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Visual Attention

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What you see is determined by what you attend to. At any given time, the environment presents far more perceptual information than can be effectively processed. Visual attention allows people to select the information that is most relevant to ongoing behavior. The study of visual attention is relevant to any situation in which actions are based on visual information from the environment. For instance, driving safety critically depends on people's ability to detect and monitor stop signs, traffic lights, and other cars. Efficient and reliable attentional selection is critical because these various cues appear amidst a cluttered mosaic of other features, objects, and events. Complexity and information overload characterize almost every visual environment, including, but not limited to such critical examples as airplane cockpits or nuclear power plant operation rooms.

To cope with this potential overload, the brain is equipped with a variety of attentional mechanisms. These serve two critical roles. **First, attention can be used to select behaviorally relevant information and/or to ignore the irrelevant or interfering information.** In other words, you are only aware of attended visual events. Second, attention can modulate or enhance this selected information according to the state and goals of the perceiver. With attention, the perceivers are more than passive receivers of information. They become active seekers and processors of information, able to interact intelligently with their environment.

The study of attention can be organized around any one of a variety of themes. In this chapter, we will concentrate on mechanisms and consequences of selection and attentional deployment across space and over time. Our review on spatial and temporal attention will consider theoretical, behavioral, and neurophysiological work. Our survey of the consequences of selection includes the effects of attention on perceptual performance, neurophysiological activity, memory, and visual awareness.

SELECTION

Given that perceptual systems cannot process all of the available information, how do such systems go about selecting a subset of the input? At the most basic level, a distinction can be made between active and passive selection. A sponge, thrown into a pool of water, is a passive selector. It

cannot soak up all the water, it will soak up some water, and selection will be based on no principle other than proximity. The front end of a sensory system acts as a type of passive selector, admitting some stimuli and not others. Thus, the eye admits as “light” only a narrow segment of the EM spectrum. Further, essentially passive, selection continues beyond the receptors. For instance, high resolution information about the retinal image is preserved only at the center of gaze. But even with these acts of passive selection, the visual system is still faced with far too much information (Broadbent, 1958). Our topic truly begins with the system’s active efforts to select.

Active selection might occur early or late in processing. Four decades ago, this was presented as a dichotomous choice. Broadbent (1958) advocated filtering of irrelevant sensory information based on physical attributes such as location. A strong version of this *early-selection* theory posits that unattended, filtered information is not processed beyond its initial physical attributes. The alternative, *late-selection* view held that selection occurs only after categorization and semantic analysis of all input has occurred (Deutsch & Deutsch, 1963; Duncan, 1980). Intermediate views include *attenuation theory* which proposes that rejected information is attenuated rather than completely filtered or completely identified (Treisman, 1960). Pashler’s (1998) review of the extensive literature to date suggests that unattended information is not completely filtered, but it is not processed to the same degree as attended information either.

Indeed, it is probably time to move away from this debate. Our review will reveal that attention is not a singular thing with a single locus, early or late. Rather, it is a multifaceted term referring to a number of different acts and loci of selection.

Spatial attention: Visual selection and deployment over space

The attentional spotlight and spatial cueing

Active attentional selection occurs over space and time. Spatial selection studies typically have subjects focus attention on a subset of the spatial array, allowing for selective report of information at the focus of attention (Averbach & Coriell, 1961; Eriksen & Hoffman, 1973; Sperling, 1960). The spotlight has been a favorite metaphor for spatial attention because it captures

some of the introspective phenomenology of attention - the feeling that attention can be deployed, like a beam of mental light, to reveal what was hidden in the world (One wonders if this feeling was the starting point for ancient extramission theories of vision in which vision was thought to require visual rays emitted from the eyes (Winer & Cottrell, 1996)).

Cueing experiments have been an important tool for understanding spatial attention as a spotlight. In a cueing paradigm, subjects are required to respond as quickly as possible to the onset of a light or other simple visual stimulus. This target stimulus is preceded by a “cue” whose function is to draw attention to the occurrence of a target in space (See Figure 1). Cues come in various forms, e.g. the brightening of an outline object (Posner & Cohen, 1984), the onset of some simple stimulus (Averbach & Coriell, 1961; Eriksen & Hoffman, 1973; Posner, Snyder, & Davidson, 1980), or a symbol, like an arrow, indicating where attention should be deployed (Jonides, 1981; Posner & Cohen, 1984). Although the mechanisms are debated, as a general rule, cues facilitate detection of and response to stimuli presented at the cued location (Cheal & Gregory, 1997; Luck et al., 1996; Shiu & Pashler, 1994; see Yeshurun & Carrasco, 1998, for an interesting exception in foveal texture segregation). Thus, Posner described attention as a “*spotlight* that enhances the efficiency of the detection of events within its beam” (Posner, 1980, p. 172).

Figure 1 near here

Attentional Shifts, Splits, and Resolution

The spotlight metaphor raises several important questions (see Cave and Bichot, 1999, for more complete review and discussion).

Question 1: When attention is deployed from one location to another, do such attentional shifts occur in a digital, instantaneous fashion, magically appearing in a new location to be attended? Or does attention move from one location to another in an analog fashion, illuminating intermediate locations as it travels across visual space? It appears that the focus of attention can move instantaneously from one location to the other without a cost for the amount of distance traveled

(Krose & Julesz, 1989; Kwak, Dagenbach, & Egeth, 1991; Remington & Pierce, 1984; Sagi & Julesz, 1985; Sperling & Weichselgartner, 1995). However, it is unclear whether attention has an effect on intermediate loci as it moves from point A to point B. The evidence remains inconclusive with Shulman, Remington, and McLean (1979) and Tsal (1983) arguing in the affirmative and Yantis (1988) and Eriksen and Murphy (1987) arguing in the negative.

Question 2: Can the spotlight of attention be split into multiple spots? That is, can attention be allocated to more than one object or one location at a time? One way to address this question is to have subjects attend to two spatially separate loci and measure attentional effects at intermediate loci. Eriksen and Yeh (1985) argued that attention could not be split into multiple beams. However, Castiello and Umiltà (1992) argued that subjects can split focal attention and maintain two attentional foci across hemifields (though see McCormick, Klein, & Johnston, 1998, for an alternative explanation). Kramer and Hahn (1995) also showed that distractors appearing between two noncontiguous locations did not affect performance for targets. Recent new evidence further supports the view that attention can be split across two locations (Bichot, Cave, and Pashler, 1999).

Indeed, another way to explore whether there are multiple attentional spotlights is to ask subjects to track the movements of multiple objects. These experiments appear to show that subjects can allocate attention to something like 4 or 5 objects moving independently amongst other independently moving distractors (Pylyshyn & Storm, 1988; Yantis, 1992). This could mean that subjects can divide the spotlight into 4-5 independently targetable beams (Pylyshyn, 1989, but see Yantis, 1992, for an account based on perceptual grouping).

Question 3: Assuming that one has allocated one's full attention to a particular location, object or event, how focused is selection at that spot? The resolution of attention is studied by measuring the effects of distracting items on target processing. Distractors typically flank the target at various spatial distances. In a widely used paradigm known as the flanker task (a.k.a., response interference task, flanker compatibility effect), the resolution of attention is revealed by examining the distance at which distractors start to impair target discrimination performance (Eriksen & Eriksen, 1974).

One general finding is that the acuity of attention is of coarser spatial resolution than visual acuity (reviewed in He, Cavanagh, and Intrilligator (1997)). Thus, items spaced more closely than the resolution of attention cannot be singled out (individuated) for further processing. This has been referred to as the *crowding effect* (Bouma, 1970; Eriksen & Eriksen, 1974; Levi, Klein, & Aitsebaomo, 1985; Miller, 1991; Townsend, Taylor, & Brown, 1971)). An example of limited attentional resolution is shown in Figure 2. The resolution of attention limits the amount of visual detail that can be brought into awareness, and He, Cavanagh, and Intrilligator (1996) demonstrated that this limitation occurs in a stage beyond early visual processing in striate cortex.

