to the rate of saccadic eye movements. The faster speed of deployment under control of top-down and bottom-up guidance is on the same scale as the speed of response to exogenous attentional cues (e.g. a flashed onset cue at a location to the left).

When we shift attention (e.g., during a difficult search), what are the units of selection? Visual selective attention is often described in terms of a “spotlight” metaphor. This metaphor captures important spatial properties of attention. The intensity of attention falls off in a gradient from the focal point. Attention can be tightly focused on a small area, leading to large performance benefits, or distributed over a large area, with smaller performance benefits (zoom lens” model, 17, 18). The spotlight metaphor presumes that attention selects things by selecting locations. While this approach can explain a body of data, there is also evidence that attention selects objects in a manner more like the “fill” operation in a graphics program than like a flashlight in a dark room. In a classic demonstration (19), cueing one end of a rectangle led to better performance at the other end of that rectangle (within-object), compared to an equally distant location that was in a separate rectangle. As another example, we can select one of two perceptual objects, which share the same location (20). Moreover, we can attend to objects which change location constantly during a trial (multiple object tracking, 21). This notion of object selection suggests that the visual scene is initially parsed into some version of objects and it is to these entities that attention is directed. Note that the nature of this parsing may be complex, since it is be possible to attend to “objects” (e.g. the nose) that are parts of other “objects” (e.g. the face).

As with most dichotomies in the study of attention, it is probably unwise to argue that attention is either purely object-based or space based. Compromise positions that acknowledge both aspects may be closer to the truth. For example, the “grouped array hypothesis” argues that an object can be conceived of as a structured array of locations. This approach maintains the idea that location is fundamental to selection, while acknowledging that the structure of the visual world influences what is selected (22). Alternatively, He and Nakayama’s (23) proposal that attention is directed to surfaces also captures the roles of both space and object in selection. What ever the units of selection may be, the resolution of those units, the smallest object or area that can be attended, declines away from the fovea and is lower than the resolution of the visual system (24).

Can selective attention be divided among two or more objects or locations at the same time? The long-standing controversy over unity of selection is discussed in the section on Divided Attention.

Temporal selective attention

Attention can be allocated over both time and across space. Several studies have shown that observers can use cues that indicate the time at which a target is likely to appear, and these cues generate both facilitation and inhibition (25). The effect of spatial and temporal cues appears to be approximately additive.

An important problem in temporal attention is how to segment rapid streams of events. This problem has been extensively studied using the Rapid Serial Visual Presentation paradigm (RSVP). Imagine flipping through the channels on a television, looking for a specific program without knowing what channel it is on. In RSVP, the “channels”, typically streams of letters, objects or scenes are presented at fixation and flash by at a rapid rate (10 Hz, 100 msec per frame is typical), and the observer must monitor the stream for one or more specific targets (e.g. the identity of two letters among a series of numbers). RSVP studies have yielded two important phenomena, which tell us about how the visual system segments events in time: the attentional blink and repetition blindness.

Attentional Blink

When observers search for two targets in an RSVP sequence of distractors, their capacity to detect the second target (T2) presented within 500 ms after the first target (T1) is severely impaired, a phenomenon known as “attentional blink” (AB) (26, 27). T2 can be accurately reported if T1 is not present or not part of the task (Figure 2). However, even when T2 is not reportable by the observer, evidence suggests that it receives considerable processing. An unreported T2 can semantically prime a third target. Similarly, a semantically related T1 can increase the chances that T2 will be correctly reported.

Recent evidence suggests that AB is a consequence of the cognitive strategy by which the visual system ensures the episodic distinction between separately presented targets (28). In many cases, AB does not occur if the second target T2 immediately follows the first target T1 (phenomenon known as “Lag-1 sparing”). More tellingly, AB is not observed if several target items are presented in direct succession (29). In such cases, two or more stimuli seem to be aggregated into a single event. Therefore, it seems that AB depends on the presence of a distractor or a mask in the position immediately after T1. On this view, the appearance of T1 triggers the opening of an “attentional gate”, which can remain open if multiple targets are presented. Once a distractor appears, however, the system attempts to shut the gate, resulting in the inadvertent inhibition of an inopportunely timed T2.

Repetition Blindness

The problem of distinguishing between repetitions of the same stimulus is related to the problem of segregating events in time. When two identical items are presented in the same RSVP stream, observers often have difficulty reporting the second occurrence, a phenomenon termed *repetition blindness* (RB)(30). As with AB, the lag between the two repeated items is critical for the occurrence of RB. The magnitude of the effect typically decreases as the lag increases. It has been hypothesized, and supported by a variety of studies, that RB occurs when items are recognized as “types” (e.g. the word “CAT”) but not individuated as instances, or tokens, of the same type (e.g. this instance of the word CAT). Rather than a literal ‘blindness’ RB may represent the assimilation of T1 and T2 into a single instance of the item.

Although AB and RB seem to be phenomenologically similar, they are distinguishable experimentally. For example, when targets and distractors become more distinct, the AB effect decreases, but this is not the case with the RB effect. Thus, AB and RB seem to reflect distinct processes in temporal attention (for more detail see chapter COGSCI-255).

What is the role of inhibition in attentional processes?

While attention is often thought of as enhancing processing of the attended stimulus, inhibition of unattended stimuli is also an important mechanism. Inhibitory mechanisms can serve to reduce ambiguity, protect capacity-limited mechanisms from interference, and prioritize selection for new objects. Here we provide four illustrations of the role of inhibition in attention: negative priming, inhibition of return, visual marking, and inhibition of distractor locations.

Negative Priming

Imagine two overlapping stimuli, one red, one green. You are asked to respond to the shape of the green stimulus on each trial. What happens to the red stimulus? Clearly, it falls on the retina and makes some impression on the visual system. Its fate can be assessed by presenting the red stimulus from this trial as the green, to-be-responded-to stimulus on the next trial. As many studies have documented, you will be slower to respond to that previously ignored shape. (Figure 3) This phenomenon, termed “negative priming” (Figure 2. For reviews, see 31, 32) is hypothesized to reflect the active suppression of the representations of ignored items (e.g. red distractors in the prime display). Negative priming has been observed for time scales from a few seconds up to as much as a month. The ignored prime and subsequent probe stimuli can be quite different from each other (e.g. a picture prime and a word probe). However, it is possible to account for negative priming effects without assuming that the prime item is actively inhibited. One alternative is response competition at retrieval. When an old item that was to be ignored is now the current target for response, the old “ignore” signal interferes with the present “respond” signal (33) .

