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Forty-Five Years After Broadbent (1958): Still No Identification Without Attention

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According to D. E. Broadbent's (1958) selective filter theory, people do not process unattended stimuli beyond the analysis of basic physical properties. This theory was later rejected on the basis of numerous findings that people identify irrelevant (and supposedly unattended) stimuli. A careful review of this evidence, however, reveals strong reasons to doubt that these irrelevant stimuli were in fact unattended. This review exposed a clear need for new experiments with tight control over the locus of attention. The authors present 5 such experiments using a priming paradigm. When steps were taken to ensure that irrelevant stimuli were not attended, these stimuli produced no priming effects. Hence, the authors found no evidence that unattended stimuli can be identified. The results support a modern version of Broadbent's selective theory, updated to reflect recent research advances.

A SELECTIVE FILTER THEORY OF ATTENTION

Our senses are constantly bombarded by a variety of stimuli, some of which are relevant to the task at hand and some of which are not. As a result, goal-directed behavior requires a high degree of selectivity at some point in the processing stream. In the case of vision, there are two well-established attentional mechanisms. The easier to observe is eye position. People fixate their eyes on interesting objects, thereby taking advantage of the increased visual acuity at the fovea. Less easily observed is covert attention (sometimes called "the mind's eye"; Jonides, 1981). People can direct attention toward interesting objects, even without a corresponding movement of the eyes (as when a person watches someone out of the corner of his or her eye). Despite the existence of these selective attention mechanisms, it has been found that irrelevant stimuli are often identified; that is, they activate learned conceptual representations. These findings have led many researchers to the conclusion that attention is not necessary for the identification of objects. In this article, we argue that such a conclusion is not justified on the basis of the available evidence. The fact that a stimulus is irrelevant to the task at hand does not necessarily mean that the stimulus will be unattended. We propose that the identification of irrelevant stimuli results from the allocation of attention to the irrelevant stimuli rather than from true identification without attention.

We argue that unattended items receive very little processing beyond the registration of simple physical features. Broadbent (1958) championed this position more than 45 years ago, although his views were subsequently discredited. We begin by discussing Broadbent's selective filter theory of attention and discuss how this theory has held up in light of the research advances made in the subsequent decades. We argue that Broadbent's core architecture has actually held up remarkably well. Although certain predictions of this theory were disconfirmed long ago, we argue that the problem is not with Broadbent's central claim that identification requires attention. Rather, the problem is with minor peripheral claims, which we now know to be incorrect, regarding the speed at which attention can be reallocated. We therefore propose an updated version of selective filter theory that takes into account recent research findings.

In the second section of this article, we review in depth the literature on the processing of unattended items and relate this

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literature to our selective filter theory. We argue that because previous studies generally failed to ensure that the supposedly unattended stimuli actually were unattended, the evidence for identification without attention is weak. We emphasize the critical yet mostly ignored distinction between *leakage* through the attentional filter (semantic processing of irrelevant items while attention is focused elsewhere) and *slippage* (allocation of attention to irrelevant items, perhaps unintentionally). Evidence of leakage would falsify selective filter theory, whereas evidence of slippage would not—in fact Broadbent explicitly predicted that slippage would occur.

In the third section of this article, we present new data to fill in critical gaps in the existing literature. Specifically, we tried to prevent attentional slippage and at the same time provide a very sensitive test for leakage. As shown below, we found no evidence for leakage through the attentional filter. We conclude, therefore, that selective filter theory is still alive and well.

Broadbent's Original Selective Filter Theory of Attention

Broadbent proposed a stage model of perception. According to this model, initial processing occurs on all stimuli impinging on the organism to extract basic physical properties (such as pitch, color, and orientation). Representations of these physical features are stored (temporarily) in immediate memory. Unlike the processing of physical features, Broadbent argued that the processing of nonphysical, *semantic* features (those based on the meaning of an object, such as the identity of a word; Neisser, 1967, p. 209) is subject to severe capacity limitations. Because of this limited capacity, a selective filter is needed to select certain stimuli to be processed further and to filter out other, irrelevant stimuli. After the selected stimuli are processed semantically, the resulting information can be stored in long-term memory or used to formulate an appropriate response. Because of the critical role of the selective filter, Broadbent placed considerable emphasis on how selection is accomplished. He proposed that people attend to a particular physically definable stream of information (called a *channel*); stimuli that fall outside that stream are not processed beyond the extraction of the physical features necessary to segregate the streams. Channel selection is guided by top-down influences (e.g., current goals) as well as bottom-up influences (e.g., stimulus intensity).

The most controversial part of Broadbent's theory was its extreme view on cognitive architecture. Specifically, it allows for very little parallel processing of stimuli. Of course, Broadbent knew that people appear to simultaneously process information from multiple sources. Broadbent proposed several mechanisms that allowed the system to behave as though it was processing this information in parallel at the macro level. First, parallelism in early processing can be exploited to mimic parallelism of the system as a whole. Specifically, Broadbent argued that attention can be directed to relevant stimuli on the basis of their particular physical properties and their association with the organism's current drives (e.g., Broadbent, 1958, p. 298). Broadbent also noted that certain physically salient stimuli (e.g., a sudden loud sound) would capture attention (e.g., Broadbent, 1958, pp. 86, 106). To the extent that attention can be directed to relevant or potentially important stimuli on the basis of their physical properties, without identifying less salient or less relevant stimuli, an organism can appear to process all stimuli impinging on it while, in fact, processing only those stimuli that require an overt response. Second, rapid switching of attention can be exploited to mimic parallelism at the macro level, while information processing remains serial at the micro level. Specifically, Broadbent argued for an iconic memory storage system that can retain information while attention switches between stimuli, in much the same way that a multitasking computer system spreads CPU time across various tasks (e.g., Broadbent, 1958, p. 231). Finally, Broadbent acknowledged that when very little external information is required, participants are able to attend and process multiple stimuli simultaneously (e.g., Broadbent, 1958, pp. 17, 23, 33–35).

We should note that although Broadbent believed that people selectively filter information because they are incapable of processing the large amounts of information with which they are confronted, he was not very specific on what the capacity limits were. Broadbent did suggest that in information-poor environments parallel processing was possible even if information came from separate channels, although the implication was that such parallel semantic processing is relatively rare. Subsequently, there has grown to be a substantial literature on people's ability to split their attention between objects or regions of space (see Pashler, 1998, Chapter 3, for a review). Although important, the issue of capacity limitation is largely orthogonal to the main focus of this article, which is the role of attention in object identification.

This brief sketch obviously leaves open many questions. For example, under what circumstances does attention shift? How quickly does attention shift? What counts as a basic physical feature? What are the characteristics of immediate memory? In the next section, we examine how the last 45 years of research have answered these questions, providing details needed to develop a more modern version of filter theory. Although Broadbent's original theory was based largely on studies of audition, we focus on studies of vision. This decision was motivated by two factors. First, most of the attention research in the intervening years has been carried out on vision, not audition. Second, as we argue below, it is easier to control the focus of attention in vision than in audition.

A Modern Version of Selective Filter Theory

Broadbent's theory was quickly superseded as a variety of experiments (e.g., Moray, 1959; Treisman, 1960) demonstrated that participants engaged in one task are sometimes influenced by semantic information from perceptual channels unrelated to that task. For much of the intervening 45 years, Broadbent's original view has been criticized as extreme and almost certainly wrong (e.g., Ashcraft, 1998, p. 73). Later, we evaluate the evidence that unattended stimuli are processed semantically. Before doing so, however, it is necessary to bring Broadbent's theory up to date by discussing the subsequent findings in several research areas related to visual attention. We do so paying particular attention to how the attentional filter is integrated into the broader cognitive system. As recognized by Broadbent (and ignored by many of his detractors), this broader cognitive system is often able to compensate for the limited ability to process items in parallel.

The Locus of Selective Attention: The Basic Neurophysiology of Vision

Broadbent argued that attention operates at an early perceptual level, before stimulus identification. However, others have instead argued that attention operates on the results of the identification process (e.g., Deutsch & Deutsch, 1963; Driver & Tipper, 1989). This debate has cooled recently due in large part to the discovery of neurophysiological effects of attention in perceptual areas of the cortex (see Driver, 2001, p. 58, for an example of a converted late-attention theorist). In this section, we describe this work and how it supports Broadbent's major architectural assumptions concerning an early locus of attention. A fringe benefit of this discussion is that it helps make many vague concepts such as "physical features" and "semantic features" more concrete.

Neurophysiologists have uncovered many key details about how the visual processing system is organized. One of the most fundamental details is that neurons in the visual system have a distinct hierarchy. This hierarchy can be seen both in the structure of connections between brain areas (upstream projections run from superficial layers primarily into cortical layer IV, whereas downstream projections run from both superficial and deep layers and land primarily outside layer IV; Van Essen & Maunsell, 1983) and in the firing patterns of individual neurons (neurons at lower levels of the hierarchy respond exclusively to simple visual properties, whereas neurons at later levels have larger receptive fields and some respond to more complex properties; Cowey, 1994; Maunsell, 1993). This hierarchy is divided into two streams, a *ventral* pathway that processes object identities and a *dorsal* pathway that processes motion, location, and the targeting of actions (Maunsell & Newsome, 1987; Milner & Goodale, 1995; Mishkin, Ungerleider, & Macko, 1983).

The Ventral Pathway

First, consider the object identification (or ventral) pathway. Cells on the retina called ganglion cells project to two bodies in the thalamus (a structure in the middle of the brain), referred to as the lateral geniculate nuclei (LGN). Both the ganglion cells (Kuffler, 1953) and cells in LGN (Hubel & Wiesel, 1961; Wiesel & Hubel, 1966) are maximally sensitive to relatively small spots of a particular color. Cells in LGN then project to the cortex in visual area one (V1, also known as the striate cortex because its layering is visible with the naked eye; Brodmann 1909/1994) where individual cells are usually selective for line segments of a particular orientation, spatial frequency, and color (Hubel & Wiesel, 1959, 1968). These cells then project into area V2. Neurons in V2 also respond to line segments, regardless of whether these line segments are defined by differences of luminosity; for example, cells in V2 respond to texture gradients (Merigan, Nealey, & Maunsell, 1993; von der Heydt & Peterhans, 1989) and illusory contours (Peterhans & von der Heydt, 1989). The main projection from V2 along the ventral pathway is to V4. Cells in V4 have similar response properties to those in V2 except that they have much larger receptive fields. V4 in turn projects to the inferior temporal cortex (IT). Cells in IT can have extremely complex response properties, apparently responding selectively to such stimuli as faces and hands (Gross, 1992). Thus, IT is where cells first appear to respond to the identity (or meaning) of objects, the classic semantic property.