Figure 2 near here

Object-based Attention

As reviewed above, the spotlight metaphor is useful for understanding how attention is deployed across space. However, this metaphor has serious limitations. For example, attention can be allocated to regions of different size. Thus, the spotlight has a variable width of focus (*zoom lens model*), adjustable by subject's volition or by task demands (Eriksen & St. James, 1986; Eriksen & Yeh, 1985). Moving from metaphor to data, the speed of response to a stimulus is dependent on how narrowly attention is focused. The spatial distribution of attention follows a gradient with decreased effects of attention with increased eccentricity from its focus (Downing & Pinker, 1985; Eriksen & Yeh, 1985; Hoffman & Nelson, 1981; LaBerge, 1983; Shaw & Shaw, 1977). The spatial spread of attention around an attended object can also be measured with a probe technique (Cepeda et al., 1998; Kim & Cave, 1995).

Moreover, the focus of attention may be yoked to the overall load or difficulty of a task. In order for attention to remain focused on a target, the overall perceptual load of the task must be sufficiently high to ensure that no capacity remains to process other non-target events. In the absence of a sufficiently high load, attention spills over to non-target events (Kahneman & Chajczyk, 1983; Lavie, 1995; Lavie & Tsal, 1994). Lavie proposes that the early/late selection

debate in attention can be resolved by considering the overall perceptual load of a task (but see Jiang and Chun, 1998).

The spotlight metaphor runs into more serious difficulties when one considers that attention can be allocated to 3D layouts (Atchley, Anderson, & Theeuwes, 1997; Downing & Pinker, 1985) and restricted to certain depth planes defining surfaces in space (Nakayama & Silverman, 1986). Thus, selection occurs after 3D representations have been derived from the 2D input (Marrara & Moore, 1998).

Along these lines, researchers have proposed that attention selects perceptual objects rather than simply "illuminating" locations in space (see Cave and Bichot, 1999, for a review). Such "object-based" attention can be considered independent of spatial selection (Duncan, 1984; Kahneman & Henik, 1981; Kanwisher & Driver, 1992). As an example, Neisser and Becklen (1975) presented two different movie sequences that overlapped each other in space. People were throwing a ball in one movie and playing a hand game in another. Subjects were asked to attend to only one of the two overlapping movies. Throughout viewing, subjects were able to follow actions in the attended movie and make responses to specific events in it, as instructed by the experimenter. Odd events in the unattended movie were rarely noticed. Because both scenes overlapped each other, this demonstrates a selective attention that cannot be space-based. Rather selection was based on objects and events. See Simons and Chabris (1999) for a modern version and extension of this study.

Figure 3 near here

Figure 3a and 3b illustrate two other stimuli examples that argue against the spotlight metaphor. Subjects were asked to attend to one or two objects, occupying the same locations in space. Performance suffered when they had to attend to two objects rather than just one (Baylis & Driver, 1993; Duncan, 1984). Since the overlapping or abutting objects occupied the same location, the performance differences must be due to attentional allocation over object-based representations.

Object-based representations are "sophisticated" in the sense that they represent more than the raw visual input. For example, visual objects undergo substantial occlusion and fragmentation in real world raw images. Perceptual objects are created out of bits and pieces in the image by perceptual grouping and completion operations (Kanizsa, 1979; Kellman & Shipley, 1991; Nakayama, He, & Shimojo, 1995). It makes sense to direct attention to these object representations rather than the raw image features. Indeed, He and Nakayama (1992) have shown that attention cannot access raw image features, selecting the surfaces (objects) that the fragments represent instead (see Figure 3c; see also Rensink & Enns, 1995; Wolfe & Bennett, 1997). As a general rule, object-based deployment of attention is influenced by factors that determine perceptual grouping (Behrmann, Zemel, & Mozer, 1998; Driver and Baylis, 1989; Egly, Driver, & Rafal, 1994; Kramer & Jacobson, 1991; Moore, Yantis, & Vaughan, 1998; see also Berry & Klein, 1993, Kramer, Tham, & Yeh, 1991; see Cave & Bichot, 1999, for a review).

How is object-based selection achieved? A leading theory proposes that internal representations known as "object files" support our ability to attend to objects as they undergo occlusion and fragmentation or change over time (Kahneman & Treisman, 1984; Kahneman et al., 1992). Object files are episodic representations that "maintain the identity and continuity of an object perceived in a particular episode." (Kahneman & Treisman, 1984, p. 54). For instance, Kahneman et al. (1992) briefly presented two letters, each within a different outline box. Then the boxes moved to different locations, immediately after which another target letter appeared in one of the boxes. Subjects responded faster if the target was identical to the letter that had appeared earlier in the same box. This object-specific advantage was greater than when the target matched a letter that previously appeared in a different object. Phenomena like apparent motion can also be discussed in terms of object files. If the timing and spacing are correct, motion is perceived from two images flickering on and off in alternation (Anstis, 1980; Cavanagh & Mather, 1990). Object files provide the link to weave these two events into one, allowing the distinct states to be perceived as a single moving object (Chun & Cavanagh, 1997; Kanwisher & Driver, 1992).

To sum, converging evidence suggests that visual selection can operate over object-based representations. However, the broader literature indicates that location does play a critical role in visual attention (see Cave & Bichot, 1999), so understanding the spatial properties of attentional deployment and selection remains an important enterprise.

The visual search paradigm

The preceding work was performed with very simple displays. However, the visual world rarely presents only one or two potential objects worthy of attention. A somewhat more realistic situation is found in the "visual search" paradigm. In visual search tasks, subjects look for a designated target item among a number of distracting items. This simple paradigm allows researchers to examine how visual stimuli are differentiated, what stimulus properties attract attention, how attention is deployed from one object to the next, how one keeps track of what was attended, and so on. Not surprisingly, the visual search paradigm has been used extensively. Laboratory versions typically use highly artificial stimuli (colored line segments, letters, etc). Still, these tasks approximate the visual search tasks that everyone does all the time (Wolfe, 1994b), whether it involves the efficient search for salient yellow dandelion flowers on a grassy lawn or the less efficient, frustrating search for a street sign when driving through an unfamiliar neighborhood at night. A sample lab task is shown in Figure 4. Fixating on the asterisk in the center, try to notice whether there are unique visual objects in the display. You should first notice the white "X" which appears to "pop out" of the array. This is an example of an easy, efficient search. Now try to locate the black letter "T". This exemplifies a more difficult, inefficient type of search.

Figure 4 near here

In a typical lab study, subjects would perform many searches for such targets amongst a variable number of distractors. The total number of items in the display is known as the set size. The target is presented on some percentage of the trials, typically 50%. Subjects press one button if the target is present and another button if only distractors appear. Subjects are typically instructed

to respond as quickly and accurately as possible. Both reaction time (RT) and accuracy are measured. In RT tasks, the display is usually present until a response is made. In accuracy tasks, the display is usually presented very briefly, followed by an interfering visual mask.

Critical insights into the mechanisms of search and attention can be obtained by examining the efficiency of search tasks. There are several ways to quantify search efficiency. The most common method is to vary the number of items in the display (set size) and RT as a function of set size. The slope of the RT X set size functions is a measure of search efficiency. A slope of zero msec/item indicates that the target item, when present, is detected without interference from the distractor items. Steeper slopes indicate less efficient search and a greater the cost for each additional distractor. For search tasks in which acuity limitations are not an issue, slopes tend to range from 0 msec/item for the most efficient searches (e.g. a search for a red target among green distractors) to 20-30 msec item on target-present trials of inefficient searches (e.g. a search for a vowel among consonants) (See Figure 4b). Slopes for target-absent trials tend to be about twice those for target present (Chun & Wolfe, 1996; Wolfe, 1998c). Steeper slopes are found if the individual items take a long time to identify (e.g. Imagine trying to find a cluster of 16 dots among clusters of 17 dots) or if eye movements are required to resolve items.

Accuracy measures are the second common method for quantifying search performance. Efficient searches produce high levels of accuracy independent of set size even when the display is presented very briefly. For less efficient tasks accuracy declines as set size increases unless exposure time is increased to compensate (Bergen & Julesz, 1983; Palmer, 1994).