Inhibition of Return

Previously ignored stimuli are not the only representations that might be purposefully inhibited. The phenomenon of "inhibition of return" (IOR) shows that actively attended items are also suppressed once attention is deployed elsewhere. It is proposed that this serves to bias the attentional system toward novelty and away from perseveration on salient but irrelevant stimuli, thereby facilitating attentional “foraging” (34). In a classic IOR paradigm, attention would be attracted to an object or location and then redirected elsewhere (Figure 4). If observers are then asked to respond to the initially attended item, they are slower than if the item had never been attended (25). Whereas negative priming can inhibit specific semantic categories, objects or actions, IOR is a phenomenon of spatial selection. As with other aspects of selective attention described above, IOR seems to operate in both space-based and object-based coordinate systems. IOR can apply to the last few attended items over a time course of seconds. Note that IOR represents a *tendency* not to return, not an absolute prohibition on return.

Visual Marking

While negative priming and IOR are typically revealed by impairments in the observer’s performance, “visual marking” is an inhibitory process that is typically revealed by an improvement in the observer’s performance (35). In a typical marking study, the items in a visual search array would be presented in two steps: a “preview” of half of the distractors followed by the presentation of the entire display. Typically, observers search the full display as though the previewed items were not present. For example, consider a search for a red vertical among green vertical and red horizontal distractors. Typically, this “conjunction” search is of intermediate efficiency. However, if all the green verticals are previewed, the subsequent search becomes, in effect, a highly efficient search for a red vertical among red horizontals. This effect seems to involve the inhibition of the previewed items and not merely the prioritization of new, onset stimuli. Marking is not simply a memory for old locations; if the previewed distractors change shape when the full display appears, they will compete with the new distractor stimuli. Marking is also adaptive, in that it is not observed when the preview items might contain the target.

Inhibition of distractor locations

Spatially focused attention ("spotlight of attention") has a specific structure, advocate some recent studies, rather then just being a spatial gradient of enhanced activity that falls off monotonically with growing distance. Behavioral and neurophysiologic evidence suggest the focus of spatial attention has not only an excitatory center but also a narrow inhibitory surround region (36, 37). Due to this center surround architecture when attention is deployed to certain area of space enhancing processing of selected items there is inhibition or suppression of nearby surround distractor locations. Studies show that probe detection at distractor locations close to a search target is slowed and neuronal response reduced relative to distractor locations further away from the target.

What happens when observers are asked to divide attention across several stimuli?

Thus far, we have treated visual attention as a process operating on one location and/or object at one time. Here we consider the possibility that attention can be split between multiple stimuli or tasks, as mentioned earlier. To some extent, this is a definitional issue. Consider a search for a red letter "T" among red and black "L's". There will be top-down guidance to all red items. This is sometimes considered to be evidence for the deployment of attention to all red locations. However, this guidance to red should be distinguished from the selective attention that allows an observer to recognize one of the red items as a "T" or an "L". While most would agree that attention can be guided to all red items, there is less agreement about whether attention can be divided in a manner that permits recognition processes to work simultaneously on two or more, spatially separated letters or other objects.

Empirical data, as well as everyday experiences, tell us that our ability to perform concurrent tasks or process multiple inputs is limited. However, not all combinations of tasks are equally difficult and not all interference happens at the same processing stage. Here we can only skim the surface of the large literature on divided attention. One can ask about dividing attention within a task. Is it possible to "attend" to more than one item at a time in a visual search task or an attentional cuing task? If attention is directed to two items, is it divided or merely stretched, with some attentional resources going to the space between the intended objects of attention?

Alternatively, one can also ask about dividing attention between two tasks. Is it possible to track the motion of objects while searching for a target (38) ? Is it possible to attend to some letters and still detect the presence of an animal in a superimposed scene (39)? Where are the bottlenecks in processing and when can different tasks coexist in the nervous system (reviewed in 40, for more detail see COGSCI-263)?

Dual-tasks

In dual-task paradigms, observers perform two tasks on the same trial. Interference between the tasks has been shown to be influenced by task similarity, practice, and the difficulty of the individual tasks (41-45). Thus, two dissimilar, highly practiced and simple tasks can be performed well together, while two similar, novel and complex tasks cannot. Three different theoretical accounts have been put forth to explain dual task interference: the task-general resource view (central capacity sharing, 46); the task-specific resource view (crosstalk interference, 47); and the central bottleneck view (response selector, 48). The task-general resource view postulates that processing for different tasks proceeds in parallel with the central resource flexibly divided among different tasks in a graded fashion. On the other hand the task-specific resource view argues that there are task-specific resources and the occurrence of interference depends on similarity or confusability of mental representations involved in the tasks. Unlike either of the former views the central or single-channel bottleneck view proposes that certain critical mental operations must be carried out sequentially (e.g. decisions to respond) resulting in interference when two tasks require those operations at the same time.

As ever, the experimental data show that these accounts are not mutually exclusive. Thus, interference between tasks depends on the nature of the tasks, and is greatest when the tasks overlap in their processing demands as would be predicted by a crosstalk account. However concurrent tasks can interfere with each other even if there is no detectable overlap in the tasks' processing demands. Two factors are important here. The tasks themselves might require bigger amounts of processing capacity as predicted by central capacity accounts. Secondly, the two tasks might each require a complex series of responses thus placing heavy demands on the response selector at the executive level of processing.

Attention to multiple spatial locations

While early investigations suggested that the spatial focus of attention must be unitary (Posner, 1980), more recent studies suggest that attention can be divided among at least two spatial locations, without also boosting intervening locations (49); (50) It is important that the observer have an incentive to split the attentional focus. To produce this split, it is useful if the cues for attention are highly predictive and if there is distracting information in the space between the loci worth inhibiting.

Evidence for some variety of simultaneous attention to multiple objects has been available for over 20 years in the form of studies of multiple object tracking studies (MOT, 51). In the typical MOT experiment, the observer is presented with an array of identical items (e.g., disks, see Figure 5). Some of the items are designated as targets and the observer's task is to track these targets for seconds or minutes as the items move independently. Most observers can track 4-5 targets, suggesting that one can attend to multiple objects simultaneously. An important caveat here is that the processes used in tracking differ from those used in selective attention. For example, observers often fail to notice when targets change color (52) and find it difficult to recall information about a specific target, such as its starting location or its original name (53). It may be that, in MOT, attention is used to index locations of targets, not the targets themselves (for more detail see COGSCI-271).