The Dorsal Pathway

Information on the motion (or dorsal) pathway follows a similar route early on. Magno ganglion cells on the retina project to the magno cellular layers of the LGN. These cells then project to V1 (where processing of dorsal pathway information remains largely segregated from ventral pathway information). Response properties in LGN and V1 are similar for the dorsal and ventral pathways, except that dorsal pathway cells are generally less selective for color and are more sensitive to movement and flicker (Merigan & Maunsell, 1993). Dorsal pathway cells in V1 have major projections to V2, V3, and middle temporal (MT). The function of V3 is not well understood (its existence in primates is not even universally agreed on; Kass & Lyon, 2001). Neural responses of dorsal pathway cells in V1 and V3 appear to be similar (Levine & Shefner, 1991). V1, V2, and V3 all have major projections into MT (DeYoe & Van Essen, 1988). Cells in MT respond to more complex patterns of motion. Consider, for example, a plaid stimulus consisting of bars moving up and bars moving to the right. A person viewing this plaid will see a pattern moving diagonally (up and to the right). Cells in V1 and V2 respond only to the two motions separately (up only or right only) and not to the perceived diagonal motion. Cells in MT, in contrast, do respond to the perceived diagonal movement (Movshon, Adelson, Gizzi, & Newsome, 1985). Thus, if there is any semantic processing on the dorsal pathway, it does not appear to happen until fairly far into the system, in area MT and beyond where the responses begin to correspond more closely to conscious perception.

Although the parvo–ventral and magno–dorsal pathways are often treated as entirely separate, it should be noted that there is significant interaction between the two systems. The ventral system, in particular, seems to use information from both magno and parvo cells (Ferrera, Nealey, & Maunsell, 1994; Merigan & Maunsell, 1993).

Locus of Attentional Effects

Broadbent argued that early stages of processing are unaffected by attention whereas later stages that process semantic information require attention. Mapping Broadbent's processing stages onto the visual hierarchy just described, we see that early stages where physical properties are represented include the retina, LGN, V1, V2, V3, and V4, whereas semantic properties are represented in IT and MT. Where in this hierarchical system does attention actually come into play? Clear attentional effects have been noted in V2 and all areas farther up the hierarchy. The most robust and convincing effects have been found with a technique pioneered by Moran and Desimone (1985; Reynolds, Chelazzi, & Desimone, 1999). This technique involves examining the response of a particular neuron to two stimuli separately and then to both stimuli presented simultaneously. In the latter condition, the experimenter can then direct the experimental subjects (monkeys) to attend to one of the two stimuli. The main finding is that if a monkey attends to one of two stimuli in a particular cell's receptive field, that cell will typically respond as if stimulated only by the attended stimulus. If the monkey instead attends outside the cell's receptive field, the cell's response appears to be the average of the responses to stimuli in its receptive field when presented individually.[1] This pattern has been observed in areas V2, V4, and MT (Moran & Desimone, 1985; Reynolds et al., 1999; Treue & Maunsell, 1999).

It is more difficult to test for the effects of attention in areas IT and V1 in this manner. Cells in area IT tend to have very large receptive fields; so, it is difficult to design appropriate controls where there is a stimulus outside a cell's receptive field. Conversely, in area V1, the small size of the receptive fields of cells means that it is often impossible to present multiple stimuli simultaneously within a cell's receptive field. It is possible to obtain similar attentional effects with competing stimuli placed outside a cell's receptive field, even in V1: When stimuli are crowded on the display, there is an enhanced effect of attention such that cells respond more strongly to attended stimuli and less strongly to unattended stimuli. This effect occurs even when the crowding stimuli fall outside the cell's receptive field. Motter (1993) collected data from single units in areas V1, V2, and V4. Only one of a number of stimuli was presented in the receptive field of the cell being recorded, and that one stimulus could be attended or unattended. Under such conditions, attentional effects were seen in all three areas studied. However, these effects are small, and a relatively small percentage of neurons is affected (about one third) compared with when the attended and unattended stimuli both appear in the cell's receptive field (e.g., 82% in V2 and 65% in V4 by Reynolds et al., 1999).

Evidence about attentional effects in V1 has also been obtained with various noninvasive techniques (e.g., functional magnetic resonance imaging [fMRI] and event-related potential [ERP]) on humans. These data suggest that there are attentional effects in V1 but that the effects are qualitatively different from those in cortical visual areas outside V1 (because V1 is also known as the striate cortex, these areas are referred to as *extrastriate* areas). A number of fMRI studies have found differences in V1 activation for attended and unattended moving stimuli (Somers, Dale, Seiffert, & Tootell, 1999; Watanabe, Harner, et al., 1998; Watanabe, Sasaki, et al., 1998). Martínez et al. (2001) provided an additional twist by recording both fMRI data (which have good spatial resolution but poor temporal resolution) and ERP data (which have good temporal resolution but poor spatial resolution) to the same stimuli. This technique allowed them to split the V1 response to a visual stimulus into two phases, an early phase (50–90 ms after stimulus onset), which was unaffected by attention, and a late phase (160–260 ms after stimulus onset), which was affected by attention. In contrast, the response in extrastriate cortex had only one phase, 70–130 ms poststimulus, which was affected by attention. Thus attentional modulation in V1 follows the attentional modulation in extrastriate cortex. This finding is in accord with earlier evidence from ERP studies that attentional modulation begins too late to have been initiated in V1 (e.g., Hillyard, Mangun, Woldorff, & Luck, 1995). Thus, attention probably does not directly modulate processing in V1. Rather, attentional effects in V1 are a by-product of feedback from attentionally gated extrastriate areas.

In summary, neurophysiological evidence supports Broadbent's basic structural assumptions regarding the locus of attention within the processing stream. Some early visual processing (taking place at the retina, LGN, and probably V1) occurs before any attentional filtering. However, strong attentional effects do occur relatively early in visual processing (V2 and V4), prior to the processes that appear to involve semantic properties such as the identity of objects (IT). What is less clear from the neuroscience literature is the quality of this early attentional filter. Does it block the processing of irrelevant stimuli completely or merely attenuate this processing? In areas V2 and V4, cells respond to some degree to stimuli in their receptive fields, even when attention is directed outside of the cells' receptive fields. Are responses then blocked more completely later in the processing hierarchy? Or is this information still available for semantic evaluation?

We believe that answering these questions requires additional behavioral research. Although neurophysiology is highly informative about the locus of attention, we do not believe it is as decisive in determining the functional role played by attention in visual processing. Suppose that the firing rate of a particular neuron in response to a given stimulus in its receptive field is reduced by 50% when that stimulus is unattended rather than attended. How might this reduction be interpreted by the neurons that receive projections from this neuron? In a winner-take-all network, such reductions might result in shifting the response from on to off. However, in a network that summed the activation of its inputs, such reductions would result in an analog reduction in response. Because too little is known about the behavior of these networks, it is difficult to determine how attention to one object will influence processing of other objects. In short, although the neurophysiological data make it clear that attention is doing something in early visual processing, the nature of this effect is complex and its function is not yet well understood.

Iconic and Echoic Memory

Another important aspect of Broadbent's proposed architecture is the notion of an *immediate memory* operating before the attentional filter. This memory system is easily recognized as the sensory memory later studied by Sperling (1960) and dubbed *iconic* memory (in the case of vision; *echoic* memory in the case of audition) by Neisser (1967). Over the years and across theoretical perspectives, the terminology has changed markedly; however, it remains clear that large amounts of information remain active in a relatively unprocessed state for a short period of time (a few seconds or less). Broadbent noted that such a memory would allow an observer to attend and process two stimuli sequentially even when they are presented simultaneously and proposed that certain tasks are performed in precisely this way. Suppose that a visual stimulus is presented in an unattended location. Even assuming that observers cannot identify the stimulus without attention, they can still shift attention to it later and then identify it. One might think that presenting the stimulus very briefly would prevent any possibility of a covert shift of attention. However, research on sensory memory shows that in general, this is not so: Observers can shift their attention to the sensory memory trace with much the same effect as shifting attention to the actual object. Thus, to demonstrate convincingly that such a stimulus is identified without attention, one must rule out the possibility that attention was shifted to its sensory memory trace.

One can address this issue by preventing participants from shifting attention. This strategy was attempted in early auditory

[1] This apparent averaging might be due to averaging across different states in which the cell responds to only one stimulus or the other.

attention experiments by having the participant perform a continuous task on the attended stream (e.g., repeating a story as it is presented to one ear). Unfortunately, echoic memory lasts for several seconds (Norman, 1969; Pashler 1998; but see Massaro, 1972, for an opposing view), which means that participants have many opportunities to switch attention to the supposedly unattended channel. Even though the duration of iconic memory is thought to be considerably shorter than that of echoic memory, the same basic problem remains. However, in vision, a second stimulus occurring in the same location as the first after a brief delay tends to "erase" the iconic memory trace of the first (Averbach & Coriell, 1961). This phenomenon, referred to as backward masking, makes it possible to prevent shifts of attention to a visual stimulus, by masking the stimulus before attention has had time to move to it. The absence of a similar backward masking effect for auditory stimuli makes sense given that temporal properties are critical in identifying auditory stimuli but are typically not essential for visual stimuli. Thus the visual system seems to allow later stimuli to overwrite earlier ones, whereas the auditory system records sequences of stimuli. The necessity of this auditory recording function can also explain why echoic memory lasts much longer than iconic memory.

Broadbent argued that sensory memory was used for more than simply maintaining information before it could be attended. He noted that echoic memory also appears to play a role in maintaining information before it is stored in long-term memory. Specifically, items that had previously been attended and identified could be restored to sensory memory through rehearsal. This mechanism became a staple of many theories of short-term memory (Atkinson & Shiffrin, 1968; Baddeley, 2001; Baddeley & Hitch, 1974; Sperling, 1963). Further, this mechanism may be only a part of a more general *imagery* system by which information can be reinstantiated early in the perceptual system, not only for the purpose of maintaining it in memory but also for reanalysis (Bensafi et al., 2003; Kosslyn, 1980; Kosslyn & Thompson, 2003). In vision, at least, this reinstatement can occur at the level of V1 (Kosslyn & Thompson, 2003).

In summary, iconic and echoic memory perform the functions of the preattentive immediate memory store envisioned by Broadbent. The existence of such a store makes it possible to attend and process two stimuli serially, even when they are presented briefly and simultaneously. One can reduce the utility of this store for visual stimuli by backward masking, but there are no similarly reliable techniques for eliminating sensory storage of auditory stimuli.

Selection by Physical Features

Broadbent proposed that selection could take place only on the basis of physical features. Subsequent research has borne this out. Whereas attention can be directed efficiently to items with a particular physical feature, it cannot be efficiently directed to items defined by particular semantic features.

One line of evidence that selection is performed on the basis of physical features comes from the partial report paradigm used to study sensory memory. In this paradigm, observers are shown brief displays containing a large number of stimuli, so that it would be impossible to reliably report all the elements of the display. The fact that not all stimuli can be reported indicates that there is a bottleneck somewhere in the system. Observers are given a cue instructing them to identify and report only certain elements of the display (thus the name *partial report*). Good performance in this paradigm demonstrates that observers can select only the cued stimuli to go through the bottleneck (Sperling, 1960).