Mechanisms underlying search efficiency

What determines the efficiency of visual search? Is there a qualitative or merely a quantitative difference between efficient and inefficient search? Extensive reviews of specific search results can be found elsewhere (Wolfe, 1998b). For present purposes, a few basic principles will suffice, summarized in Table 1:

Table 1 near here

Treisman's Feature Integration Theory (Treisman, 1988; Treisman & Gelade, 1980; Treisman & Sato, 1990) was an early and influential account of differences in search efficiency. It held that efficient feature searches were performed by mechanisms capable of processing all items in parallel, while all other searches relied on mechanisms that operated in a serial, item-by-item manner. In particular, attention was required to conjoin or bind multiple features into a single object. Hence, conjunction searches were serial (Treisman & Gelade, 1980), and withdrawing attention produced errors for binding features, known as "illusory conjunctions" (Treisman & Schmidt, 1982).

Although Feature Integration Theory was an elegant framework that stimulated much work in the field, the strict dichotomy between parallel and serial search tasks was not clearly supported in the data collected subsequently (see Wolfe, 1998c). Two broad classes of models have arisen to account for the data. One class abandons the serial/parallel distinction altogether. These limited-capacity models argue that all items in a search are processed at once (e.g., Kinchla, 1974) or perhaps, in groups - e.g. (Grossberg, Mingolla, & Ross, 1994; Pashler, 1987). Differences in search efficiency arise because different types of items make different demands on a limited processing resource. See Bundesen (1990, 1994), Logan (1996), Palmer (1995) for further discussion of models of this sort.

The second class of models preserves the distinction between serial and parallel processes. Following Neisser (1967), these models hold that the preattentive stages of vision are characterized

by parallel processing of basic features and that there is a bottleneck after which processing is essentially serial. Selection of items for serial processing is under attentional control. Following Treisman, these models hold that the explicit knowledge of the relationship of features to each other (binding) requires serial processing. In these models, variation in the efficiency of search is determined by the ability of preattentive, parallel processes to guide attention toward candidate targets or away from likely distractors. (Hence “*Guided Search*”, Cave & Wolfe, 1990; Wolfe, 1994a; Wolfe et al., 1989; Wolfe & Gancarz, 1996). Treisman’s modified Feature Integration Theory has similar properties (e.g. Treisman & Sato, 1990; See also Hoffman, 1979; Tsotsos et al., 1995).

In a model like Guided Search, a simple feature search is efficient because preattentive processes can direct the first deployment of attention to the likely target item. Searches like a search for an S among mirror-Ss are inefficient because no preattentive information is available to distinguish one item from the next. Conjunction searches are of intermediate efficiency because preattentive feature guidance is available but it is not as strong as in a simple feature search.

Top-down and Bottom-up control of attention in Visual Search

In any visual task such as search, attention can be deployed to stimuli in one of two ways: endogenously or exogenously (Posner, 1980). In endogenous attention, attention is presumed to be under the overt control of the subject, (e.g., “I will attend to the left-side of the display”). This is also known as “top-down”, goal-driven attention (Yantis, 1998). Endogenous attention is voluntary, effortful, and has a slow (sustained) time course. On the other hand, attention can be driven *exogenously*, by an external stimulus event that automatically draws attention to a particular location. This has been referred to as “bottom-up”, stimulus-driven attention. The flashing lights of a highway patrol vehicle draw attention exogenously. Exogenous attention draws attention automatically and has a rapid, transient time course (Cheal & Lyon, 1991; Jonides, 1981; Nakayama & Mackeben, 1989; Posner et al., 1980; Weichselgartner & Sperling, 1987).

There are a wide variety of bottom-up, exogenous visual attributes that draw attention. For instance, in visual search, spatial cues and abrupt visual onsets (sudden luminance changes) draw

attention. Hence, flat search slopes are obtained for abrupt-onset targets (Yantis & Jonides, 1984). Abrupt onsets may capture attention even when the cues were not informative of target location and even when subjects were instructed to ignore them (Jonides, 1981; Remington, Johnston, & Yantis, 1992).

Other salient visual features such as feature singletons (e.g., a red target amongst green distractors or a vertical target amongst horizontal items) can effectively draw attention but are under greater volitional control. That is, these features are easier to ignore than spatial cues or abrupt onsets (Jonides & Yantis, 1988). Specifically, the ability to ignore a singleton depends on the nature of the search task. When the task requires searching for a target defined by a singleton in one dimension (e.g., orientation), then singletons in other dimensions such (e.g. color) automatically draw attention even when this is detrimental to performance (Pashler, 1988; Theeuwes, 1991a; 1992). If, however, subjects are looking for a specific feature (e.g. vertical) then an irrelevant feature in another dimension does not capture attention.

In summary, bottom-up and top-down attentional control systems interact with each other. Hence, stimulus-driven attentional control depends on whether subjects are in singleton-detection mode (Bacon & Egeth, 1994) or have adopted the appropriate attentional control settings or perceptual set (Folk, Remington, & Johnston, 1992). More generally, nearly every visual search model proposes that the guidance of attention is determined by interactions between the bottom-up input and top-down perceptual set (Duncan & Humphreys, 1989; Grossberg et al., 1994; Muller, Humphreys, & Donnelly, 1994; Treisman & Sato, 1990; Wolfe, 1994a).

Inhibitory mechanisms of attention

Our review above discussed attentional selection, but how is selection achieved? Selection may be performed by excitation and enhancement of behaviorally relevant information, or by inhibition and suppression of irrelevant information. Of course both mechanisms may operate in concert, but the field is still debating how this occurs (Milliken & Tipper, 1998). Nevertheless, inhibitory mechanisms in selection can play a crucial role in reducing ambiguity (Luck et al.,

1997b), they can protect central, capacity-limited mechanisms from interference (Dagenbach & Carr, 1994; Milliken & Tipper, 1998), and they can prioritize selection for new objects (Watson & Humphreys, 1997). Here, we review three extensively studied inhibitory phenomena: invalid cueing, negative priming, and inhibition of return.

Invalid cueing

Inhibition effects can be measured as a decrement in performance relative to a neutral baseline. When a cue stimulus appearing before the target is informative, it will facilitate target performance compared to a baseline in which the prime is neutral. What if the prime is an invalid cue to the target? This should generate a negative expectation that slows down performance to the target. Inhibitory effects have been demonstrated using tasks such as letter matching (Posner & Snyder, 1975) and lexical decision (Neely, 1977) reviewed in Milliken & Tipper, 1998). Of particular interest is the time course of inhibition. Neely varied the stimulus onset asynchrony (SOA) between prime and target. He found that inhibitory effects are only observed for targets appearing beyond 400 ms after the prime presentation.

Negative Priming

Evidence for item-specific inhibitory effects have been studied extensively using a paradigm known as *negative priming*, a term coined by Tipper (1985). In negative priming, subjects are slower at responding to targets (probes) that were distractors (referred to as primes) on the previous trials (usually the trial immediately before) (Dalrymple-Alford & Budayr, 1966; Neill, 1977; Tipper, 1985). This suggests that the representation of the ignored primes were actively suppressed, and that this inhibition was carried over to the following trial. Remarkably, pictures can prime words and vice versa, suggesting that negative priming operates at an abstract, semantic level (Tipper & Driver, 1988). Furthermore, single trial exposures to novel figures can produce negative priming, suggesting that implicit representations of unknown shapes can be formed and retained from ignored and unremembered events (DeSchepper & Treisman, 1996).

Inhibition of Return

The inhibition of return (IOR) paradigm is similar to that used in cued orienting (reviewed earlier; Posner et al., 1980). In Posner and Cohen's (1984) demonstration of this paradigm, the target was most likely to appear in the middle of three outline boxes arranged along the horizontal axis (See Figure 1). Peripheral cues occasionally appeared, either validly or invalidly cueing the onset of a target in the peripheral boxes. The SOA between cue and target was varied and the usual facilitatory effects of cueing were obtained for targets appearing within 300 ms of the cue in the same spatial location. Interestingly, when the SOA exceeded 300 ms, target detection performance was slowed, suggesting a transient bias *against* returning attention to visited locations. Inhibition of return makes ecological sense. For instance, in serial search tasks for a target amongst distractors, IOR would prevent an observer from continually rechecking the same location (Klein, 1988; Klein & McInnes, 1999). Note that other lines of evidence argue against IOR in search. Rather, covert attention may simply be deployed at random to relevant items without regard to the previous history of search (Horowitz & Wolfe, 1998). Further research is needed to resolve these two opposing views.