What is the relationship of visual attention to the process of automaticity and awareness?

Automaticity

The attentional demands of a task can change over time. When learning to drive a car, all of the novice driver's attention may be occupied with the task. Once the task has become "automatic" the same actions seem to coexist happily with at least some other tasks (though you should avoid using the cell phone, 54). While there may not be an agreed definition of "automaticity", we can provisionally define automatic visual processing as the capacity to extract visual information with minimal (or no) attention, while engaging in other independent processes (for classic reviews see (55); (56). A task that can be performed in an automatic fashion does not imply that it is done pre-attentively but rather requires minimal engagement of attention. Much recent research has focused on the ability to identify the 'gist' of a scene or the presence of some category of object in the near absence of attention. In dual task studies, observers can devote their attention to a demanding search task and, nevertheless, report whether a natural scene contains an animal (Li et al., 2002). What is more, given sets of similar items, observers can assess the mean and distribution of a variety of basic visual feature dimensions without the need to attend to each object (e.g. size, orientation, velocity and direction of motion, center of mass just to name a few) (57, 58). Gist and summary statistic seem to be extracted automatically allowing observes to make very rapid, fairly accurate judgments about quite complex scenes.

The so-called “flanker task” has been used as another example of automatic processing of stimuli. In a flanker task, observers might be asked to selectively attend to a central letter and press one key for “A” and another for “B”. They are instructed to ignore flanking letters but they have trouble doing so. RTs are faster when the to-be-ignored flankers are congruent (A A A) than when they are incongruent (B A B) suggesting that some automatic process wandered off to read the flanking letters in the face of instructions to the contrary (59). Interestingly, it is easier to ignore the flankers if the central task is harder (60).

Awareness

Attention and conscious awareness seem to have an intimate, if rather ambiguous relationship. It is sometimes suggested that attention is required for awareness. However, since it seems reasonably clear that you can attend to this prose while still being aware of the presence of some sort of extended visual field, this requirement would seem to depend upon a very broad definition of attention. There is experimental evidence that although attention modulates awareness, we have some awareness of unattended stimuli. For example, it is possible to direct attention to visual stimuli that we are not aware of (61).

The modulation of awareness by attention can be illustrated via the phenomenon of "change blindness". In a typical change blindness demonstration, two nearly identical images are shown in succession. In a famous example devised by Ron Rensink, two scenes containing an airplane alternate with a large jet engine appearing and disappearing from frame to frame. Observers are poor at noticing this substantial change if motion transients are masked, either with an intervening gray field or by irrelevant onsets (mud splashes, (62)). In general, quite substantial changes typically go undetected, if the do not change the overall “gist” or meaning of the scene, while the same changes are trivially easy to detect if observers are attending to the location of the change (62, 63). Clearly, attention modulates the awareness of significant changes though the nature of the change in awareness remains a matter for discussion (see also the sections on Neglect and Balint syndrome; for more detail see COGSCI-260).

There is also evidence that attention can be deployed without awareness. Indeed, if attention can shift 20-30 times a second, as suggested by visual search studies, we do not have easy conscious accesses to all those acts of selection. Studies on “blindsight” patients provide a different example of attention without awareness. In blindsight, damage to the primary visual cortex results in a condition where patients report being unaware of part of the visual field. However, when asked to guess what stimuli are located in the unaware area, patients can perform at above chance levels. Furthermore, when spatially cued to the unaware area, they exhibit speeded discrimination of targets that subsequently appear in that area, demonstrating that they can attend to stimuli that they cannot “see” (61).

How is attention implemented at the neuronal level?

In this section, we examine how visual attention might be implemented in the brain. Our survey is organized by methodology (see also COGSCI-141).

Single –cell physiological recordings

Studies utilizing single cell recordings have led to several important insights about visual attention. Attentional effects are observable as early as the lateral geniculate nucleus and the primary visual cortex as well as on a variety of subcortical structures (64). These results suggest that attentional effects occur at multiple loci. Perhaps more interesting are data which bear on the question of how attention improves visual processing. In some experiments attention produces larger increases in firing rates at lower levels of stimulus contrast with smaller effects at high contrast. This is the pattern expected if attention produces a *contrast gain*. Other experiments provide evidence for a *rate gain* model with the largest effects at high contrast. In different studies attention changes the shape of neuronal tuning curves (e.g. sharper orientation tuning). Finally, attention can shrink a cell's receptive field around the attended stimulus to the exclusion of distracting stimuli. This diversity of results may reflect a diversity of attentional processes, though it has been suggested that different patterns of results may result from a single attentional mechanism responding to different stimulus conditions (65).

Single cell methods have also been used extensively to explore a fronto-parietal network involved in the allocation of attention. The lateral intraparietal area (LIP) in the parietal lobe has been proposed as the locus of a priority map that might guide attention to objects with the features of the current target off attention. The frontal eye fields (FEF) and the dorso-lateral prefrontal cortex (DLPFC) are implicated in the executive control of the deployment of attention. (e.g., (66).

Functional imaging

Functional Magnetic Resonance Imaging (fMRI) and Positron Emission Tomography (PET) show that attention modulates a wide range of loci in the brain. These methods can be used to map distinct combinations of brain areas to particular aspects of attention (e.g. 67, 68, 69). For example, visual orienting (i.e. the ability to attentionally select a particular stimulus for action) is thought to be implemented by both dorsal and ventral system (70). The dorsal system is bilateral and includes the LIP, FEF, and DLPFC network described above. It appears to be involved in voluntary, goal-directed selection of stimuli and responses. The ventral system is largely right-lateralized and comprises the temporal-parietal junction and ventral frontal cortex. It is seems to be specialized for the detection of behaviorally relevant stimuli.

Event-related potentials

While functional imaging methods provide excellent spatial information about neural processes, their temporal resolution is poor. Event-related potentials (ERP), in contrast, have high temporal resolution, at the cost of spatial precision. Thus, ERP techniques are well suited for assessing the time course of attentional effects (71). For example, consider the attentional modulation of primary visual cortex. ERP results show that this modulation can be seen in the first, "feed-forward" activation of cortex by an incoming stimulus. This rules out the alternative that attentional modulation of V1 is a feedback process (72).