Observers seem to be able to perform this selection only by means of physical cues. Observers can select on the basis of location (Sperling, 1960), color (Banks & Barber, 1977; von Wright, 1968), or size (von Wright, 1968), but not by alphanumeric category (i.e., letter vs. number; Sperling, 1960). It is interesting to note that von Wright (1968) found that observers could not select letters by their orientation; however, this was probably because determining a letter's orientation requires that one know what letter it is.

The same pattern is found in visual search paradigms, in which (typically) participants are shown a display and asked to determine if a particular item is present. If the particular item is defined by a physical feature, observers find it very quickly, regardless of the number of items in the display (for a review, see Pashler & Johnston, 1998). This finding suggests that attention can be efficiently directed to the target on the basis of this feature. In contrast, targets defined by semantic properties (e.g., letter identity) are harder to find. The time required to find the target increases sharply as additional items are added to the display, suggesting that observers must attend to items in the display sequentially (Treisman & Gelade, 1980). Thus it appears that attention cannot be allocated directly to the target on the basis of semantic features. Rather, participants in search experiments appear to direct their attention to a sequence of locations (or objects) and determine whether a target is present at each of these locations. Note that such findings do not necessarily demonstrate that identification does not occur simultaneously for all items in the display (Pashler & Johnston, 1998). However, they do argue that whatever semantic information is processed in parallel cannot be efficiently used to select the target (Duncan & Humphreys, 1989).

Shifting Attention

Since at least von Helmholtz's (1910/1925) time, it has been understood that it is possible to move attention even without moving the eyes. Broadbent recognized the importance of this fact for interpreting data from studies of attention. Evidence that stimuli from two channels could be processed simultaneously would argue against his theory, whereas evidence that there was a slight delay between processing the first and second channels would support it (because it suggests a lag while attention shifts from one channel to the next). Although this distinction works in the abstract, to apply it, one must first decide how much of a delay is required before concluding that certain processes are sequential. Broadbent reviewed the literature, noting that some procedures (such as alternating speech between the two ears) suggested that attention switching times were on the order of one sixth of a second (Cherry & Taylor, 1954), whereas others (such as the order in which simultaneously presented items are reported) suggested times of one half a second or more (Broadbent, 1958, pp. 212–215). Broadbent argued that the shorter estimates were artifactual and, thus, that switches of attention require about one half a second.

Since that time, psychologists' understanding of attention switching has progressed considerably. Researchers now emphasize the distinction between voluntary, internally (*endogenously*) driven shifts of attention and involuntary, environmentally (*exogenously*) driven shifts of attention, such as when a flash "captures" one's attention (Briand & Klein, 1987; H. J. Müller & Rabbitt, 1989; Posner, Snyder, & Davidson, 1980; Theeuwes, 1991; Weichselgartner & Sperling, 1987). Although it may seem odd that attention can be drawn to an irrelevant stimulus against one's will, it is only in the laboratory that such stimuli are truly irrelevant. As an example, if one is hunting for a rabbit in one bush, a rabbit in the next bush will also be of interest.

Although Broadbent recognized that both internal and external factors can drive shifts of attention, he did not seem to recognize that internally and externally driven shifts could have different time courses, as is now widely believed (H. J. Müller & Rabbitt, 1989; Wolfe, Alvarez, & Horowitz, 2000). Estimates of the time required to shift attention endogenously vary from about 150 ms (e.g., Remington & Pierce, 1984) to about 500 ms (e.g., M. M. Müller, Teder-Sälejärvi, & Hillyard, 1998), placing Broadbent's estimate somewhat on the high end. However, exogenous shifts occur on an even shorter time scale, down to about 50 ms (Tsal, 1983; see below for more details). Because Broadbent thought all attention shifts were slow, he greatly underestimated the potential for serial processing of stimuli presented simultaneously.

What Captures Attention?

Yantis and Jonides (1984; Jonides & Yantis, 1988) argued that abrupt onsets automatically attract attention. Although this claim appears to be true in many circumstances, it requires some qualification. In particular, recent research suggests that there is a top-down component to attentional capture. What captures attention appears to depend on what signal the observer uses to find the target; attention tends to be attracted most strongly to stimuli (even irrelevant ones) whose physical properties match this target-finding signal (Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994; Pashler, 2001; Remington, Folk, & McLean, 2001). Because the clearest cue to the appearance of the target is often its onset, observers might normally be set for onsets. But if the task involves identifying a red letter among green letters, then red objects will tend to capture attention and abrupt onsets will not. Thus, attention will be guided automatically to select items of interest to the observer, without the observer necessarily having to consciously choose a location or object to attend to.

Yantis and Jonides (1990) found that classic attention-capture effects (delayed responding in the presence of a distractor thought to capture attention) were eliminated when the participant knew the location of the target. However, it is not clear how general this finding is. Folk, Leber, and Egeth (2002) did find attention-capture effects under similar circumstances. Furthermore, although Yantis and Jonides (1990) did not observe the classic attention-capture effects, they did observe increased distractor compatibility effects when the distractor had an abrupt onset (slowed responses when the target and distractor are associated with different responses). To explain their results, Yantis and Jonides (1990) argued that the primary effect of onsets is to prioritize the order in which items are processed. When the target location is not known, objects with abrupt onsets are processed first. However, when the target is at a known location, it will be processed first and all other stimuli, even those with abrupt onsets, will be moved lower in the processing queue.

In summary, the details of what captures attention are still a matter of some debate (Pashler, 2001; Remington et al., 2001; Theeuwes & Burger, 1998). However, all theories agree that irrelevant objects do capture attention under certain circumstances. Thus it is necessary to consider the possibility of attention capture before arguing that an irrelevant object is unattended. One critical factor in assessing this possibility is the time required to shift attention.

How Quickly Is Attention Captured?

Numerous studies have attempted to measure the time required to shift attention in response to an exogenous cue (C. W. Eriksen, Goettl, St. James, & Fournier, 1989; C. W. Eriksen & Hoffman, 1974; C. W. Eriksen & Webb, 1989; C. W. Eriksen & Yeh, 1985; Jonides, 1981; Posner, 1980; Remington, 1980; Shulman, Remington, & McLean, 1979; Tsal, 1983). One approach is to vary the time between the onset of an exogenous cue and the onset of the target, known as the *stimulus onset asynchrony* (SOA). The shift time is equal to the SOA needed to obtain a cuing effect on the target response. Studies using this approach have generally arrived at shift-time estimates of 50–100 ms (C. W. Eriksen & Hoffman, 1974; Jonides, 1981; Müller & Rabbitt, 1989; Posner, 1980; Remington, 1980; Shulman et al., 1979; Tsal, 1983). Most of these studies did not allow precise estimates of the duration of the attentional shift because they did not sample SOAs very finely. One exception is the study by Tsal (1983), who systematically investigated the amount of time needed for a cue to be maximally effective at a variety of eccentricities, under the assumption that the cuing effect would be maximal when attention has sufficient time to move to the cued location before stimulus onset. His data were nicely fit by a linear model in which 50 ms is required to initiate the shift and attention moves at a rate of 1° every 8 ms. Note that these data do not necessarily imply actual analog movement of attention (Remington & Pierce, 1984). It is possible that movements of attention are discrete but it simply takes longer to initiate larger movements or that objects farther from the currently attended location take longer to capture attention. Similar estimates of attention-shifting times were found in a neurophysiological study by Goldberg and Wurtz (1972; Wurtz & Goldberg, 1972). They found an enhanced response in the superior colliculus to objects that were the target of a subsequent eye movement. This enhancement occurred 50–75 ms after the initial "on response" to the stimulus (100 ms after the stimulus appeared on the screen). Goldberg and Wurtz took pains to show that this enhanced response was independent of the actual execution of the eye movement and that it was an attentional effect as opposed to a delayed response to the cue.

In summary, the literature on attentional capture suggests that attentional shifts (at least involuntary ones) happen quite fast—in less than 100 ms (but see Ward, 2001, for a critique of these low estimates). Broadbent appears to have recognized only voluntary shifts of attention, which are thought to be relatively slow (estimates of the time course of voluntary shifts of attention range from 150 ms to over 500 ms; H. J. Müller & Rabbitt, 1989; M. M. Müller et al., 1998; Remington & Pierce, 1984; Wolfe et al., 2000).

Assembling a Theory

The evidence cited above makes several things clear. First, early visual processing extracts various physical features of the world, largely in a parallel, bottom-up manner. These features include color, contrast edges, and first-order motion ("ordinary" motion; for a discussion of the distinction between first-, second-, and third-order motion, see Lu & Sperling, 2001). The cells extracting these features act as a sort of storage, if for no other reason than because their temporal response outlasts their stimulation (Haber, 1983). Thus there appears to be strong confirmation of Broadbent's claim that there is an early sensory store that preserves the raw physical features of a scene for a brief time. It is now known that "a brief time" is on the order of a few seconds for audition and one half a second for vision.

Second, as Broadbent claimed, sensory storage can be used by limited capacity mechanisms under a variety of circumstances. In particular, sensory memory can act as a buffer allowing selection of objects that are no longer physically present. Sensory memory has also been implicated as part of a *rehearsal loop*, allowing items to stay in memory indefinitely without necessarily being committed to long-term memory. In addition, it appears that the mechanisms underlying sensory memory can be used in a variety of imagery tasks.

Third, attentional mechanisms influence the processing of these physical features in areas V2 and V4 before semantic information can be extracted in areas IT and MT. Thus there is again strong confirmation of Broadbent's claim that attention acts early, before semantic features are extracted. A great deal is now known about the way in which these physical features are represented and how attention acts on these representations in primate cortex.

Fourth, attentional selection is accomplished on the basis of physical features. Studies of attentional selection have consistently found that observers can efficiently segregate relevant from irrelevant information on the basis of physical but not semantic features. This finding strongly supports Broadbent's contention that attentional channels are defined by physical features.

Finally, Broadbent's ideas about what guides the reallocation of attention have been largely confirmed. In particular, it appears that top-down and bottom-up factors interact to determine which items will be selected. Shifts of attention between different physically defined channels can occur involuntarily given the proper stimulus and the proper top-down set. Broadbent's ideas about top-down influences were couched in the terminology of *drives* and *reinforcement*, which was prevalent at the time. Researchers now think of these influences more in terms of the observer's goals and strategies.

Thus, Broadbent's core architecture seems to have been confirmed by subsequent research. Broadbent's major misstep was to greatly overestimate the time required to shift attention. This failure ultimately led to the premature rejection of the claim that has become synonymous with Broadbent's theory: There is no identification without attention.