Temporal Attention: Visual Selection Over Time

Inhibition of return provides a good segue from spatial to temporal aspects of attention. The visual input changes from moment to moment. Perceivers need to extract behaviorally relevant information from this flux. How quickly can visual information be taken in? If there are limitations, what visual processes are affected? To address these questions, we must consider how attention is allocated in time as well as space.

A standard technique for studying temporal attention is to present rapidly presented sequences of visual items at rates of up to 20 items per second (rapid serial visual presentation, RSVP). This taxes processing and selection mechanisms to the limit, allowing researchers to assess the rate at which visual information can be extracted from a stream of changing input.

Single target search

Perhaps the most interesting property of temporal selection is that people are very good at it. For example, Sperling and his colleagues (1971) presented RSVP sequences of letter arrays. Each frame contained 9 or 16 letters each and were presented at rapid rates of 40 to 50 ms. The task was to detect a single target numeral embedded in one of the frames (also see Eriksen & Spencer, 1969; Lawrence, 1971). Accuracy performance in this sequential search task provides an estimate of the "scanning" rate, allowing Sperling to demonstrate that practiced observers can scan through up to 125 letters per second. This is higher than even the most liberal estimates of scanning rates from the spatial search literature (Horowitz and Wolfe, 1998). In another impressive demonstration of sequential search, Potter (1975) presented subjects with RSVP sequences of natural scene stimuli and asked them to search for target photos defined by verbal cues such as "wedding" or "picnic." Subjects performed well in such tasks at rates of up to 8 pictures per second, suggesting that the "gist" of successive scenes could be extracted with only 125 msec per scene. Thus RSVP tasks show that it is possible to extract meaning from visual stimuli at rates much faster than the speed with which these meanings can be stored in any but the most fleeting of memories (Chun & Potter, 1995; Potter, 1993; see also Coltheart, 1999).

The attentional blink and attentional dwell time

Although it is possible to report on the presence of a single target, presented in one brief moment in time, it does not follow that it is possible to report on a target in every brief moment in time. Intuition is clear on this point. While you can imagine monitoring a stream of letters for a target item at, say 15 Hz, you are unlikely to believe that you could echo all of the letters presented at that rate. This limitation can be assessed by presenting a second target (which we will refer to as T2) at various intervals after the first target (T1). This is known as the attentional blink paradigm described below.

Figure 5 near here

Broadbent and Broadbent (1987) asked subjects to report two targets presented amongst an RSVP stream of distractors. The temporal lag between T1 and T2 was varied systematically across a range of intervals from 80 to 320 msec. Thus, the time course of interference could be examined as a function of time (See Figure 5A). This paradigm revealed a striking, robust impairment for detecting T2 if it appeared within half a second of T1 (See also Weichselgartner and Sperling (1987) and Figure 5B). This inability to report T2 for an extended time after T1 has come to be known as the attentional blink (AB) - a term coined by Raymond, Shapiro and Arnell (1992). Raymond et al. first proved that AB was an attentional effect rather than a sensory masking effect. This was illustrated by comparing dual-task performance with a control condition using identical stimulus sequences in which subjects were asked to ignore a differently colored target (T1) and just report a probe (T2). No impairment was obtained, suggesting that AB reflected the attentional demands of attending to and identifying T1. Raymond et al. also demonstrated that AB is dependent on the presence of a distractor or mask in the position immediately after T1 (called the +1 position). When this item was removed and replaced with a blank interval, AB disappeared. Although AB is not a masking effect itself, perceptual and/or conceptual interference with T1 is important (Chun & Potter, 1995; Grandison, Ghirardelli, & Egeth, 1997; Moore et al., 1996; Seiffert & Di Lollo, 1997). Interestingly, when T2 appears in the +1 position, it may be processed together with T1 (Chun & Potter, 1995; Raymond et al.), allowing it to be reported at relatively high accuracy (known as Lag-1 sparing, see Figure 5B).

Thus, the AB reveals limitations in the rate at which visual stimuli can be processed, and it can be used to study fundamental questions of early/late selection and visual awareness (to be discussed in a later section). The reasoning behind the AB paradigm is simple. If a stage of processing is limited in capacity, then this will take a certain amount of time to complete (Duncan, 1980; Eriksen & Spencer, 1969; Hoffman, 1978; Pashler, 1984; Shiffrin & Gardner, 1972; Welford, 1952). This impairs or delays the system's ability to process a second stimulus presented during this busy interval, causing the attentional blink (Chun & Potter, 1995; Jolicoeur, 1999; Shapiro et al., 1994, 1997).

Duncan, Ward, and Shapiro (1994; Ward et al., 1996) used AB to reveal the speed of attentional deployment, dubbed attentional "dwell time". Duncan et al. demonstrated that even distractor events to be ignored could produce significant AB. Duncan et al. considered this as evidence in favor of a long, 200-500 msec dwell time. On the other hand, visual search data can be interpreted as supporting serial search at a rate of one every 20-50 msec (Kwak et al., 1991). Even the AB literature supports two different dwell time estimates. Attention to T1 causes a blink of several hundred msec. At the same time, until T1 appears, the categorical status of items can be processed at RSVP rates of 8-12 Hz (Broadbent & Broadbent, 1987; Chun & Potter, 1995; Lawrence, 1971; Potter, 1975, 1993; Shapiro, Driver, Ward, & Sorensen, 1997).

Perhaps these are estimates of two related but not identical aspects of attentional processing. Let us expand the standard metaphor of an attentional bottleneck into an attentional conveyor belt (See Figure 5C). Preattentively processed items are loaded onto the conveyer belt for further processing. One timing parameter describes how fast some mental demon can load items onto the conveyor belt. We can imagine the preattentive item moving along as if in some mental assembly line - its parts being bound into a recognizable whole. At the other end of the conveyor, another mental demon decides if the now-assembled item is worth keeping. If it is, that is, if it is a target, the demon must do something in order to save that item from oblivion, corresponding to Stage 2 of the Chun and Potter (1995) model. That "something" takes time, too. Suppose the loading demon puts item on the conveyor every 20-50 msec while the second demon can only properly handle one target item every 300 msec. This would give us both dwell times. In standard visual search, efficiency is governed by the loading demon. The discovery of a single target by the second demon ends the trial. In an AB task, the second demon grabs T1 and cannot go back to capture T2 until 300 msec or so have past. The intervening items are no longer physically present when the second demon returns. If one of them was T2, then T2 is 'blinked'.

This account has a number of useful properties. Note that this is a "serial" conveyor belt but multiple items are being processed on it at the same time. This suggests a possible compromise solution to the serial/parallel arguments in visual search. Note, too, that we could call the first demon

"early selection" and the second "late selection" and offer a compromise solution to that debate as well. Returning to the dwell time debate, visual search estimates for short dwell times may be based on loading demon operations (Treisman & Gelade, 1980; Wolfe et al., 1989), while Duncan et al.'s proposal for long dwell times may correctly refer to the second demon.

Repetition Blindness

In addition to the attentional blink, there are other factors that influence the subject's ability to report targets in RSVP. The AB is typically measured for two visual events that are different from each other, so what would happen if the two targets were identical? One might expect repetition shouldn't matter at all, or it may help performance through perceptual priming (Tulving & Schacter, 1990). The surprising finding is that performance is worse for repeated targets, a phenomenon known as *repetition blindness* (RB), first reported by Kanwisher (1987). As an example, some subjects expressed outrage at sentences like, "Unless they are hot enough, hotdogs don't taste very good" because they failed to perceive the second repetition of the word "hot" (Kanwisher & Potter, 1990). RB is the result of a failure to create separate object files for the second of two repeated items (Kanwisher, 1987). As noted in an earlier section, object files are used to represent perceptual events (Kahneman & Treisman, 1984). In RB, the visual system fails to treat the second repetition as a different object from the first. Thus no object file is created for the second event, and it is omitted from explicit report. Kanwisher's token individuation hypothesis is supported by a variety of studies (Bavelier, 1994; Chun, 1997; Chun & Cavanagh, 1997; Hochhaus & Johnston, 1996).