The N2pc component of the ERP signal has proven quite useful, since it is associated with the focusing of selective attention on a target item. This signal has been found to shift rapidly from one item to another during a visual search task, attesting to attention moving in a serial manner among multiple items in a display (73).

Neglect and Balint's syndrome

Important information about brain mechanisms has also come from studies of localized brain damage. For example, a lesion to the right posterior parietal cortex leaves the visual system intact, but results in the patient ignoring a region of space contralateral to the lesion (74). It therefore represents a loss of attentional, but not visual, capabilities. This "visual neglect" is especially interesting because it implicates attention in conscious perception while also showing that quite sophisticated processing can occur in the absence of attention (75). For example, a word presented in the neglected region that is not consciously perceived may speed the response to a semantically-related word subsequently shown in a non-neglected region. Similarly, patients show above chance performance in a forced choice comparison task between two pictures presented in the neglected field. Studies of neglect suggest that it is caused by inter-hemispherical competition between the cortical circuits that control the deployment of attention. For example, damage to the right cerebral cortex may allow the attentional circuits in the left cerebral cortex to dominate. As the left cerebral cortex is responsible for processing the right visual hemifield, attention is directed more often (or even exclusively) to the right visual hemifield, causing the patient to ignore objects that occur to the left of the point of fixation.

If attentional circuits in both cerebral hemispheres are damaged, then neither may dominate, resulting in a phenomenon known as Balint's syndrome (76). A patient with this syndrome can perceive an isolated object regardless of where it is located, but demonstrates a striking inability to perceive more than one object at a time.

Conclusion

Visual attention can be seen as a set of cognitive and physiological mechanisms modulating visual information. Mainly, these processes: (i) Allow for a subset of relevant stimuli to be processed rapidly and accurately at the expense of irrelevant ones (selective attention). (ii) Seem to be necessary for the integration of visual information into objects (binding) that can be successively identified, recognized and remembered.

The selection processes, both excitatory and inhibitory, can affect stimuli at different locations in space (spatial attention) or at different moments in time (temporal attention). In addition, more than one location can be selected at a time (divided attention). Whether a stimulus is attended or not, also modulates the awareness of the stimulus itself.

Visual attention has no unique location in the brain. On the contrary, different selection processes take place at different stages of the visual pathways and feature integration involves several areas of both cerebral hemispheres, suggesting again that attention is not a separate and unified system, but a set of differentiated selection processes.

References

1. Posner MI, Snyder CR, Davidson BJ: Attention and the detection of signals. *Journal of experimental psychology*. 1980;**109**(2):160-174.

2. Wojciulik E, Kanwisher N, Driver J: Covert visual attention modulates face-specific activity in the human fusiform gyrus: fMRI study. *Journal of neurophysiology*. 1998;**79**(3):1574-1578.

3. O'Craven KM, Rosen BR, Kwong KK, Treisman A, Savoy RL: Voluntary attention modulates fMRI activity in human MT-MST. *Neuron*. 1997;**18**(4):591-598.

4. Desimone R, Ungerleider LG: Neural mechanisms of visual processing in monkeys. In: *Handbook of neuropsychology,,* p. Eds. Boller E, J.Grafman). Elsevier Science: Amsterdam, 1990.

5. Humphreys GW, Duncan J, Treisman A: Attention, space, and action : studies in cognitive neuroscience. Oxford University Press: Oxford ; New York, 1999.

6. Wolfe JM, Cave KR, Franzel SL: Guided search: an alternative to the feature integration model for visual search. *J Exp Psychol Hum Percept Perform*. 1989;**15**(3):419-433.

7. Treisman AM, Gelade G: A feature-integration theory of attention. *Cognitive psychology*. 1980;**12**(1):97-136.

8. Desimone R, Duncan J: Neural mechanisms of selective visual attention. *Annual review of neuroscience*. 1995;**18**:193-222.

9. DeSchepper B, Treisman A: Visual memory for novel shapes: implicit coding without attention. *J Exp Psychol Learn Mem Cogn*. 1996;**22**(1):27-47.

10. Stankiewicz BJ, Hummel JE, Cooper EE: The role of attention in priming for left-right reflections of object images: evidence for a dual representation of object shape. *J Exp Psychol Hum Percept Perform*. 1998;**24**(3):732-744.

11. Wolfe JM, Horowitz TS: What attributes guide the deployment of visual attention and how do they do it? *Nat Rev Neurosci*. 2004;**5**(6):495-501.

12. Itti L, Koch C: Computational modelling of visual attention. *Nat Rev Neurosci*. 2001;**2**(3):194-203.

13. Wolfe JM: Guided Search 4.0: Current Progress with a model of visual search. *Integrated models of cognitive systems*. 2007:99-119.

14. Rauschenberger R: Attentional capture by auto- and allo-cues. *Psychon Bull Rev*. 2003;**10**(4):814-842.

15. Sully J: Outlines of psychology. D. Appleton and Co.1892.

16. Horowitz TS, Wolfe JM, Alvarez GA, Cohen MA, Kuzmova YI: The speed of free will. *Quarterly journal of experimental psychology (2006)*. 2009:1-27.

17. Eriksen CW, Yeh YY: Allocation of attention in the visual field. *Journal of Experimental Psychology: Human Perception & Performance*. 1985;**11**(5):583-597.

18. Eriksen CW, Yeh YY: Allocation of attention in the visual eld. *Journal of Experimental Psychology: Human Perception and Performance*. 1985;**11**(5):583-597.

19. Egly R, Driver J, Rafal RD: Shifting visual attention between objects and locations: evidence from normal and parietal lesion subjects. *Journal of Experimental Psychology: General*. 1994;**123**(2):161-177.

20. Blaser E, Pylyshyn ZW, Holcombe AO: Tracking an object through feature space. *Nature*. 2000;**408**(6809):196-199.

21. Sears CR, Pylyshyn ZW: Multiple object tracking and attentional processing. *Canadian Journal of Experimental Psychology*. 2000;**54**(1):1-14.

22. Vecera SP, Farah MJ: Does visual attention select objects or locations? *Journal of Experimental Psychology General*. 1994;**123**:146-146.