Because this point is central to our thesis, we illustrate it with a concrete example. Suppose that two words are flashed on a screen with no masks, so that their iconic images last approximately half a second. Broadbent would predict an observer could identify only one of these words, because by the time the participant shifted attention to the second word, its icon would have faded. However, if we estimate the time to identify a word at about 100 ms (as suggested by Chung, Mansfield, & Legge, 1998), our revised filter theory would predict that an observer could identify both words. Identifying both words would take only the time to read the first word (100 ms), plus the time to shift attention (50 ms), plus the time to read the second word (100 ms). Thus, our theory can easily explain the finding that two briefly presented, unmasked words (one relevant and one irrelevant) can both be identified (Fuentes & Tudela, 1992; Shaffer & LaBerge, 1979).

The updated theory we have presented is actually quite straightforward. We have brought together established beliefs about cognitive architecture and attention shifting. In doing so, we have found that Broadbent was wrong about how quickly attention shifts. However, with current estimates for the time to shift attention, fast shifts of attention offer an alternate explanation of evidence previously seen as refuting Broadbent's claim that attention is required to identify objects. In the remainder of this article, we focus on this basic claim. In the next section, we review the existing data bearing on the issue of how much information processing is possible without attention. After taking into account the existence of flexible attentional switching between channels, we find little evidence that unattended objects can be identified.

PROCESSING WITHOUT ATTENTION: PREVIOUS RESEARCH AND THEORIES

Our central claim is that stimuli in unattended channels are not identified. That is, although various physical features of unattended objects (such as color, motion, and orientation) can be processed, the identities of these objects are not computed and thus no semantic information about them can be accessed. This claim is contrary to many reports that irrelevant and supposedly unattended objects are identified. In this section, we examine these reports and assess the quality of the evidence. In doing so, we emphasize a distinction between two ways in which an irrelevant object can come to be processed (leakage vs. slippage). This distinction has occasionally been made (e.g., Kahneman & Chajczyk, 1983; Pashler, 1998, p. 61), but it is more often overlooked.

Leakage occurs when attentional resources are not allocated to irrelevant items, yet some semantic processing of these items "leaks" through the attentional filter, causing these items to be identified. In contrast, slippage occurs when the attentional resources are allocated to irrelevant items as the result of inadequate control ("slips") of attention, causing these items to be identified. There are several reasons why slippage might occur:

> To quickly locate the target stimulus, participants must look for certain features that define the target. If an irrelevant stimulus shares some of these "target-finding" features, then it might inadvertently capture spatial attention (Folk et al., 1992).
>
> Many tasks require the participant to perform a series of subtasks, each of which requires its own attentional settings. For instance, in a task that requires that a target be located and then identified, locating the target may involve a "diffuse" attention mode, and identifying it might involve focused attention (Ballard, 1991; Sagi & Julesz, 1985). In such situations, one part of the task may allow or even require that

> information about the irrelevant distractor be processed (for instance, to determine that it is not the target).
>
> In some cases the unattended stimulus (the distractor) remains on the screen after the necessary information has been extracted from the target. In this case, attention may be shifted to the irrelevant item after the target has been identified. This irrelevant item may then be able to affect responses to the target at a decision-making stage (Broadbent & Gathercole, 1990).
>
> If the distractor consistently precedes the target, it may serve as a useful warning signal that the target is about to be presented. Participants may attend to the distractor item to gain this temporal information. They might also process such a distractor out of curiosity or because identification mechanisms would otherwise be idle.

Both leakage and slippage can result in the identification of an irrelevant stimulus. Our selective filter theory is inconsistent with leakage but is consistent with (in fact, predicts) slippage. Thus, it is important to ascertain whether the identification of irrelevant stimuli has been shown in cases for which slippage was unlikely. If so, then we can infer that leakage occurred, and we can reject the claim that unattended stimuli are not identified. Such cases, we maintain, are very difficult to find.

Filtering Paradigms

To search for evidence of leakage, one must construct a paradigm in which there are well defined *attended* and *unattended* items. Such paradigms have been termed *filtering paradigms* (Kahneman & Treisman, 1984). In these studies, irrelevant stimuli (often called *distractors* or *flankers*) are typically presented in a different location than that of the target. Participants are assumed to devote their attention to the target and thus away from these irrelevant stimuli. A variety of such paradigms have been developed in an attempt to determine how much processing is performed on these supposedly unattended distractors. In this section, we review the data from these paradigms.

Dichotic Listening

The classical example of a filtering paradigm is dichotic listening. In the prototypical dichotic listening experiment, participants are required to shadow (i.e., repeat verbatim as quickly as possible) speech presented to one ear. The question is what processing, if any, is performed on stimuli presented to the irrelevant ear. A variety of methods have been used to assess such processing. In early studies, participants were simply asked what information they recalled from the irrelevant message (Cherry, 1953). It was found that participants could determine only certain physical characteristics of the irrelevant message, such as the gender of the speaker.

Later studies, in which a variety of methods were used, did demonstrate some semantic processing of the irrelevant message. For instance, participants occasionally recognize instructions given following their own name (Moray, 1959). Also, participants occasionally switch to shadow the irrelevant ear when the content of the message switches ears (Treisman, 1960). In addition, participants required to paraphrase (rather than shadow) one message choose to paraphrase ambiguous sentences in ways that are consistent with words played to the irrelevant ear (Lackner & Garrett, 1972). Finally, participants classically conditioned to associate certain words with electric shock have a heightened galvanic skin response (GSR) to these words even when played to the irrelevant ear (Corteen & Dunn, 1974; Corteen & Wood, 1972; Moray, 1969). These studies seemed to refute Broadbent's position that unattended stimuli are not identified, instead favoring something more like Treisman's (1960) attenuation theory. According to attenuation theory, the absence of attention only attenuates signals, rather than preventing their processing altogether. Treisman argued that some words have lower thresholds as a result of being important (such as a person's own name) or contextually appropriate. Consequently, even an attenuated signal could activate these words. In our terminology, Treisman's claim was that these words are activated by leakage not slippage.

Given what was believed at the time, Treisman's (1960) proposal seems to be compelled by these results. However, 40 years later it seems just as likely that these effects were due to slippage as to leakage. For example, in the message-switching experiment (Treisman, 1960), participants switched ears to shadow the message on only 6% of trials. Furthermore, this low rate occurred even though participants complained that the switch of context was confusing. Is it not possible that the confused participants briefly lost their attentional focus? If they did, these errors could be attributed to slippage rather than to leakage. Furthermore, it is possible that in some cases participants made anticipation errors. Consider this example of an actual error: The participant said "sitting at a mahogany table," when the to-be-shadowed channel contained "sitting at the mahogany three possibilities" and the irrelevant channel contained "let us look at these table with her head." The interesting thing here is that following "sitting at a mahogany," the participant might simply guess that the next word should be "table," even without having processed the irrelevant channel. Given these two factors, 6% errors cannot be seen as very impressive evidence that the irrelevant, unattended channel was not completely blocked.

Moray's (1959) results were somewhat more compelling. He found that on 33% of trials (8 out of 24), participants noticed their own name presented in the irrelevant passage. This number increased to 80% (12 out of 15) when participants were asked to listen for "instructions" in the irrelevant passage (making it likely that they tried to listen to that passage). One possible concern with this study is that, given the equipment available at the time, Moray probably was not able to insert the names of his participants into the tape without introducing changes in tone and timing, which might have attracted attention to the irrelevant channel. The basic result has recently been replicated using techniques to avoid these problems (Conway, Cowan, & Bunting, 2001; Wood & Cowan, 1995). Unlike Moray, however, these authors presented isolated words rather than continuous speech, which raises new issues (see below). Still, Conway et al.'s (2001) study raises two issues that are important for understanding Moray's study. Conway et al. ran an experiment that was similar to Moray's except that participants were classified as low- or high-memory span. The vast majority of those recognizing their own name came from the low-memory span group. This finding is interesting for two reasons. First, it suggests that failures to report one's name are not due to memory failures because the participants who failed the most were the high-memory span participants who presumably had the best memories. Second, it raises the possibility that demonstrations of unattended processing may occur for only a minority of participants who are particularly distractible. This hypothesis will be explored further in conjunction with Experiment 2 reported below.

Although studies finding that people can recognize their name in an otherwise irrelevant stream do demonstrate that (at least some) observers are processing this material, our general concerns about the ease of switching between channels in audition still apply here. In particular, echoic memory has a relatively long lifetime (Glucksberg & Cowen, 1970; Klapp & Lee, 1974), allowing relatively infrequent checks to discover important information on the irrelevant channel (a form of slippage). It is interesting to note that a recent study (Bundesen, Kyllingsbaek, Houmann, & Jensen, 1997; see also Pashler & Harris, 1999) found that in a visual task, people do not detect their own name presented in an irrelevant location (although once attended, a person's name is more likely to be remembered than some other word). The fact that an unattended name presented visually evokes no recognition suggests that input modality, not the special status of a name, is the critical factor. The special nature of auditory processing appears to allow slippage of attention to occur in these situations.

The GSR research suffers from many of the same problems just discussed. In these studies, a set of words is associated with shock, and then the experimenter looks for heightened GSR to these words when they appear on the unattended channel. In the initial experiments using this technique (Moray, 1969), only a minority of participants (2 or 3 out of 12) showed any effect of the unattended stimuli. Corteen and colleagues (Corteen & Dunn, 1974; Corteen & Wood, 1972) found more consistent GSRs to the conditioned stimuli; however, they used materials that consisted of word lists rather than prose. Isolated stimuli in lists may give participants more opportunity to switch attention between the ears. In fact, isolated stimuli placed in the unattended channel have been shown to receive more processing than when the same stimuli are placed in unattended continuous prose, perhaps because their onsets attract attention (Dupoux, Kouider, & Mehler, 2003; Newstead & Dennis, 1979; Poulton, 1956). Thus it is possible that these GSR effects are not due to leakage but are rather due to slippage. P. M. Forster and Govier (1978) replicated the work of Corteen and Wood (1972) using prose rather than word lists. Like Corteen and Wood, they found a significant number of heightened GSRs to shock-associated words on the irrelevant channel. However, the data pattern for words presented on the irrelevant channel was quite different from that for words presented on the shadowed channel. Synonyms of the shock-associated words were more likely to produce a heightened GSR when presented on the shadowed (attended) channel, whereas words that were phonetically similar to the shock-associated words were more likely to produce a heightened GSR when presented on the irrelevant channel. Thus, the irrelevant channel seems to respond more strongly to the physical characteristics of the stimulus, whereas the shadowed channel responds more strongly to the semantic characteristics.

Dawson and Schell (1982) also looked for heightened GSRs to shock-associated words in the irrelevant channel of a dichotic listening experiment. However, they divided trials into two categories: those for which there was evidence that the participant had switched attention (shadowing failures, recall of irrelevant material, or explicit identification of words from the irrelevant channel) and those for which there was no such evidence. Although overall performance was consistent with that found by Corteen and colleagues (Corteen & Dunn, 1974; Corteen & Wood, 1972), most of the GSR effect was due to trials on which there was evidence that the participant had switched attention to the irrelevant channel.