NEURAL MECHANISMS OF ATTENTION

Thus far, this chapter has approached attention from a cognitive / experimental psychology standpoint. In this section, we examine how attentional behavior is implemented by the brain. A wide variety of methodologies exist to study the "attentive brain" (Parasuraman, 1998). Each technique has pros and cons, complementing each other as "converging operations" (Garner, Hake,

& Eriksen, 1956). Here we survey a variety of neurophysiological methodologies and summarize critical findings as they relate to the cognitive descriptions of the attentional mechanisms described in the previous section.

Single-cell Physiological Method

The single-cell recording method measures activity from individual neurons presumed to be participating in a perceptual or cognitive operation. An obvious advantage is that this methodology provides the highest spatial (individual neuron) and temporal (spike potentials) resolution of all the methods used to study attentional function in the brain. Current limitations include the invasiveness of cellular recording and the fact that only a few neurons can be examined at any given time. The latter feature makes it difficult to examine how multiple brain areas interact with each other to perform a particular task (c.f., note that researchers are developing methods to simultaneously record from multiple neurons and multiple cortical areas). Nevertheless, single-cell neurophysiology has led to several important insights.

What parts of the visual system show attentional modulation of activity (see Maunsell, 1995, for a review)? In some sense, this is the neuronal equivalent of the early/late selection debate, and neurophysiological evidence support the view that attention operates at multiple stages in the visual system. An early selection account is supported by studies that demonstrate attentional modulation in V1 (Motter, 1993; see Posner & Gilbert, 1999, for a review). Modulatory activity is even more prominent in extrastriate regions such as V4 (Haenny & Schiller, 1988; Luck et al., 1997; Moran & Desimone, 1985; Motter, 1993, 1994; see Motter (1998) for a review), as well as specialized cortical areas such as MT, where motion processing is enhanced by attention (Treue & Maunsell, 1996). Finally, attentional deployment is reflected in frontal eye field (FEF) neural activity that differs for targets and distractors (Schall and Hanes, 1993). Thus, like the behavioral data, the physiological data suggest that attentional effects occur at multiple loci.

A critical function of attention is to enhance behaviorally relevant information occupying a location in space while filtering out irrelevant information appearing at different spatial locations.

What is the neural correlate of this spatial filter or attentional spotlight? In a now-classic study, Moran and Desimone (1985) identified one type of filtering process in V4 neuronal responses (See Figure 6). They presented two stimuli within the receptive field of a V4 neuron being recorded. One of the stimuli was "effective" for producing the cell's response, and the other "ineffective" stimulus wasn't. Monkeys were required to hold fixation on the same spot in all conditions, only their attentional focus varied. The main finding was that when monkeys attended to the location occupied by the ineffective stimulus, the cell failed to respond to the presence of the effective stimulus. In other words, attention modulated the cell's response such that the presence of a competing (effective) stimulus was filtered out. This can be characterized as an operation that resolves ambiguity or competition from neighboring items (Luck et al., 1997a, 1997b; Motter, 1993).

Figure 6 near here

These results can be extended to spatial search paradigms. Chelazzi, Miller, Duncan, and Desimone (1993) employed a match-to-sample task in which monkeys were first shown a single target stimulus, then asked to make an eye movement to the same target item in a subsequent array which also contained a distractor item. Neural activity to the distractor stimulus was initially present, but subsequently suppressed at around 200 ms after the onset of the search array, illustrating a neural correlate of competitive selection. As noted earlier, behavioral data show that attentional selection can be restricted to a set of items that contain a target attribute (e.g., search can be restricted to red items if subjects know that the target is red (Egeth et al., 1984; Wolfe et al., 1989)). A neural correlate for such "Guided Search" has been identified by Motter (1994) for area V4 and by Bichot and Schall (1999) for the FEF. In Motter's study, monkeys were required to select an elongated bar target on the basis of color and then report its orientation. V4 neurons whose receptive fields included stimuli of the target color maintained their activity while V4 neurons whose receptive fields contained items of different colors had depressed activity.

Bichot and Schall (1999) demonstrated analogous effects of visual similarity in the FEF. The FEF plays an important role in visual selection and saccade generation (see Schall and Bichot, 1998, and Schall and Thompson, 1999, for reviews). A fundamental finding is that the activity of FEF neurons evolve to discriminate targets from distractors in search tasks, prior to initiating a saccade to the target (Schall and Hanes, 1993). Interestingly, the activity of FEF neurons was stronger to distractors that shared visual features to the target, suggesting a neural correlate of Guided Search. Bichot and Schall also discovered effects of perceptual history, as FEF activity was stronger to distractors that were targets on previous training sessions. This finding reveals a neurophysiological correlate of long-term priming, important for understanding how visual processing is modulated by perceptual experience.

Event-related Potentials

The massed electrical activity of neurons can be measured through scalp electrodes. This non-invasive method can be used to assess neural activity in humans as well as animals. When these electrical events are correlated in time with sensory, cognitive, or motor processing, they are called "event-related potentials" (ERPs). ERP waveforms consist of a set of positive and negative voltage deflections, known as components. The sequence of ERP components that follows a stimulus event is thought to reflect the sequence of neural processes that is triggered by the onset of the stimulus. The amplitude and latency of each component is used to measure the magnitude and timing of a given process. In addition to being non-invasive, ERP measures provide high temporal precision. But, anatomical precision is limited for a number of reasons (see Luck, 1998). This can be overcome by combining ERP measures with other imaging techniques (Heinze et al., 1994), described in the next section.

The millisecond temporal resolution makes ERPs very useful for the study of attention. Consider the classic debate between early versus late selection (Broadbent, 1958; Deutsch & Deutsch, 1963). The locus-of-selection issue cannot be definitively resolved based on behavioral data because these reflect the sum of both early and late responses (Luck & Girelli, 1998). The

temporal resolution of ERP, however, allows researchers to directly measure the impact of attentional processes at early stages of information processing. Evidence for early selection was first provided by Hillyard and colleagues in the auditory modality (Hillyard et al., 1973). Using a dichotic listening paradigm in which subjects attended to information from one ear versus the other, Hillyard et al. demonstrated that early sensory ERP components beginning within 100 ms post-stimulus were enhanced for attended stimuli. Importantly, these results generalize to visual selection in which subjects were required to attend to one of two spatial locations. Early components of the ERP waveform (P1 and N1) were typically larger for stimuli presented at attended locations versus unattended locations (reviewed in Mangun, Hillyard, & Luck, 1993). These effects also begin within 100 ms of stimulus onset, providing clear evidence for attentional modulation at early stages of visual information processing.

These early selection mechanisms also generalize to visual search tasks using multi-element displays (Luck, Fan, & Hillyard, 1993). A particularly interesting ERP component, the N2pc, reflects the focusing of attention onto a potential target item in order to suppress competing information from the surrounding distractor items (Luck & Hillyard, 1994). In fact, the N2pc may serve as a marker of where attention is focused and how it shifts across space. Recent evidence shows that this N2pc component rapidly shifts from one item to the next during visual search (Woodman & Luck, 1999). This finding lends provocative support to theories that propose attention moves in a serial manner between individual items rather than being evenly distributed across items in the visual field. The debate between serial and parallel models is a classic one that cannot be resolved by behavioral data or computational analyses (Wolfe, 1998; Townsend & Ashby, 1983). However, the Woodman and Luck study indicates how neurophysiological data can provide novel insights towards resolving such classic questions.

ERP methodology has been successfully applied to understanding higher-level attentional processes also. Recall that in the attentional blink (AB) a target in RSVP can "blink" a subsequent target from awareness due to attentional limitations. Are such unreportable items semantically identified within the brain somewhere? Luck, Vogel, and Shapiro (1996; Vogel et al., 1998) used

ERP measures to examine this question. They looked at the N400 component which is sensitive to semantic mismatch. For example, consider the following sentence, "He went home for dinner and ate a worm." The last word "worm" does not fit the context of the sentence and will trigger an N400. Thus, the presence of N400 would indicate that a word has been processed up to its semantic meaning. If blinked items are suppressed early and not recognized, then little or no N400 should be observed for blinked targets. If AB is produced by capacity limitations after initial identification has occurred, then the N400 should be preserved even for blinked words which could not be reported. Luck et al. demonstrated that the N400 was preserved, providing direct evidence of semantic processing without awareness (or, at least, without awareness that lasts more than a few hundred milliseconds). Thus, electrophysiological techniques such as ERP can provide direct indices of perceptual and cognitive processing, not readily obtainable through behavioral measures alone.