23. He ZJ, Nakayama K: Visual attention to surfaces in three-dimensional space. *Proceedings of the National Academy of Sciences of the United States of America*. 1995;**92**(24):11155-11159.

24. Intriligator J, Cavanagh P: The spatial resolution of visual attention. *Cognitive Psychology*. 2001;**43**(3):171-216.

25. Posner MI, Cohen Y: Components of visual orienting. In: *Attention and Performance X: Control of Language Processes,* p. 551-556 (Ed. Bonwhuis HBaD). Erlbaum: Hillsdale, N.J., 1984.

26. Broadbent DE, Broadbent MH: From detection to identification: response to multiple targets in rapid serial visual presentation. *Percept Psychophys*. 1987;**42**(2):105-113.

27. Raymond JE, Shapiro KL, Arnell KM: Temporary suppression of visual processing in an RSVP task: an attentional blink? *J Exp Psychol Hum Percept Perform*. 1992;**18**(3):849-860.

28. Wyble B, Bowman H, Nieuwenstein M: The attentional blink provides episodic distinctiveness: Sparing at a cost. *J Exp Psychol Hum Percept Perform*. 2009;**35**(3):787-807.

29. Kawahara J, Kumada T, Di Lollo V: The attentional blink is governed by a temporary loss of control. *Psychon Bull Rev*. 2006;**13**(5):886-890.

30. Kanwisher NG: Repetition blindness: type recognition without token individuation. *Cognition*. 1987;**27**(2):117-143.

31. Fox E: Pre-cuing target location reduces interference but not negative priming from visual distractors. *Q J Exp Psychol A*. 1995;**48**(1):26-40.

32. Tipper SP: Does negative priming reflect inhibitory mechanisms? A review and integration of conflicting views. *Q J Exp Psychol A*. 2001;**54**(2):321-343.

33. Hinton GE: Connectionist learning procedures. *Artificial intelligence*. 1989;**40**(1-3):185-234.

34. Klein RM: Inhibition of return. *Trends Cogn Sci*. 2000;**4**(4):138-147.

35. Watson DG, Humphreys GW: Visual marking: prioritizing selection for new objects by top-down attentional inhibition of old objects. *Psychol Rev*. 1997;**104**(1):90-122.

36. Hopf JM, Boehler CN, Luck SJ, Tsotsos JK, Heinze HJ, Schoenfeld MA: Direct neurophysiological evidence for spatial suppression surrounding the focus of attention in vision. *Proceedings of the National Academy of Sciences*. 2006;**103**(4):1053.

37. Cave KR, Zimmerman JM: Flexibility in spatial attention before and after practice. *Psychological Science*. 1997;**8**(5):399.

38. Alvarez GA, Horowitz TS, Arsenio HC, Dimase JS, Wolfe JM: Do multielement visual tracking and visual search draw continuously on the same visual attention resources? *J Exp Psychol Hum Percept Perform*. 2005;**31**(4):643-667.

39. Li FF, VanRullen R, Koch C, Perona P: Rapid natural scene categorization in the near absence of attention. *Proc Natl Acad Sci U S A*. 2002;**99**(14):9596-9601.

40. Pashler HE: Attention. Psychology Press: Hove, 1998.

41. McLeod PD: A dual task response modality effect: Support for multiprocessor models of attention. *Quarterly Journal of Experimental Psychology*. 1977;**29**:651 - 667.

42. Treisman AM, Davies A: Divided attention to ear and eye. In: *Attention and Performance,* p. 101-117 (Ed. Kornblum S). Academic Press1973.

43. Spelke ES, Hirst W, Neisser U: Skills of divided attention. *Cognition*. 1976;**4**:215-230.

44. Sullivan L: Selective attention and secondary message analysis: A reconsideration of Broadbent's filter model of selective attention. *The Quarterly Journal of Experimental Psychology*. 1976;**28**(2):167-178.

45. Duncan J: Divided attention: the whole is more than the sum of its parts. *J Exp Psychol Hum Percept Perform*. 1979;**5**(2):216-228.

46. Kahneman D: Attention and effort. Prentice-Hall: Englewood Cliffs, N.J.,, 1973.

47. Wickens CD: Engineering psychology and human performance. 2 ed. Harper Collins: New York, 1992.

48. Pashler H, Johnston JC: Attentional limitations in dual-task performance. In: *Attention,* p. 155-189 (Ed. Pashler H). Psychology Press/Erlbaum (Uk) Taylor & Francis, Hove: Erlbaum, England UK, 1998.

49. Jans B, Peters JC, De Weerd P: Visual Spatial Attention to Multiple Locations at Once: The Jury Is Still Out. *Psychological Review*. 2010;**117**(2):637-682.

50. Cave KR, Bush WS, Taylor TGG: Split Attention as Part of a Flexible Attentional System for Complex Scenes: Comment on Jans, Peters, and De Weerd (2010). *Psychological Review*. **117**(2):685-695.

51. Pylyshyn ZW, Storm RW: Tracking multiple independent targets: evidence for a parallel tracking mechanism. *Spat Vis*. 1988;**3**(3):179-197.

52. Saiki J: Multiple-object permanence tracking: limitation in maintenance and transformation of perceptual objects. *Prog Brain Res*. 2002;**140**:133-148.

53. Pylyshyn ZW: Some puzzling findings in multiple object tracking: I. Tracking without keeping track of object identities. *Visual Cognition*. 2004;**11**(7):801-822.

54. Strayer DL, Johnston WA: Driven to distraction: Dual-task studies of simulated driving and conversing on a cellular telephone. *Psychological science*. 2001;**12**(6):462-466.

55. Schneider W, Shiffrin RM: Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological review*. 1977;**84**(1):1-66.

56. Shiffrin RM, Schneider W: Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. *Psychological review*. 1977;**84**(2):127-190.

57. Chong SC, Treisman A: Representation of statistical properties. *Vision research*. 2003;**43**(4):393-404.

58. Williams DW, Sekuler R: Coherent global motion percepts from stochastic local motions. *Vision research*. 1984;**24**(1):55-62.

59. Eriksen BA, Eriksen CW: Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*. 1974;**16**(1):143-149.

60. Lavie N, Tsal Y: Perceptual load as a major determinant of the locus of selection in visual attention. *Perception and Psychophysics*. 1994;**56**(2):183-197.