Although the experiments by P. M. Forster and Govier (1978) and Dawson and Schell (1982) both demonstrate semantic effects of irrelevant distractor words, they also indicate that these effects are greatly reduced when steps are taken to ensure that the irrelevant channel is unattended. It is plausible that if both studies had participants shadow more difficult material (as P. M. Forster & Govier, 1978, did) and rejected trials on which there was reason to suspect a shift of attention (as Dawson & Schell, 1982, did), the semantic effects of irrelevant words would disappear entirely.

Thus, despite the large number of experiments demonstrating semantic processing of *irrelevant* information in dichotic listening, there is reason to be skeptical that there is any semantic processing of *unattended* information. Following Holender (1986), we conclude that there are strong reasons to believe that participants switched their attention to the irrelevant ear in these studies. When studies have controlled for this possibility, the effect has shrunk or even disappeared.

Visual Filtering Tasks

In contrast with his views on auditory attention, Holender (1986) concluded that attentional filtering in vision might not be very selective:

> The picture that emerges from the data [on visual attention] is that within a region extending a few degrees around fixation characteristics of attention are opposite to those observed in dichotic listening. Concurrent identification of both the relevant and the irrelevant stimulus is easy and even unavoidable; selection is difficult and even impossible unless the discriminability of the irrelevant stimulus is very low. (p. 11)

This conclusion is supported by a large number of studies demonstrating the processing of irrelevant visual stimuli (e.g., Bradshaw, 1974; Dallas & Merikle, 1976; Driver & Baylis, 1989; Driver & Tipper, 1989; B. A. Eriksen & Eriksen, 1974; C. W. Eriksen & Hoffman, 1972; Gatti & Egeth, 1978; Kahneman & Chajczyk, 1983; Kahneman & Henik, 1981; Kahneman, Treisman, & Burkell, 1983; Neill, Lissner, & Beck, 1990; Neill & Valdes, 1992; Neill, Valdes, Terry, & Gorfein, 1992; Shaffer & LaBerge, 1979; Tipper, 1985; Tipper & Cranston, 1985; Tipper & Driver, 1988; Yantis & Johnston, 1990). Nevertheless, we believe that Holender's strong conclusion is premature. In particular, we know of no studies in which slippage of attention to the irrelevant stimuli was not a strong possibility. Next, we review the literature on visual filtering tasks in more detail, dividing it into three categories: the basic flankers task, negative priming, and flanker experiments with words.

The Basic Flankers Task

The most commonly used visual filtering task requires the participant to explicitly identify or categorize one target letter in a display that also contains one or more irrelevant flanking letters (for this reason, it is often referred to as the *flankers task*). Participants are usually informed in advance of the location of the target letter that they will have to identify. Typically, participants are to press the left button if the target letter belongs to one category (e.g., an *A* or *H*) and the right button if it belongs to a different category (e.g., an *S* or *C*). To test for processing of unattended stimuli, researchers systematically vary the identity and location of the flanking letters in the display. Many researchers have found that responses are faster when the flanking letters are assigned the same response as that assigned to the target letter than when they are assigned a different response (Driver & Baylis, 1989; B. A. Eriksen & Eriksen, 1974; C. W. Eriksen & Hoffman, 1973; C. W. Eriksen & Schultz, 1979; Flowers & Wilcox, 1982; Grice & Gwynne, 1985; Miller, 1987; Yantis & Johnston, 1990). Because of the importance of response compatibility, this effect is sometimes referred to as the *flanker compatibility effect*.

Several recent studies have searched for conditions under which the flanker compatibility effect can be eliminated (Lavie, 1995; Lavie & Tsal, 1994; Miller, 1991; Yantis & Johnston, 1990). Yantis and Johnston (1990), noting the preponderance of data demonstrating that irrelevant flankers are processed, took several steps to eliminate the effects of flankers. Here we list the steps they took, dividing them into those that appear to be directed at preventing slippage (S1 and S2) and those that appear to be directed at preventing leakage (L1–L4).

The steps intended to prevent slippage were as follows:

S1. The cue validity was always 100%. Because participants always knew where the target would appear, they were presumably motivated to attend only to that location.

S2. Although participants were always informed (via a valid cue) where the target would appear, it did not always occur in the same place. The goal was to prevent inhibition of return (a reduction in attention to previously attended locations; see Maylor, 1985; Posner & Cohen, 1984).

The steps intended to prevent leakage were as follows:

L1. Many stimuli were presented simultaneously, resulting in increased perceptual load (thought by some to deter processing of the irrelevant information due to capacity limitations; Lavie, 1995; Lavie & Tsal, 1994).

L2. Stimuli were displayed in a circle so that targets and flankers would be equally crowded. This procedure differs from the typical flanker procedure, in which the flankers appear to the right and left of the target and thus are less crowded than the target (i.e., each flanker has only one neighbor, whereas the target has two neighbors; Flom, Weymouth, & Kahneman, 1963).

L3. Stimuli were separated by more than 1° because, according to some theories, attention cannot be directed with greater resolution than 1°.

L4. The identity of the targets varied from trial to trial (called a *varied mapping* rather than a *consistent mapping* task) to prevent participants from automating their responses to the target (although not all the experiments in their article adhered to this precaution).

Yantis and Johnston (1990) found that these steps nearly eliminated the flanker compatibility effect. The one exception was a small amount of inhibition when the flankers immediately adjacent to the target were incompatible with the target response rather than neutral (there was no evidence of facilitation when these adjacent items were compatible). Thus, consistent with our theory, Yantis and Johnston found little evidence that the irrelevant elements of their displays were identified. They concluded that although some attentional failure may be inevitable, focusing attention on one item can largely prevent semantic processing of other items. However, it should be noted that Yantis and Johnston were attempting to address a somewhat different issue from what we are addressing here. They wanted to determine whether the identification of irrelevant stimuli can be suppressed completely, by taking steps to prevent both slippage (S1 and S2) and leakage (L1–L4). In contrast, we want to know whether the identification of unattended stimuli (i.e., leakage) occurs in the absence of slippage. In other words, we are asking whether leakage is possible, not trying to prevent it. This perspective is reflected in the experiments reported below, in which we actually encouraged leakage while preventing slippage. It could be argued that even though Yantis and Johnston found no evidence for leakage under their conditions, leakage might be possible under more favorable conditions (e.g., with a lower perceptual load).

Miller (1991) also examined factors that might prevent slippage or leakage but took a different approach than did Yantis and Johnston (1990). Rather than taking a large number of steps at the same time, he examined each factor individually to determine whether any one factor is responsible for the flanker compatibility effect. These individual factors often reduced the flanker compatibility effect but did not eliminate it. Unfortunately, for our purposes, it will not suffice to eliminate only one cause of slippage without controlling others. According to our proposal, a flanker compatibility effect should occur when attention slips to the irrelevant flanker. If there are several reasons why participants might accidentally attend to the flankers (e.g., flanker onsets might attract attention, the participant may not know where to attend, or the flankers are presented for extended periods of time), eliminating these factors one at a time might have only modest effects.

Although the analyses provided by Yantis and Johnston (1990) and by Miller (1991) do not provide definitive evidence that leakage or slippage is the cause of flanker compatibility effects, they nonetheless provide insight into its possible causes and thus what factors need to be controlled in future studies. In the rest of this section, we examine each of these factors and the evidence that each plays a role in causing flanker compatibility effects.

L1: Perceptual load. One factor discussed by both Yantis and Johnston (1990) and Miller (1991) is perceptual load. The idea is that people have a limited attentional capacity for processing visual events. When processing of the display is relatively simple, attention can be allocated to the entire display so that all elements will be processed. However, as processing becomes more complicated, it requires more capacity until, at some point, the capacity necessary to handle the entire display exceeds the amount available. At this point (and this point only), a prioritization scheme decides which elements of the display will be attended. The remaining elements of the display will be unattended and therefore not identified. Thus when a participant is asked to do a simple task on a simple display, the entire display is processed, including any irrelevant items. However, when either the task or the stimuli become complicated, capacity is shifted away from irrelevant stimuli, resulting in reduced compatibility effects.

This theory has been developed and tested by Lavie (1995; Lavie & Tsal, 1994).[2] Lavie's theory, which was intended to cover a wide range of conditions, does not define capacity demands rigorously but rather relies on an intuitive assessment. The major question (in the context of our theory) of whether capacity is allocated serially or in parallel is left open. Parallel processing might occur when, as the attended task becomes simpler, it fails to "fill" the limited capacity channel. Under such conditions, the system might be designed to use the extra channel capacity to identify additional stimuli in parallel (regardless of the observer's intentions). This would be a case of leakage because identification cannot be limited to a single attended stimulus. However, it is also possible that this capacity is allocated serially. When the perceptual component of a task is easy, it can be finished more quickly, leaving more time to process alternative stimuli serially. On this proposal, the excess processing capacity is spread across time. This would be a case of slippage because semantic processing occurs for only a single attended stimulus at a time. Lavie's data do not clearly distinguish between these possibilities (parallel vs. serial allocation of capacity). We illustrate this point with a few examples from Lavie's work.

Lavie (1995, Experiment 1; see also Lavie & Fox, 2000) manipulated perceptual load by presenting the target at a known location, either by itself or in a row of neutral distractor letters (not assigned to a response). In addition, a compatible or incompatible flanker appeared outside the area where the target and distractors appeared. Lavie found a flanker effect only when the target appeared alone. Lavie claimed that without the other stimuli in the row of letters, there was extra capacity available to process the flanker. This capacity could be allocated to both the target and flanker simultaneously. However, we offer the following alternative based on a serial allocation of capacity. When there are only two stimuli, the participant identifies the target first and then moves to the flanker (see Pashler & Johnston, 1989; Salthouse, 1986). In the *high load* condition, the participant perceptually processes the target and then moves on to other stimuli in the same row. By the time he or she gets around to the flanker, the target response has already been made. The same criticism holds for the study by Lavie and Cox (1997), which varied the number of distractors that were similar to the target while holding constant the overall number of distractors. Because attention tends to be attracted to items that are similar to targets (Folk et al., 1992), the attentional focus would likely be attracted to the flanker when it was the only item similar to the target and to the distractors when they were also similar to the target.

Lavie (1995) also used a go/no-go procedure that is subject to a similar critique. In this procedure, she presented participants with three items: a primary target (to be categorized), a secondary target (whose identity determines whether the participant is to respond or not), and a flanker (Lavie, 1995, Experiments 2 and 3). By increasing the difficulty of the go/no-go judgment, she increased the perceptual load and eliminated the flanker compatibility effect. However she also greatly increased the overall response times (by more than 300 ms). It is quite possible that while participants were perceptually grappling with the difficult go/no-go decision, they had already decided on a response to the priming target (should they be required to produce one). If so, the effect of the flanker on response selection time would not necessarily be reflected in the observed "go" response times (RTs).