Functional imaging: Positron Emission Tomography (PET) and functional Magnetic Resonance Imaging (fMRI)

Positron Emission Tomography (PET) and functional Magnetic Resonance Imaging (fMRI) methodologies allow non-invasive imaging of brain activity during performance of sensory, cognitive, and motor behavior. PET measures cerebral blood flow (rCBF) while fMRI measures deoxygenation signals in the brain (see Corbetta, 1998; Haxby, Courtney, & Clark, 1998). Both imaging techniques rely on the assumption that these metabolic measures are correlated with neuronal activity within the brain. Advantages of imaging techniques include their non-invasive nature and the ability to measure brain activity across the entire brain with relatively high spatial resolution compared to ERP. The temporal resolution is somewhat limited by the slowness of blood flow changes. Nevertheless, the spatial resolution and global imaging scale has allowed these two imaging techniques to provide critical insights into the neural networks that mediate attentional processing in the human brain.

One seminal contribution of functional imaging was to demonstrate that attention modulates the activity of extrastriate cortical areas specialized for feature dimensions such as color or motion. Importantly, this modulation depended on which feature was used as a template for selection (Corbetta et al., 1991). For instance, if attention was focused on the speed of the motion of the objects, increased rCBF activity was obtained in motion processing regions (presumed analogues of macaque areas MT/MST) (Corbetta et al., 1991; O'Craven et al., 1997). Attention to color activated a dorsal region in lateral occipital cortex and a region in the collateral sulcus between the fusiform and lingual gyri (Clark et al., 1997; Corbetta et al., 1991). Wojciulik, Kanwisher, & Driver (1998) showed that attentional modulation also occurs for more complex stimuli such as faces (Face stimuli are selectively processed in an extrastriate area called the fusiform gyrus (Haxby et al., 1994; Kanwisher, McDermott, & Chun, 1997; Sergent, Ohta, & MacDonald, 1992)). In fact, attention modulates activity in specialized extrastriate areas even competing objects of different types occupy the same location in space, providing evidence for object-based selection (O'Craven, Downing, & Kanwisher, 1999).

Attention also modulates visual processing in early visual areas such as V1 (Brefczynski & DeYoe, 1999; Gandhi, Heeger, & Boynton, 1999; Somers et al., 1999; Tootell et al., 1998). Most important, attentional modulation was demonstrated to occur in a retinotopic manner in visual cortex, revealing the physiological correlate of the spatial spotlight of attention. In other words, attending to specific locations enhanced cortical activity in a manner that corresponded closely with the cortical representations of the visual stimuli presented in isolation (See Figure 7). Note that attentional modulation effects were larger at extrastriate retinotopic areas in most of these studies, supporting psychophysical evidence that the resolution of attentional selection is limited at a processing stage beyond V1 (He et al., 1996).

Figure 7 near here

In addition to revealing modulation effects, functional imaging has illuminated our understanding of mechanisms that drive attention to different spatial locations (Corbetta et al., 1993;

Nobre et al., 1997). Corbetta et al. demonstrated that the superior parietal cortex may play an important role in shifting attention around locations in space. This would be particularly important for visual search tasks which require attention to move from one object to the other (according to some models). Consistent with this, significant superior parietal activation was obtained when subjects searched for conjunction targets defined by color and motion (Corbetta et al., 1995). Moreover, this activity was higher during search for conjunctions than for search for targets defined by individual color or motion features. This corroborates behavioral and theoretical work proposing that conjunction tasks require a serial spatial scanning mechanism (Treisman & Gelade, 1980; Wolfe et al., 1989; Yantis & Johnson, 1990).

SEEING: ATTENTION, MEMORY, AND VISUAL AWARENESS

The research reviewed so far described behavioral and neural mechanisms of attention, but how does this explain everyday visual experience? Namely, does attention play a central role in how we consciously perceive the world? Put more simply, can we see without attention? Does attention affect the appearance of things?

Answering this requires a definition of "seeing." One way to frame this problem is to posit two levels of seeing (Kihlstrom, Barnhardt, & Tataryn, 1992; Mack & Rock, 1998). *Implicit seeing* occurs when visual stimuli have been identified, as measured by their impact on performance, but can't be explicitly reported by the subject. Masked priming paradigms provide a good example of implicit seeing. Masked prime stimuli that are too brief to reach awareness, nevertheless facilitate performance for a subsequent target (Marcel, 1983). *Explicit seeing* occurs when subjects can explicitly report what visual event had occurred. This does not necessarily require perfect identification or description, but it should allow one visual event to be distinguished from another in a manner that can somehow be verbalized or articulated. Implicit and explicit seeing are not necessarily dichotomous and may represent different ends of a continuum of visual awareness.

This implicit/explicit seeing distinction appears tractable when the criterion is operationally defined as the overt reportability of a visual event. However, problems arise when we try to apply

such terms to the phenomenal awareness of visual events, and the latter usage is more intrinsically interesting than the former. For instance, imagine you're sitting at a café looking out at a busy, colorful street scene. You clearly "perceive" the scene in a conscious manner. What do you "explicitly see" in such a situation? Recent work described below makes it clear that the phenomenal answer is *not* clear. Nevertheless, generalizations can be offered. Although objects outside the focus of attention (and awareness) can influence behavior, attention critically mediates the ability to experience, learn, and/or report something about visual events.

Attention and explicit seeing

Several researchers have argued that attention is needed for conscious perception (Nakayama & Joseph, 1998; Mack & Rock, 1998; Treisman & Kanwisher, 1998). Recall that subjects could only remember details from the attended movie in Neisser and Becklen's (1975) study (see "Object-based Attention" section). Also consider studies by Rock and Gutman (1981) and Goldstein and Fink (1981) who presented subjects with a series of drawings which consisted of two overlapping line shapes. Subjects were instructed to selectively attend to one of the two figures, inducing a state of *inattention* for the unattended figure. The question is whether the unattended forms are perceived. Subjects consistently failed to recognize the form of unattended items even when they were queried immediately after presentation. Rock and Gutman suggested that the form of unattended items were not perceived, hence "attention is necessary for form perception" (p. 275).

A similar conclusion can be drawn from a related finding known as *inattention blindness* (Mack & Rock, 1998; Mack et al., 1992; Rock et al., 1992). This paradigm is simple and does not require the subject to actively ignore or inhibit the unattended event. In Rock et al.'s study, subjects performed several trials of a length judgment task for two lines bisecting each other in the form of a cross at the center of the computer screen. On one of the trials, an additional test figure was presented along with the cross figure, and subjects were queried of their awareness of this test stimulus. The remarkable finding is that a large proportion of subjects did not even notice the test

figure, suggesting inattention blindness. Mack and Rock (1998) concluded that attention is needed for conscious experience.

Much recent work in a new paradigm known as *change blindness* brings these lab results into the real world. People think that they simultaneously recognize multiple items. However, this appears to be an illusion. They are greatly impaired in their ability to notice changes in any but the currently attended object unless the change alters the 'gist' or meaning of a scene (Simons & Levin, 1997). Awareness of the identity and attributes of visual objects can be probed by asking subjects to detect changes made across film cuts (Levin & Simons, 1997), between alternating images (Rensink, O'Regan, & Clark, 1997), or across eye movements (McConkie & Currie, 1996). Subjects perform miserably at detecting changes, even when this involves changing the identity of a real person in the real world asking for your directions to the local library (Simons & Levin, 1997)! Thus, while a great amount of detailed information is available in natural scenes, the amount of information that is consciously retained from one view to the next, or from one moment to the next, appears to be extremely low. Understanding these limitations is critical for understanding how visual information is integrated across views and eye movements (Henderson, 1992; Irwin, 1992).