61. Kentridge RW, Heywood CA, Weiskrantz L: Attention without awareness in blindsight. *Proceedings of the Royal Society B: Biological Sciences*. 1999;**266**(1430):1805.

62. O'Regan JK, Rensink RA, Clark JJ: Change-blindness as a result of 'mudsplashes'. *Nature*. 1999;**398**(6722):34.

63. Rensink RA: Seeing, sensing, and scrutinizing. *Vision research*. 2000;**40**(10-12):1469-1487.

64. Shipp S: The brain circuitry of attention. *Trends in Cognitive Sciences*. 2004;**8**(5):223-230.

65. Reynolds JH, Heeger DJ: The normalization model of attention. *Neuron*. 2009;**61**(2):168-185.

66. Buschman TJ, Miller EK: Serial, Covert Shifts of Attention during Visual Search Are Reflected by the Frontal Eye Fields and Correlated with Population Oscillations. *Neuron*. 2009;**63**(3):386-396.

67. Kincade JM, Abrams RA, Astafiev SV, Shulman GL, Corbetta M: An event-related functional magnetic resonance imaging study of voluntary and stimulus-driven orienting of attention. *J Neurosci*. 2005;**25**(18):4593-4604.

68. Corbetta M, Kincade JM, Ollinger JM, McAvoy MP, Shulman GL: Voluntary orienting is dissociated from target detection in human posterior parietal cortex. *Nature neuroscience*. 2000;**3**(3):292-297.

69. Nobre AC, Sebestyen GN, Gitelman DR, Mesulam MM, Frackowiak RS, Frith CD: Functional localization of the system for visuospatial attention using positron emission tomography. *Brain*. 1997;**120 (Pt 3)**:515-533.

70. Corbetta M, Shulman GL: Control of goal-directed and stimulus-driven attention in the brain. *Nature reviews*. 2002;**3**(3):201-215.

71. Mangun GR: Neural mechanisms of visual selective attention. *Psychophysiology*. 1995;**32**(1):4-18.

72. Kelly SP, Gomez-Ramirez M, Foxe JJ: Spatial attention modulates initial afferent activity in human primary visual cortex. *Cereb Cortex*. 2008;**18**(11):2629-2636.

73. Woodman GF, Luck SJ: Electrophysiological measurement of rapid shifts of attention during visual search. *Nature*. 1999;**400**(6747):867-868.

74. Danckert J, Ferber S: Revisiting unilateral neglect. *Neuropsychologia*. 2006;**44**(6):987-1006.

75. Driver J, Vuilleumier P: Perceptual awareness and its loss in unilateral neglect and extinction. *Cognition*. 2001;**79**(1-2):39-88.

76. Balint R: Seelenlahmung des "Schauens", optische Ataxia, raumliche Storung der Aufmerksamkeit. . *Monatsschrift fur Psychiatrie und Neurologie*. 1909;**25**(51-81).

Further Reading

Wright RD: Visual attention. Oxford University Press, USA1998.

Humphreys GW, Duncan J, Treisman A: Attention, space and action: studies in cognitive neuroscience. Oxford University Press1999.

Shapiro K: The limits of attention: Temporal constraints in human information processing. Oxford University Press2001.

Wolfe JM, Horowitz TS: What attributes guide the deployment of visual attention and how do they do it? *Nature Reviews Neuroscience*. 2004;**5**(6):495-501.

Kastner S, Ungerleider LG: Mechanisms of visual attention in the human cortex. 2003.

Egeth HE, Yantis S: Visual attention: Control, representation, and time course. *Annual Review of Psychology*. 1997;**48**(1):269-297.

Chun MM, Wolfe JM: Visual attention. *Blackwell handbook of perception*. 2001:272-310.

Reynolds JH, Chelazzi L: Attentional modulation of visual processing. *Annual Review of Neurosceince.* 2004; **27**,611-647.

Driver J, Frackowiak RSJ: Neurobiological measures of human selective attention. *Neuropsychologia*. 2001;**39**(12):1257-1262.

Luck SJ, Vecera SP: Attention: From tasks to mechanisms. 3rd ed. Wiley and Sons: New York, 2002. 235-286.

Pashler HE: Attention. Psychology Press: Hove, 1998.

Cross-References

COGSCI-288: Visual Search

COGSCI-263: Divided Attention

COGSCI-260: Change Blindness/Inattentional Blindness

COGSCI-255: Attentional Blink & Repetition Blindness

Figure legend

Figure 1. Depiction of a search for a vertical line in a homogeneous filed of distractor lines (a) and heterogeneous filed of lines (b).

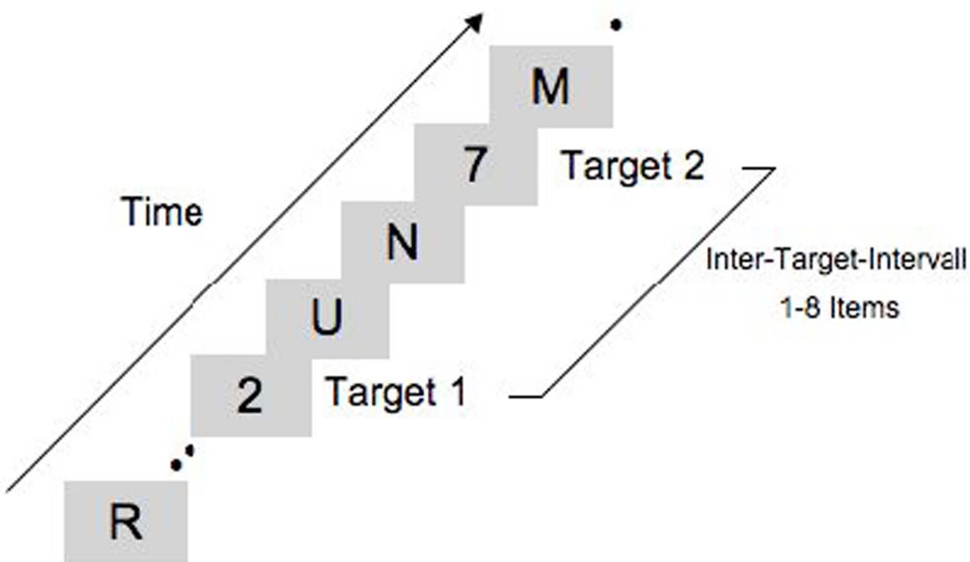
Figure 2. An example of a prototypical procedure used to measure the attentional blink . a) Depiction of the experimental design. The targets are numbers and distractors are letters. The task is to detect the appearance of a number embedded in a stream of letters. b) Example of observed data representing the attentional blink. The graph show percentage correct answers for the second target (T2) is the first target (T1) has been correctly reported.