L2: End effects. There is considerable evidence that stimuli at the beginning and end of an array or list are more salient than the middle stimuli (Flom et al., 1963); however, we know of little evidence that they are more likely to produce leakage in an attentional filtering task such as those under discussion. Miller (1991) did not examine this effect; so, given that all of his flankers occurred at end positions, it could be a factor in making his effects as robust as they were.

L3: Distance between flankers and target. The effect of placing distractor items extremely close to the target, in contrast, has been well documented (B. A. Eriksen & Eriksen, 1974; C. W. Eriksen & Hoffman, 1972; Miller, 1991). Specifically, C. W. Eriksen and colleagues (B. A. Eriksen & Eriksen, 1974; C. W. Eriksen & Hoffman, 1973; C. W. Eriksen & St. James, 1986) have used flanker experiments to argue that it is impossible to exclude the identification of irrelevant stimuli within 1° of the target. Miller (1991) also found that increasing spatial separation reduced the flanker compatibility effect. Furthermore, Moran and Desimone (1985) found it impossible to teach monkeys to attend to one of two stimuli, both of which fell in the receptive field of the same cell of cortical area V1 (and were thus within about one quarter of a degree). However, there are reasons to doubt that spacing places a rigid limitation on the ability to focus attention. Pashler (1998, p. 94) pointed out that one can pick out single letters in a page held at arms length (which are about one tenth of a degree apart), suggesting that one can focus attention very narrowly. Conversely, experiments with words have often found effects of irrelevant flanking words much farther in the periphery than 1° (e.g., Fuentes, Carmona, Aris, & Catena, 1994; Gatti & Egeth, 1978; Underwood & Thwaites, 1982), although the distractors must be of sufficient size so that they are legible with the limited acuity in the periphery (Merikle & Gorewich, 1979). Thus flanker effects are not limited to closely spaced stimuli.

It is also possible that the widely reported effects of distance from the target are due more to slippage than to leakage. Closely spaced flankers seem especially likely to attract attention; we do not know how close to the attended location an object can be before attentional orienting mechanisms consider it a possible target. Indeed, recent studies have demonstrated larger attention-capture effects for distractors near the target, although the impli-

[2] Note that Lavie's (1995) theory is similar to that of Broadbent, who also believed in parallel processing up to some capacity limit. However, Broadbent appears to have put the capacity limit much lower than Lavie, giving the work a different spirit. Lavie's theory was also foreshadowed by Treisman (1969); however, Treisman's proposal involved the mandatory analysis of multiple features of a given object (e.g., the inability to ignore an object's form when inspecting its color). Treisman proposed that this mandatory processing occurred because the analyzers for these other dimensions would otherwise be idle and that they could not withhold available capacity. Treisman specifically denied Lavie's proposal that it is possible to spread capacity across multiple objects.

cations of this finding for flanker studies have yet to be worked out (Theeuwes & Godijn, 2001; Wu & Remington, 2003).

L4: Variable versus constant mapping of targets to responses. It has been claimed that when one consistently maps a stimulus onto a response, that mapping eventually becomes automatic, using no attentional resources (Schneider & Shiffrin, 1977). Thus it might be expected that *consistently mapped* (CM) stimuli will produce flanker compatibility effects even when, under comparable conditions, *variably mapped* (VM) stimuli do not. If so, the findings of flanker studies (which in general use only CM stimuli) might not generalize to tasks using VM stimuli. Unfortunately, we know of no attentional filtering studies that have directly compared CM with VM tasks within the same experiment. Yantis and Johnston (1990) found effects of irrelevant letters only when they used a CM task. However, in their VM tasks they were looking for facilitation from items assigned to the same response, whereas in their CM tasks they were looking for inhibition from items assigned to the opposite response. It is not clear which factor is critical. In short, there is currently little evidence regarding whether CM stimuli can increase the chance of leakage.

We now turn our attention from those factors thought to affect leakage to those factors thought to influence the misallocation of attention (slippage).

S1: Cue validity. One hundred percent cue validity is clearly an important factor in preventing attention from being allocated to irrelevant stimuli. Common sense suggests that this is the case—if stimuli are sometimes relevant to the task it seems only reasonable to attend to them. As we noted above, the degree to which participants can divide their attention remains controversial, and a full discussion of this issue is beyond the scope of this article. Here we note that, to the extent dividing attention is possible, the stimuli that attention is divided between could not count as unattended. Furthermore, even if participants cannot divide their attention, there is good reason to think that participants will sometimes attend to locations at which targets appear, even if targets appear there relatively infrequently. The large literature on *probability learning* suggests that participants' predictions of what sort of trial will occur next (and thus what type of trial they should prepare for) match the probabilities of various trial types rather than the optimal strategy of picking the most likely trial type (e.g., Gardner, 1957; Grant, Hake, & Hornseth, 1951; Voss, Thompson, & Keegan, 1959). Several authors have successfully used this probability matching model to predict RT distributions in divided attention experiments (C. W. Eriksen & Yeh, 1985; van der Heijden, 1989).

S2: Inhibition of return. Inhibition of return is the removal of attention from previously attended locations. To prevent inhibition of return from reducing participant's attentional focus, Yantis and Johnston (1990) varied the location of the target from trial to trial. Although we agree with the basic concern that attention may naturally shift to new locations, we doubt that this operates on the time scale necessary for one trial to affect the next. The data that support such concerns (Maylor, 1985; Posner & Cohen, 1984) come from shorter, within-trial time intervals following involuntary allocation of attention. In studies with voluntary attention, there seems to be no inhibition of return (Posner & Cohen, 1984). Miller (1991) presented participants with rows of three letters, in which the letters on the left and right were the same. He then had participants report either the central letter or the two flanking letters. These two types of trials were either intermixed or blocked. Miller actually found a larger flanker compatibility effect when the two types of trials were intermixed (25 ms vs. 44 ms). This finding suggests that to the extent that inhibition of return to a single target location does cause participants to lose attentional focus, the confusion from having multiple possible target locations causes even more slippage. In any case, data from our own experiments (discussed below) indicate that the effects of distractor items can be eliminated even when the attended location remains unchanged across trials.

S3: Abrupt onsets. Miller (1991) examined two additional possible causes of slippage not mentioned by Yantis and Johnston (1990). The first of these possible causes is attention capture by abrupt onsets. As noted in our discussion of shifting attention, a number of authors have argued that stimuli that abruptly appear in an otherwise blank location can capture attention (e.g., Yantis & Jonides, 1984). Miller examined whether attention capture by flanker onsets is responsible for the flanker compatibility effect. To do this, he independently manipulated whether the targets and flankers had abrupt onsets. He found that the flanker compatibility effect did not interact with whether the stimuli had abrupt onsets and thus concluded that onsets were not responsible for the flanker compatibility effect. Nevertheless, the RT difference between compatible and incompatible flankers was largest when both flankers and targets were onsets (about 31 ms when both flankers and targets were onsets, 21 ms when only the flankers were onsets, 16 ms when only the targets were onsets, and 14 ms when neither were onsets).[3] Numerically, these data are consistent with the hypothesis that the presence of abrupt onsets increases the flanker compatibility effect. Miller's failure to find a significant interaction might be because he did not analyze this interaction separately. Instead, his analysis of variance contained two other conditions: flankers identical to target and neutral flankers, which acted in an unexpected manner (e.g., flankers identical to the target were as slow as incompatible flankers with nononset flankers). We would also like to note that nononset targets provide an object for participants to focus attention on before target onset, and thus nononset targets might produce less of a flanker compatibility effect because attention is more focused on the target and less likely to slip to the distractors (see S4 below).

S4: A place marker on which to focus attention. In most flanker effect experiments, a set of stimuli appears on a blank or nearly blank screen. It is assumed that the participant attends to one particular location, yet little is known about whether it is possible to focus attention accurately when faced with a blank screen or about how attention is moved from an inaccurate initial focus to fall on the target. It is possible that the flankers are actually briefly attended before the participant can focus on the target. To examine this issue, Miller (1991) chose to present a sequence of four 200-ms frames, each containing a triplet of letters. In one of the triplets, the center letter was one of two possible target letters and the participant was to classify that letter. The other letters in the triplets could be compatible or incompatible with this target. The idea is that after the first frame, there was an object present for participants to focus their attention on, so that

[3] RTs were estimated by scanning the graph presented in the paper and fitting it with a grid.

there should be little or no flanker compatibility effect when the target appeared in the second, third, or fourth frame.

The critical experiment was Miller's (1991) Experiment 5, in which the identity of the flankers changed after the second frame (i.e., the first two frames contained one flanker and the next two frames contained another). Miller obtained a flanker compatibility effect regardless of the frame in which the target appeared (at least on RT) and therefore concluded that the ability to fixate attention on a particular object is not an important factor in producing flanker effects. Curiously, however, the flanker effect was weakest when the target appeared in the third frame (in RT the flanker effect was about half the size it was when the target appeared in other frames, and in accuracy it disappeared altogether; both interactions were statistically significant). The first and second frames both contained the flankers that appeared on the first frame. By hypothesis, these flankers were attended because participants had not yet focused their attention. By the time the fourth frame was presented, the second set of flankers had been previewed for 200 ms, plenty of time for attention to have slipped to them. It is only on the third frame where attention was likely to have been focused exclusively on the target with no preview of the flanker, and under these conditions, the flanker compatibility effect was greatly reduced. This finding seems to implicate a lack of attentional focus as a cause of the flanker compatibility effect.

Paquet and Lortie (1990) tested the hypothesis that having a marker on which to focus attention affects flanker effects in a slightly more straightforward manner. They found that placing a fixation marker at the location of the target cut the flanker effect in half. This finding strongly suggests that the flanker effect is at least partially due to an inadequate focus of attention prior to stimulus onset.

In addition to the possible causes of slippage mentioned by Yantis and Johnston (1990) and Miller (1991), there are two other reasons one might attend to an irrelevant item that need to be addressed: grouping of flankers with the target and distractor duration.

S5: Grouping of flankers with the target. In the typical flanker experiment, a group of letters is presented simultaneously on the screen. The close proximity, similar appearance, and common onset may induce observers to perceive these letters as a single object (Wertheimer, 1923/1938). Because attention is widely thought to be allocated to entire objects (e.g., Duncan, 1984; Vecera & Farah, 1994), it is plausible that attention is allocated to the target and flankers as a group. Supporting this hypothesis, Driver and Baylis (1989) found that flanker effects are substantially reduced when some effort is made to break the grouping of letters. Furthermore, there may be a specific tendency to group the letter stimuli typically used in flanker experiments because of their very special nature as elements of words. Although the basic flanker task requires that the letters be identified as individual objects, in the real world letters more typically act as features of words. Thus it would not be surprising if letters were automatically grouped and identified as larger units. In this regard, it is worth noting that Ruthruff and Miller (1995) found essentially no flanker effects from letters when the stimuli were not arranged horizontally and therefore did not resemble a word.