The *attentional blink* paradigm described earlier is also pertinent to the issue of perceptual awareness. Recall that subjects typically fail to report a target appearing within about 500 ms following a correctly identified target. Joseph, Chun, and Nakayama (1997) demonstrated that even a "preattentive" task such as orientation pop-out target detection was impaired during AB. Thus, withdrawing attention makes it impossible to complete even the simplest and most efficient searches (see also Braun & Julesz, 1998; Braun & Sagi, 1990; Braun, 1998 ; Joseph, Chun, & Nakayama, 1998).

Perhaps many of these findings can be understood by noting that attention is necessary to prevent visual events from being overwritten by subsequent stimuli. Enns and Di Lollo (1997) demonstrated that under conditions when attention is not focused on an item, that item is subject to substitution or erasure by other, subsequent stimuli even when those other stimuli do not overlap the contours of the 'erased' visual target. They termed this *attentional masking*. One could argue

that change blindness is caused by the erasure of one scene by the next, and the same logic can be applied to unreportable targets appearing during the attentional blink (Chun & Potter, 1995; Giesbrecht & Di Lollo, 1999). Hence, attentional selection is required if the perceptual consequences of stimuli are to persist long enough to be reported.

Attention and implicit seeing

The studies reviewed above demonstrate that attention is very important for consciously perceiving and reporting on visual events. However, it is critical to remember that unattended stimuli do not simply disappear into oblivion, rather they may be implicitly registered (Treisman & Kanwisher, 1998). Using the overlapping line shapes similar to those in the Rock and Gutman (1981), De Schepper and Treisman (1996) have shown that the unattended shapes have an impact on performance in subsequent trials (negative priming, see "Inhibitory mechanisms of attention" section). In the inattentional blindness paradigm, Mack has shown that people are "less" blind to stimuli such as one's name or faces, suggesting that some meaning is extracted from those apparently unattended objects. Moore and Egeth (1997) employed an interesting variant of the inattentional blindness task to demonstrate that Gestalt grouping occurs without attention.

As reviewed earlier, unreportable items in the attentional blink are nevertheless identified (Luck et al., 1996; Shapiro et al., 1997). Likewise, it is plausible that "unperceived" events in change blindness tasks are registered unconsciously to influence scene interpretation (Simons, 2000). Similarly in the attentional blink phenomenon, unreportable visual targets that do not reach awareness are nevertheless identified (implicitly seen). In sum, attention limits what reaches conscious awareness and what can be reported through explicit seeing, but sophisticated implicit perception may proceed for unattended, unreportable visual stimuli.

Attention and Memory

Attention is also important for encoding information into visual working memory. Working memory for visual objects is limited in capacity, but interestingly the unit of capacity and selection is an integrated object rather than a collection of individual features comprising the object. Luck

and Vogel (1997) showed that objects comprised of four conjoined features can be stored as well as the same number of objects comprised of one feature, even though the number of individual features is much larger for the integrated stimuli. Attentional encoding of these items into visual working memory makes all of their features available to awareness and report (Allport, 1971; Duncan, 1980; Luck & Vogel, 1997).

Not only does attention influence what you experience and remember, experience and memory influence what you attend to (see Chun and Nakayama, 2000, for a review). Memory traces of past perceptual interactions bias how attention should be allocated to the visual world (Chun & Jiang, 1998; Desimone & Duncan, 1995). For instance, there is a bias to orient towards novel items (Johnston et al., 1990). “Familiar” items can be examined more efficiently (Wang, Cavanagh, & Green, 1994). Furthermore, subjects attend more quickly to items which share the same color, spatial frequency, or location to targets attended to on preceding trials, a finding described as *priming of pop-out* (Maljkovic & Nakayama, 1994, 1996, 1998). In addition, the invariant context of a target experienced over time can guide attention and facilitate search (*contextual cueing*, Chun & Jiang, 1998, 1999).

Attention and the phenomenology of conscious perception

Finally, one may ask whether attention affects the phenomenology of conscious visual experience (Prinzmetal et al., 1997, 1998). Most of the research reviewed in this chapter concern *when* (how fast) a stimulus is perceived or *whether* it is perceived at all. This does not address the question of *how* a stimulus appears (Prinzmetal et al., 1998). Namely, how does attention affect the perceived brightness, color, location, or orientation of objects? 19th century researchers relied on introspection to suggest that attention may increase the intensity and clarity of images (James, 1890; Titchener, 1910). However, Prinzmetal and his colleagues (1997, 1998) used a matching procedure to demonstrate that attention did not affect the perceived intensity or clarity of a stimulus and had only a small, inconsistent effect on the veridicality of the perceived color or location of a stimulus.

The main, consistent effect of reducing attention was to increase the variability in perceiving a wide variety of basic visual attributes.

Although attention does not change the experienced clarity and intensity of stimuli, it may determine *how* you perceive stimuli, especially ambiguous ones. Consider Rubin's ambiguous figure (Rubin, 1915/1958) which induces a percept that oscillates between two faces or a vase. Attention appears to determine which figure is perceived. In ambiguous motion displays, attention mediates the ability to track moving stimuli (Cavanagh, 1992). In binocular rivalry, presenting different images to each of the two eyes induces competing percepts which oscillate, and form-selective cortical areas in the brain are modulated according to what the subject "consciously" perceives (Leopold & Logothetis, 1996; Logothetis & Schall, 1989; Tong, Nakayama, & Kanwisher, 1998). Although the role of attention in binocular rivalry is unclear, it is intriguing that cortical areas important for attentional shifts are active as rivalrous percepts alternate (Lumer, Friston, & Rees, 1998). In several visual illusions, attentional cues can make a stationary line appear as if it were dynamically shooting out of a point in space (Hikosaka, Miyauchi, & Shimojo, 1993; see also Downing & Treisman, 1997, and Tse, Cavanagh, & Nakayama, 1998) or distort the form of simple figures (Suzuki & Cavanagh, 1997). Hence, attention can influence how you see and experience the perceptual world.

CLOSING REMARKS

A large number of behavioral paradigms have elucidated many important mechanisms of attention. Attention is important for selecting and inhibiting visual information over space and over time. New paradigms continually emerge to illuminate how attention influences memory and perceptual awareness. Particularly exciting are the new technological developments such as fMRI that provide researchers with unprecedented tools for studying the neural basis of visual attention.

Our review of visual attention mirrors the state of the field, and if little else, one may come away with the sense that attention refers to a very diverse set of operations. Further integrative understanding should be a worthy goal of future research and theorizing. Such an understanding

would specify how various attentional mechanisms interact with other perceptual, motor, and cognitive systems. However, we believe future research will be guided by the same, fundamental questions that have motivated the field up to now. How does attention facilitate our interactions with a rich visual world characterized by information overload? What ecological properties of the environment and what computational capacities of the brain constrain attentional selection? Finally, how does attentional selection and deployment influence the everyday qualia of seeing?

SELECTED READINGS

Coltheart, V. (Ed.). (1999). *Fleeting memories: Cognition of brief visual stimuli*. Cambridge, MA: MIT Press.

This edited volume contains chapters on visual cognition with a special focus on temporal attention in sentence, object, and scene processing. More information on the RSVP paradigm, the attentional blink, repetition blindness, inattentional amnesia, and scene processing can be found here.

Dagenbach, Dale, & Carr, Thomas H. (Eds.). (1994). *Inhibitory processes in attention, memory, and language*. San Diego, CA: Academic Press.

This edited volume offers specialized chapters that discuss inhibitory processes in attention. Kramer, A. F., Coles, M. G. H., & Logan, G. D. (Eds.). (1996). *Converging Operations in the Study of Visual Selective Attention*. Washington, DC: American Psychological Association.

This edited volume covers an extensive range of topics in selective attention. The chapters offer discussion of most of the major paradigms and issues in selective attention research.

Pashler, H. (1998). *The Psychology of Attention*. Cambridge, MA: MIT Press.

An integrative and exhaustive survey of what the past few decades of attention research have taught us about attention.

Pashler, H. (Ed.). (1998). *Attention*. East Sussex: Psychology Press Ltd.

Concise, edited volume of chapters on a variety of basic topics in attention. Useful, introductory surveys on the following topics can be found here: visual search, attention and

eye movements, dual-task interference, inhibition, attentional control, neurophysiology and neuropsychology of selective attention, as well as computational modeling.