Figure 3. An example of a prototypical procedure used to measure negative priming modified from Harold Pasher (1998), Attention, Psychology press, page 206. Target items are green letters and, distractor items are red letters. The observers are required to identify the target in both the prime and probe displays. Negative priming represent slower response to the probe target in the ignore repetition condition than in the control condition.

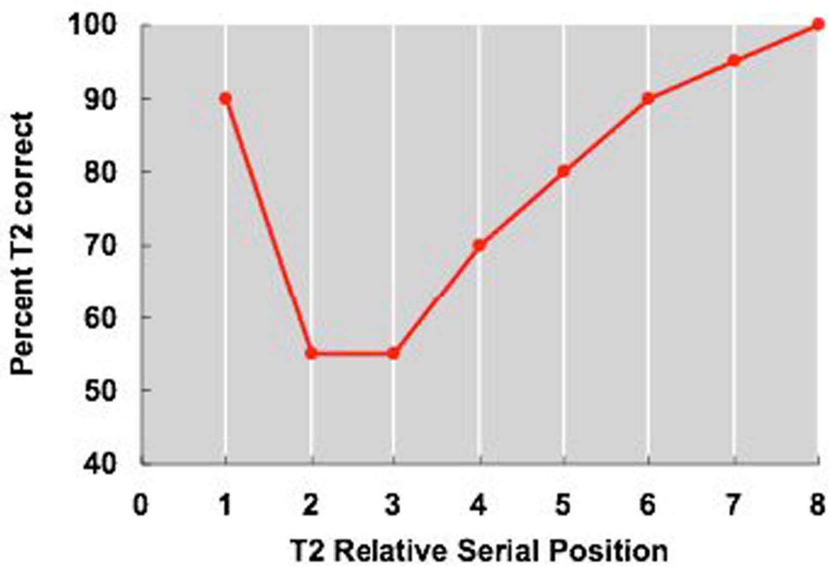
Figure 4. Cuing task used to elicit inhibition of return (a) and results from Posner and Cohen (1984) (b). CTOA stands for cue –target onset asynchrony.

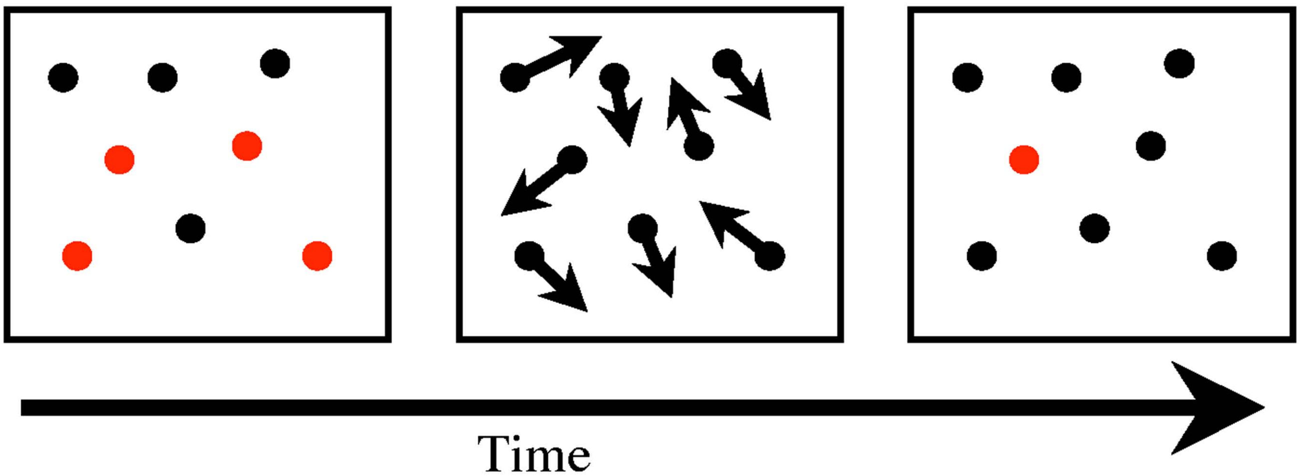
Figure 5. An example of a multiple object tracking (MOT) trial. A simple MOT trial might start with the presentation of a number of identical objects, a subset of which are highlighted to indicate that they are the targets to be tracked. Once the targets stop flashing, the objects would then move around the display in a random fashion for several seconds. Because all the objects are identical, the only way the observer can keep track of the targets is by continuously attending to them. This ensures that attention is sustained across the duration of the trial. At the end of the trail, an object is highlighted and the observer indicates whether it was a target or a distractor.

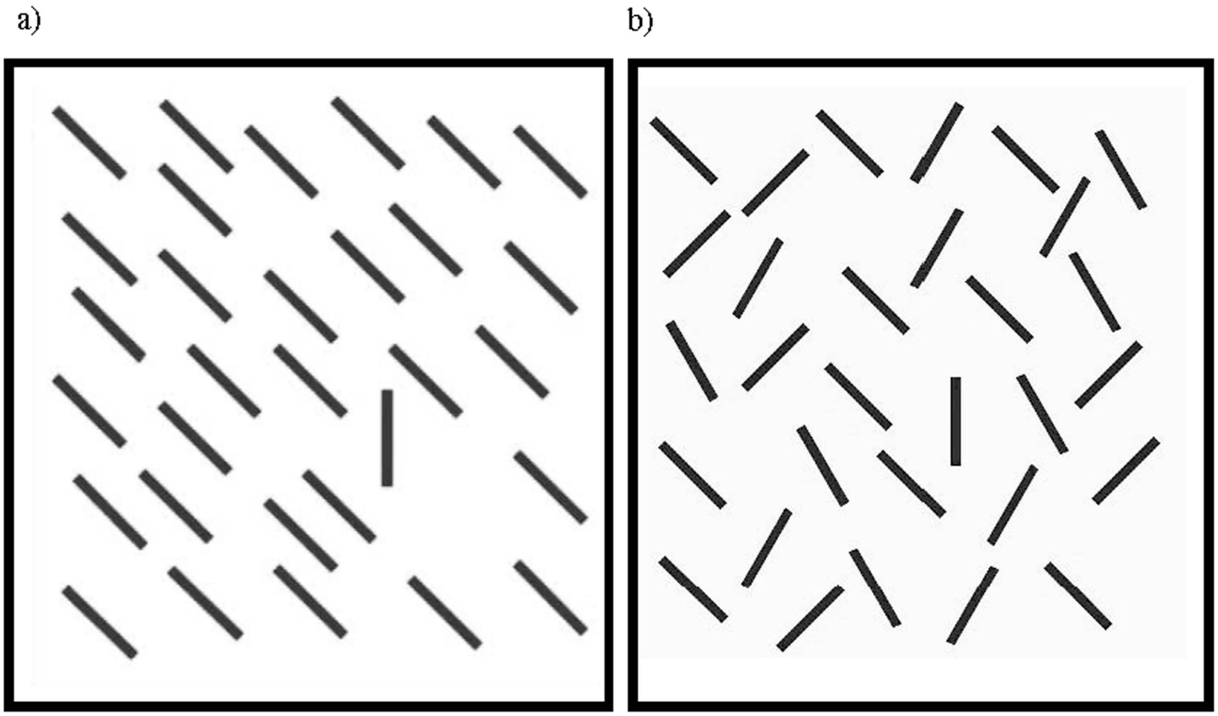
a)