S6: Distractor duration. It is interesting to note that neither Yantis and Johnston (1990) nor Miller (1991) discussed short distractor duration as a critical step to prevent shifts of attention. Presumably observers presented with only a few objects will eventually attend to all of them. Thus, even if steps are taken to prevent irrelevant stimuli from being initially attended, they might attract attention shortly thereafter. Thus, to ensure that slippage does not occur, one must present distractors briefly and then mask them (to prevent iconic storage). We believe that the relatively long durations used in the experiments conducted by Yantis and Johnston (until the participant responded) are a primary contributor to the evidence they did find for occasional attentional failures. That they did not get larger compatibility effects with these long exposure durations may have been due to the large number of irrelevant stimuli, which made it unlikely that attention would accidentally shift to any particular distractor (see the discussion of perceptual load above).

Summary of flanker effects. Despite the popularity of the flanker paradigm, and the many studies using it that found influences of irrelevant stimuli, we know of no studies that compel the conclusion that letters can be identified without attention. All reported effects could be caused by participants shifting attention between target and distractor stimuli serially. Indeed, one study that did attempt to eliminate slippage found little effect of distractors (Yantis & Johnston, 1990; see also Ruthruff & Miller, 1995). However this study made a simultaneous attempt to prevent leakage, making it unclear what was responsible for the reduction of the flanker effect.

Negative Priming

In the flankers paradigm, processing of irrelevant stimuli is measured by the degree to which target responses are faster when the irrelevant stimuli are assigned to the same response category as the target. Over the last 20 years, an alternative measure, called *negative priming*, has gained some prominence (Allport, Tipper, & Chmiel, 1985; Tipper, 1985; Tipper & Cranston, 1985). In the negative priming paradigm, items that appear as irrelevant distractors on Trial N are sometimes subsequently presented as targets on Trial N + 1. Typically, participants respond more slowly to these target items that were previously ignored, when compared with neutral controls. Negative priming provides evidence that the distractors were identified, just as the positive priming found in the flanker experiments provides evidence the distractors were identified.

There are cases in which negative priming has been argued to be a more sensitive measure than the flanker effects discussed above (Allport et al., 1985). Thus, negative priming has been used by some to argue that an absence of compatibility effects does not imply that the primes were not processed (Allport et al., 1985). However, in all studies demonstrating negative priming that we are aware of, slippage was a strong possibility, if not virtually guaranteed. First, in the typical negative priming study it is very difficult to select the target over the distractor. For example, the target and distractor usually appear in unpredictable locations and are distinguished only by their color. Such conditions force participants to allocate attention, at least initially, to the distractor to distinguish it from the target. Recent studies argue that when this is not the case, negative priming is reduced or disappears entirely (Moore, 1996; Paquet, 2001; Ruthruff & Miller, 1995; Schmuckler, Joordens, & Yuen, 1999). Second, the distractor item is usually not masked and in fact often remains present until the participant has responded to the target. We have noted above that the duration of the distractor stimulus may be a crucial factor in determining the likelihood of attentional slippage. This factor is even more crucial in the case of negative priming because the priming effect is measured on the subsequent trial. Consider what might happen in a (rare) negative priming experiment in which participants know the location of the target in advance. On display onset, the distractor might be unattended and therefore not identified, resulting in no priming effect on the processing of the concurrent target. But sometime after display onset (perhaps even after a response has been selected), attention might slip to the distractor. The distractor is then identified and inhibited, resulting in negative priming on the subsequent trial (Pashler, 1998). Thus, although negative priming might, in a sense, be a more sensitive measure, it may be more sensitive only because it provides more opportunity for attentional slippage. Indeed, Ruthruff and Miller (1995) have shown that negative priming effects (and flanker effects) trend toward zero under experimental conditions that minimize attentional slippage to the distractor items.

Stroop Effects and Flanker Effects With Word Stimuli

The classic demonstration of the failure of selection in visual processing is an experiment by Stroop (1935; see MacLeod, 1991, for a review). Stroop presented participants with a list of words written in various colors of ink and asked them to name the ink color. The words could be either congruent color names (the name of the ink color) or incongruent color names (the name of a color other than the ink color). The key finding was that the ink color was named more slowly when the words were incongruent than when the words were congruent. This effect, which now bears Stroop's name, is very robust and can be easily demonstrated. The Stroop effect by itself does not imply that unattended stimuli are processed, because one must attend to the word to identify the ink color. However, this effect does illustrate that it is sometimes impossible to ignore irrelevant attributes of attended material.

More recently, the Stroop task has been generalized in several ways. Of particular interest, it has been shown that the Stroop effect holds even when the ink color and the word are separated spatially. Gatti and Egeth (1978), for instance, asked participants to name the color of a patch presented foveally while irrelevant color words were presented in the periphery. They found that incongruent color names interfered with naming and congruent color names facilitated naming, even at 5° of eccentricity. Similar effects have been found by Merikle and Gorewich (1979), Kahneman and Chajczyk (1983), and Kahneman and Henik (1981). This finding suggests that participants identify color words even when they are irrelevant to the task and are presented in an irrelevant location. Although some studies have shown a substantial reduction in this effect at greater eccentricities, Merikle and Gorewich (1979) have found that this reduction can be explained by reduced acuity in the periphery.

These Stroop studies (with color names separated from the to-be-named color patch) have been generalized to other semantic relationships between words and a central target. For example, Rosinski, Golinkoff, and Kukish (1975) found that pictures with congruent names printed nearby were named faster than those with incongruent names nearby. Many studies have also placed two irrelevant words on either side of a fixated target word that must be categorized (e.g., Broadbent & Gathercole, 1990; Fuentes et al., 1994; Fuentes & Tudela, 1992; Shaffer & LaBerge, 1979; Underwood & Thwaites, 1982). Participants respond faster when the peripheral words belong to the same category as the target or are related to it in meaning. These studies are similar to the flanker compatibility studies considered above in that the effects are based on the flanking stimuli sharing a categorization with the targets (thus we refer to these paradigms as *flankers-with-words*). However, because words have richer semantics than letters, the issues raised are somewhat different.

There are at least two separate issues at stake when examining effects generated by supposedly unattended words. One (the main focus of this article) is whether spatial attention is required for words to be identified. A second issue is whether there is a nonspatial capacity-limited resource (usually referred to as central attention) that is necessary for the semantic processing of words. (Note that there is considerable evidence that these two types of attention are distinct, e.g., Johnston, McCann, & Remington, 1995.) Neely and Kahan (2001) examined this second issue in a recent review that focused on the Stroop and flankers-with-words paradigms. They concluded,

> On the basis of the preponderance of evidence [across experiments] we conclude that unless visual feature integration is impaired through misdirected spatial attention, [semantic activation] is indeed automatic in that it is unaffected by the intention for it to occur and by the amount and quality of the attentional resources allocated to it. (Neely & Kahan, 2001, p. 89)

They also stated, "We believe the best evidence favors the claim that when there is no requirement for attention to be focused on a word's individual letters, words in spatially unattended locations automatically activate their meanings" (Neely & Kahan, 2001, p. 78).

Neely and Kahan (2001) were comfortable in assuming that words can be identified without spatial attention given the large number of studies (discussed below) taken to support this claim (e.g., Broadbent & Gathercole, 1990; Fuentes et al., 1994; Fuentes & Tudela, 1992; Gatti & Egeth, 1978; Kahneman & Chajczyk, 1983; Kahneman & Henik, 1981; Merikle & Gorewich, 1979; Shaffer & LaBerge, 1979; Underwood & Thwaites, 1982; van der Heijden, Hagenaar, & Bloem, 1984). Neely and Kahan made a clear case for the robustness of these effects; however, because they did not distinguish between effects caused by slippage and those caused by leakage, the case for processing without attention is less clear. As with basic flanker studies, most studies that found compatibility effects from unattended words used flankers that remained on the screen for a considerable duration. Some studies presented stimuli until the participant responded (Broadbent & Gathercole, 1990; Shaffer & LaBerge, 1979), and most presented stimuli, unmasked, for durations just short enough to prevent eye movements without presenting them quickly enough to prevent shifts of attention (200 ms in Gatti & Egeth, 1978; Merikle & Gorewich, 1979; Kahneman & Chajczyk, 1983; 150 ms in van der Heijden et al., 1984; Fuentes & Tudela, 1992; "brief" in Kahneman & Henik, 1981). As we have noted, these exposure durations allow for multiple shifts of attention (slippage) to the distractor words or their iconic traces. Furthermore, these studies usually involve sudden onsets of stimuli that might tend to group together, in the absence of a place to focus attention. This raises doubts about the claim that semantic activation does not require attention. Such a claim requires evidence that it is leakage and not slippage that is responsible for semantic priming.

Daniel Kahneman and colleagues (Kahneman & Chajczyk, 1983; Kahneman & Henik, 1981) proposed a slippage explanation for the apparent reading of irrelevant words without attention that is very similar to our own theory. In particular, they argued that in Stroop experiments such as those discussed above, the irrelevant color names attract attention and it is only because they attract attention that they cause a Stroop effect. The evidence for this claim came in two forms. First, when the task was to name the color of a color patch (so that any word presented was equally irrelevant), presenting a neutral word along with the color word cut the effects of the color word approximately in half (Kahneman & Chajczyk, 1983). Kahneman and Chajczyk (1983) interpreted this effect (known as *Stroop dilution*) as indicating that attention was captured by only one of the words and only that word produced priming. Second, when the task was to name the color of one of two words (cued by being surrounded by a circle rather than a square), the identity of that word had a much larger effect than the identity of the irrelevant word (Kahneman & Henik, 1981). This finding was taken by Kahneman and Henik (1981) as evidence that a word is more likely to be identified if it is attended.

Kahneman and Henik's (1981) interpretation of their data has been challenged. Van der Heijden et al. (1984), for instance, presented two words in colored ink, one of which had a circle around it (the target) while the other had a square around it (the distractor). Participants were to name the color of the circled word, while ignoring the other word. When, across trials, the target word could be congruent or incongruent with the ink color, van der Heijden et al. (1984) found little effect of the irrelevant word (replicating Kahneman & Henik's, 1981, results). However, when they removed the incongruent trials (resulting in much faster response times overall), the effect of the irrelevant word was much greater. Van der Heijden et al. (1984) argued that the real reason Kahneman and Henik had found so little effect of the irrelevant stimuli was that the representation of these stimuli decayed too quickly. They proposed that attention maintained representations in memory rather than filtering the initial processing of the stimuli.

Kahneman and Chajczyk's (1983) interpretation of Stroop dilution has also been challenged. Brown, Roos-Gilbert, and Carr (1995) replicated Kahneman and Chajczyk's (1983) work (demonstrating Stroop dilution) but included conditions in which participants fixated one of the two words. Brown et al. (1995) reasoned that the fixated word would be more likely to capture attention and therefore, according to Kahneman and Chajczyk's theory, target RTs would be unaffected by the unfixated word. Contrary to this prediction, fixating one of the words had only a small effect on the amount of Stroop dilution. They concluded that Stroop dilution occurs because perceptual interference slows processing of both words, not because only one word is identified. A similar study conducted by Brown, Gore, and Carr (2002), using an exogenous cue (rather than fixation) to manipulate attention, came to a similar conclusion.