Parasuraman, R. (Ed.). (1998). *The attentive brain*. Cambridge, MA: MIT Press.

This edited volume contains detailed discussion of methods (single cell electrophysiology, ERP, fMRI, PET, etc.), components of attention, and development and pathologies of attention. A particularly important volume for understanding the cognitive neuroscience of attention, as well as current issues and debates.

ADDITIONAL TOPICS

Attentional Networks

As evidenced in this chapter, there are different types of attention performing different functions. In addition, different aspects of attention appear to be mediated by different parts of the brain. These papers describe the function and anatomy of such attentional networks.

Posner, M. I., & Petersen, S. (1990). The attention system of the human brain. *Annual Review of Neuroscience*, 13, 25-42.

Posner, M. I., & Dehaene, S. (1994). Attentional networks. *Trends in Neurosciences*, 17, 75-79.

Attention and Eye Movements

Perhaps one of the most important functions of attention is to guide eye movements (where visual acuity is the highest) towards objects and events that are relevant to behavior. Attention and eye movements are tightly coupled, and this book chapter reviews the relationship between the two.

Hoffman, J. (1998). Attention and eye movements. In H. Pashler (Ed.), *Attention* (pp. 257-295).

East Sussex: Psychology Press Ltd.

Attention and object perception

This article reviews how attention influences the perception of objects. The authors also discuss the role of attention in perceptual awareness, and they review evidence for modularity of visual function in the brain.

Treisman, A. M., & Kanwisher, N. G. (1998). Perceiving visually presented objects: recognition, awareness, and modularity. *Current Opinion in Neurobiology*, 8, 218-226.

Computational Modeling of Attentional Processes

Computational models are useful for describing and understanding complex functions such as attention. Considerable effort has been put into such quantitative models of attention. Bundesen (1994) and Mozer and Sitton's (1998) chapter provides a useful review, while the other articles represent some of the most influential computational models in the field of attention.

Bundesen, C. (1994). Formal models of visual attention: A tutorial review. In A. Kramer, G. Logan, & M. G. H. Coles (Eds.), *Converging operations in the study of visual selective attention*. Washington D. C.: APA. (See also Bundesen, 1990)

Grossberg, S., Mingolla, E., & Ross, W. D. (1994). A neural theory of attentive visual search: Interactions of boundary, surface, spatial, and object representations. *Psychological Review*, 101, 470-489.

Logan, G. D. (1996). The CODE theory of visual attention: An integration of space-based and object-based attention. *Psychological Review*, 103, 603-649.

Mozer, M. C., & Sitton, M. (1998). Computational modeling of spatial attention. In H. Pashler (Ed.), *Attention* (pp. 341-393). East Sussex: Psychology Press Ltd.

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Neuropsychology of Attention

Our understanding of attentional processing has been greatly informed by the neuropsychological investigations of attentional disorders caused by specific brain damage. These findings are reviewed in Humphreys' chapter (this volume). Further information on deficits such as neglect or Balint's syndrome can be found in Driver (1998) or Rafal (1995).

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Table 1. Principles of Search Efficiency

Factors that decrease search efficiency	Factors that increase search efficiency
In general, as target-distractor differences get smaller, search becomes less efficient (e.g., Foster & Westland, 1992; Nagy & Sanchez).	Large target-distractor differences in features such as color, orientation, motion, size, curvature, some other form properties, and some 3D properties (such as stereopsis, lighting, and linear perspective). See Wolfe (1998b) for a review.
Increasing distractor inhomogeneity. Consult Duncan and Humphreys (1989) for a detailed discussion of the role of similarity in visual search.	Increasing distractor homogeneity (Duncan, 1988).
Targets defined by conjunctions of two or more basic features (Treisman & Gelade, 1980; e.g. color X orientation: a red vertical line among green vertical and red horizontal distractors).	Conjunction targets can be found efficiently if the differences in target and distractor features are sufficiently salient (Wolfe, Cave, & Franzel, 1989).
Targets defined only by the spatial arrangement of basic features are, as a general rule, not found efficiently (Wolfe & Bennett, 1997). Thus, search for an “S” among mirror-reversed Ss will proceed at a rate of 20-30 msec per item on target present trials.	Difficult searches can become more efficient with extensive practice (Heathcote & Mewhort, 1993; Treisman, Vieira, & Hayes, 1992). However, such perceptual learning is specific to the stimuli trained on.

Figure Captions

Figure 1. Posner cueing paradigm. Subjects fixates at central box at the beginning of trial. The outline of one peripheral box brightens briefly. At variable SOA's from the cue, a target appears in one of the boxes. Subjects press a button in response to target onset as quickly as possible (adapted from Posner & Cohen, 1984).

Figure 2. Attentional resolution. While fixating the cross in the center of the left-hand diagram, notice that it is fairly easy to attend to any of the items in the surrounding arrays. This is possible because each item is spaced at less than the critical density for individuation. The diagram on the right has a density that exceeds the resolution limit of attention, producing crowding effects. Fixating on the central cross, it is difficult to move attention from one item to another (He, Cavanagh, & Intrilligator, 1997, with permission).

Figure 3. (A) Object-based attention. Each target is comprised of two overlapping objects, a box or a line. The box that could be large or small with a gap to the left or right. The line that could be tilted right or left and comprised of either dashed or dotted line. Attending and reporting two attributes from a single object was easier than reporting two attributes, each from different objects. (Adapted from Duncan, 1984). (B). Sample stimulus adapted from Baylis and Driver (1993). The task was to determine the relative vertical height of the apices formed at the angled outline of the center white figure. Depending on the subject's perceptual set, these apices can be considered to part of one object (white figure) or two objects (black figures). Task performance was lower when the apices belonged to two objects, as manipulated by perceptual set. (C). In a search for a reversed L shape target, performance is much easier when the L shapes are perceived to be in front of the square than when they are perceived to appear behind the square (the apparent depth was manipulated using binocular disparity). Even though the retinal images were essentially identical in both conditions, setting the L shapes behind the squares causes the perceptual system to "complete" their shapes behind the occluder (look like squares behind occluding squares), making it difficult for observers to attend to the L shape fragment alone. This demonstrates that attention operates over surfaces (objects) rather than raw visual features (adapted from He & Nakayama, 1992).

Figure 4. Visual search and hypothetical data. In the left figure, fixating on the asterisk, notice that the white X is much easier to detect than the black T. The right figure shows hypothetical data for visual search tasks of varying efficiency (Adapted from Wolfe, 1998, with permission).

Figure 5. Temporal Attention. (A) The RSVP paradigm. The task is to search for two letter targets presented amongst digits at a rate of 10 per second. (B) The attentional blink. Percent correct performance on reporting T2 given correct report of T1 is impaired at lags 2 to 5 (corresponding to SOA's of 200 - 500 ms). (Adapted from Chun & Potter, 1995). (C) A conveyor belt model of multiple attentional dwell times.

Figure 6. (A) Moran and Desimone's (1985) paradigm for studying selective attention in extrastriate cortical area V4. Monkeys fixate on the asterisk. The receptive field of the recorded neuron is indicated by the dotted frame, and this was plotted for the effective stimulus (red bar, shown here in black). When the animal attended to the location of an effective stimulus (red bar), the cell gave a good response. However, when the animal attended to the location of the ineffective stimulus (green bar, shown here in white) the cell gave almost no response, even though the effective stimulus was present in the receptive field. Thus, the cell's responses were determined by the attended stimulus. (Adapted from Moran & Desimone, 1985) (B) ERP changes in a spatial-attention task. Subjects focused attention on one of the quadrants at a time. ERPs were recorded from 30 scalp sites (dots on the schematic head), and the bottom figure shows a larger P1 component in response to upper-left flashes while subjects attended to the upper left quadrant. The scalp distribution of the P1 component for attended upper-left flashes (measured at 108 msec) is shown on the rear view of the head with darker areas representing greater positive voltages. (Mangun et al., 1993, with permission).

Figure 7. fMRI data that reveals retinotopic mapping of cortical activation produced by (A) shifts in spatial attention from the middle to the periphery (increasing polar angle) and (B) by the same visual targets presented in isolation (Brefczynski and DeYoe, 1999, with permission). Note the close correspondence between the two patterns of cortical activation.