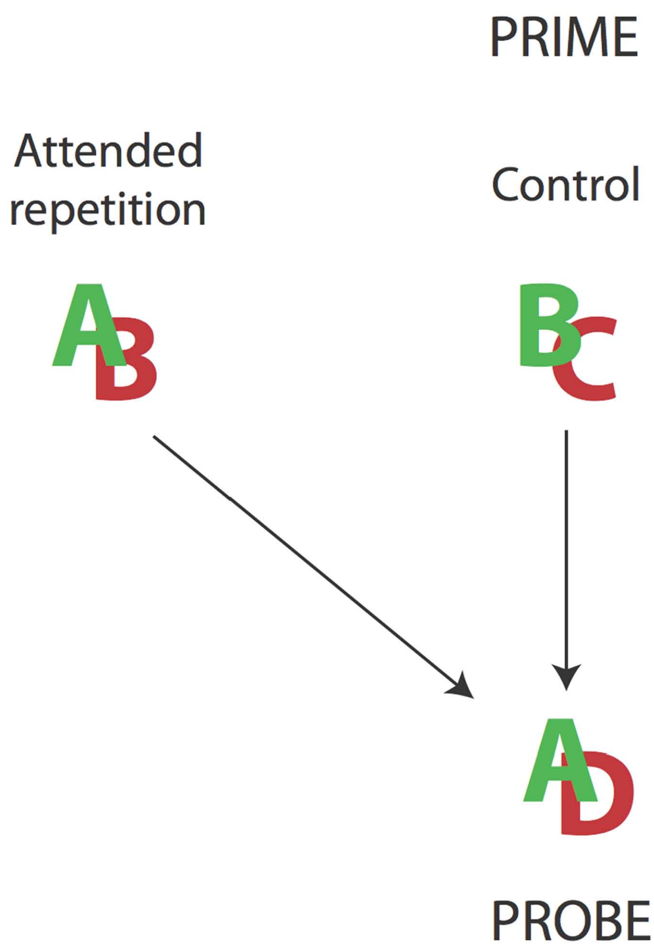

Time
M
7
Target 2
N
Inter-Target-Intervall
1-8 Items
U
2
Target 1
R

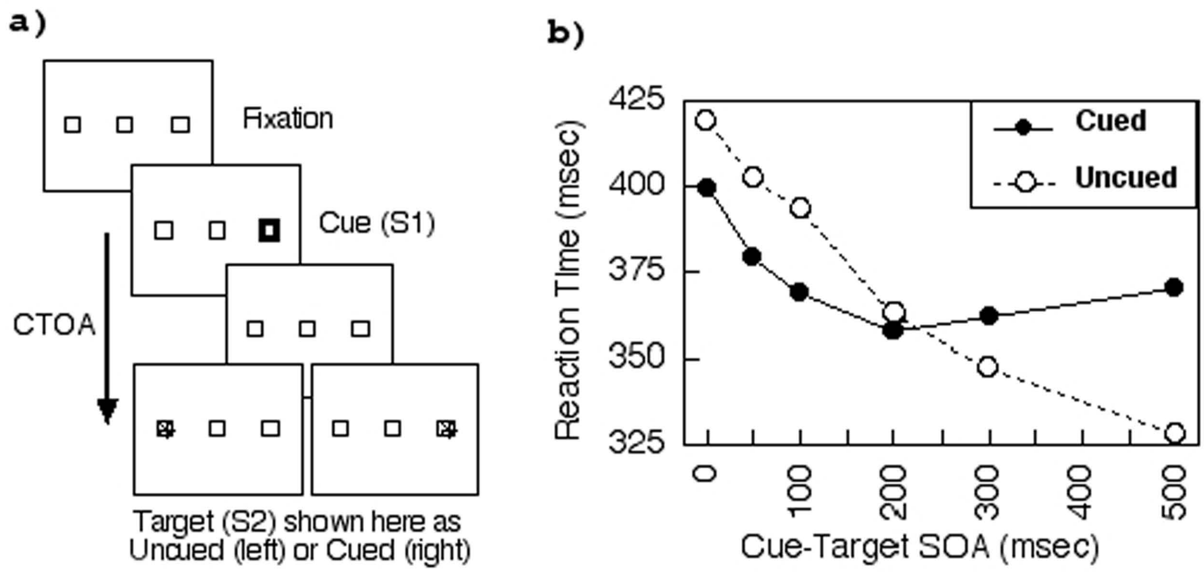
b)


Percent T2 correct
100
90
80
70
60
50
40
0
1
2
3
4
5
6
7
8
T2 Relative Serial Position


Time




PRIME
Attended repetition
Control
Ignored repetition
A B
B C
B A
A D
PROBE


a)
Fixation
Cue (S1)
CTOA
Target (S2) shown here as
Uncued (left) or Cued (right)
b)
Cued
Uncued
Reaction Time (msec)
425
400
375
350
325
0
100
200
300
400
500
Cue-Target SOA (msec)