Taken at face value, each of these studies presents a considerable challenge to Kahneman and colleagues' (Kahneman & Chajczyk, 1983; Kahneman & Henik, 1981) theory (and, by extension, our own theory). However, each of these studies involved a fairly complex paradigm, in which participants' optimal strategy was not obvious. In van der Heijden et al.'s (1984) experiments, for example, participants were clearly doing something different when the conflicting words were removed (as they were much faster on the neutral and congruent trials, which were the same across experiments). One possible change in strategy is suggested by the fact that Stroop effects increase as the proportion of congruent trials increases (Carter et al., 2000; Logan & Zbrodoff, 1979; Lowe & Mitterer, 1982). Botvinick, Braver, Barch, Carter, and Cohen (2001) argued that the aggregate level of conflict in a display determines how selectively observers process irrelevant stimuli in filtering paradigms. Participants may make a strategic (although not necessarily conscious) decision about the degree of effort put into avoiding the processing of the words. In fact, with fewer conflicting words, there may actually be an incentive to read the words. Notice also that participants must either start in a *diffuse attention mode* to discover where the circle is or check each location serially. In either case, it is doubtful that the irrelevant word (the one in the square) is truly unattended. Thus, even if the critical factor in van der Heijden et al.'s (1984) study turns out to be the time allowed for the word in the irrelevant location to decay, we do not know that processing of that word was accomplished without attention.

Similar issues can be raised with regard to Brown et al.'s (1995, 2002) studies. Because a substantial proportion of the color words were congruent, participants may have had little motivation to ignore them. Furthermore, issues of attention shifting are inherent in the critical conditions where participants fixate an irrelevant word while attempting to name an eccentric color patch. Participants must search for the color patch after recognizing that the item at fixation is not the target. This search may lead them, at least temporarily, to the second word. Thus, although these studies raise questions about the role of attention in producing Kahneman and colleagues' (Kahneman & Chajczyk, 1983; Kahneman & Henik, 1981) results, they fall short of compelling the conclusion that unattended words are identified.

To demonstrate convincingly that slippage is not responsible for Stroop-like effects, one must present the distractor so that it does not attract attention. One obvious way to guarantee this is to present the distractor briefly (for less than the time required for a shift of attention, ~50 ms) in an initially unattended location and mask it. We know of two published studies that met these conditions: Underwood and Thwaites (1982) and Fuentes et al. (1994). However, we do not feel that either study strongly compels the conclusion that the words are identified without attention. Fuentes et al. measured the effect of masked primes on lexical decision. In their study, primes 4.3° to the right of fixation were presented 850 ms prior to the target and masked after 30 ms. Participants could easily have attended those stimuli (out of a natural curiosity or because they used this prime as a signal that the trial was beginning) and then still had time to shift their attention back toward the location of the upcoming target stimulus. In fact, there was not only sufficient time for a covert shift, there was even time for an overt eye movement. Therefore, it is possible that Feuntes et al. failed to adequately motivate participants to ignore the irrelevant stimuli.

Underwood and Thwaites (1982) also used masked priming in a lexical decision experiment, with brief masked distractors presented at a different location than the target. Their conditions come closer to ruling out slippage than those of any other experiment.

The distractors were presented simultaneously with the target, so there was a clear disadvantage to attending to it (i.e., the onset of the target would be missed). Distractors were presented briefly (50 ms) in a location known by the participant to be irrelevant and then masked. That this study is alone in finding priming from a masked word in a location that can be presumed to be unattended makes it worthy of further investigation: more so because the effect was somewhat esoteric in that the priming involved an inhibitory effect of a homophone on a word semantically related to its alternate spelling (i.e., *waist* inhibits *rubbish* because *waste* is semantically related to *rubbish*). It is not clear why such an effect should occur even if the primes were attended and fully processed. Below we present several experiments using a similar masking procedure in a more conventional priming paradigm. In these experiments, we find no evidence for processing of the primes without attention.

Other Paradigms

Although the view that unattended words are identified seems widely accepted on the basis of data from flanker experiments, two recent studies in which other paradigms were used suggest a different conclusion. First, McCann, Folk, and Johnston (1992) found that word frequency effects were additive with the effects of a spatial cuing manipulation (valid vs. invalid spatial cues). Using additive factors logic (Sternberg, 1969) and other considerations, they inferred that the stage affected by spatial attention operates before the stage that is influenced by word frequency. Specifically, they argued that on invalidly cued trials, spatial attention must be reallocated to the location of the word before later processes, which are influenced by word frequency, can begin. If one assumes that word identification is at or after the stage influenced by word frequency (as is commonly believed), then McCann et al.'s results suggest that words are not identified until they are attended. However, some have argued that identification occurs before the stage influenced by word frequency. Besner and Smith (1992), for example, claimed that frequency effects occur during the retrieval of semantic information that occurs after identification.

Second, Besner and Stolz (1999) demonstrated that the Stroop effect can be eliminated when attention is focused on the letter level rather than the word level, arguing that a focus on letters prevents identification of the color words. Thus, unlike the filtering paradigms we have discussed (but much like the original Stroop paradigm), the participant must attend to the distractor word and extract a property from it other than its meaning. It is interesting to note that when one is focused on just a part of the word, the meaning of the entire word no longer seems to be processed. Although it is not clear what the underlying mechanisms are, it may be that attention to the parts actively inhibits the integration necessary to perceive the whole (Neely & Kahan, 2001). Thus people may need to attend to objects as wholes before they are identified.

Summary of the Current Literature

In reviewing the literature, we find overwhelming evidence that participants identify irrelevant stimuli. What is less clear is whether such stimuli are truly unattended. The possibility remains open that attention slips to these irrelevant items. Thus, despite the mountain of studies supposedly showing identification without attention, we feel that the case is not nearly as strong as is commonly believed.

FIVE NEW EXPERIMENTS

Although our review of the literature reveals little evidence of leakage, there is also relatively little evidence against leakage. There simply are few studies that can be interpreted unambiguously. The purpose of this section, therefore, is to conduct a sensitive test for leakage while preventing attentional slippage. As we show below, our experiments provide little evidence that words presented outside the focus of attention are identified.

Motivation for Our General Paradigm

To test for processing of irrelevant words in the absence of slippage, we expanded on the masked priming paradigm developed by K. I. Forster and Davis (1984). Attention was manipulated endogenously by controlling the relevance of different locations (i.e., controlling the probability that the target would occur in different locations: Experiments 1–4) or exogenously by presenting a cue expected to capture attention (i.e., flickering pseudo words: Experiment 5). Primes were presented in either relevant–cued or irrelevant–uncued locations and (in the critical conditions) masked before attention could shift to them (~50 ms).

Task: Lexical Decision

We chose to use a lexical decision task, in which participants determine whether a letter string is a word or not, for a number of reasons. The most important reason is that priming effects have been extensively documented with this task for attended word primes, even when presented for very short durations and masked (e.g., K. I. Forster & Davis, 1984; Rajaram & Neely, 1992; Segui & Grainger, 1990). We know of no other task in which brief, masked primes have consistently generated such robust effects. Thus, lexical decision is a good task for detecting the identification of brief, masked primes.

A second reason to use lexical decision is that there have been at least two reports of priming with brief, masked presentations of unattended words using the lexical decision task (Fuentes et al., 1994; Underwood & Thwaites, 1982). Although it is possible that slippage occurred in these cases (see the previous section), these studies provide arguably the strongest available evidence for leakage.

The final reason to study lexical decision is that priming in this paradigm seems to require identification of the prime. Under masked conditions such as those used in the present experiments, there are a number of findings that imply that the prime has been identified. One example is the finding that repetition priming effects are much stronger for words than for nonwords (see K. I. Forster, 1998, for discussion of this issue). This finding implies that the priming effect is not occurring at the letter level, because faster processing of letters would presumably benefit both words and nonwords. Another example is that under certain conditions, priming is obtained for nearly identical letter strings if the prime is a nonword (e.g., *convenge–CONVERGE*) but not if it is a word (e.g., *converse–CONVERGE*), again implying that the prime was identified (K. I. Forster & Veres, 1998; if not they should act similarly to their nonword counterparts). In addition, priming effects are found for words that are morphological relatives (e.g., K. I. Forster & Davis, 1984; K. I. Forster, Davis, Schoknecht, & Carter, 1987; Frost, Forster, & Deutsch, 1997; Grainger, Colé, & Segui, 1991) or are translation-equivalent terms in two different languages (Gollan, Forster, & Frost, 1997; Grainger & Frenck-Mestre, 1998), showing that aspects of a word's meaning are important in generating priming effects.

Preventing Slippage

Preventing slippage of attention to the primes requires at least two things. First, participants' attention must be focused on the target location (and away from the distractor location) before the prime is presented. Otherwise, identification of the prime might occur before attention is focused on the target. Therefore, we used premasks that gave participants an object to focus on and an object to ignore (see Figure 1). We also helped participants to focus their attention on the upcoming target location by always presenting the targets in the same known location (except in Experiment 3). A second requirement to prevent slippage is that primes be masked before participants have the opportunity to shift attention to them. Otherwise, the primes might be identified following an attention shift. Therefore, in the critical conditions we presented primes for only 55 ms before masking them. Note that participants are not, in general, aware of the identity of masked primes presented for such short durations even when attended.[4] The absence of conscious awareness of the primes, however, has not prevented numerous studies from obtaining robust priming from such stimuli (e.g., Castles, Davis, & Lechter, 1999; Ferrand & Grainger, 1992; K. I. Forster & Davis, 1984; Fuentes et al., 1994; Grainger & Ferrand, 1996; Underwood & Thwaites, 1982). These steps address all of the factors noted by Miller (1991) and Yantis and Johnston (1990) as possible causes of slippage, except for inhibition of return. As we noted in our previous discussion, the positive effects of consistent target placement (allowing a sharper focus of attention) are likely to outweigh the possible negative effects (inhibition of return to the target location).

Maximizing Sensitivity to Leakage

To make our paradigm as sensitive as possible to the effects of leakage (if any), we took a number of steps. First, we used repetition primes. Repetition priming is by far the strongest form of priming with masked primes and has been extensively documented (e.g., Castles et al., 1999; Ferrand & Grainger, 1992; K. I. Forster, 1998; K. I. Forster & Davis, 1984; Frost et al., 1997; Gollan et al., 1997; Grainger & Ferrand, 1996). Of particular importance, repetition priming is far more reliable than associative priming (e.g., *doctor–NURSE*) when the primes are masked (e.g., Perea & Gotor, 1997). In pilot studies with attended words, we found that repetition priming effects were even larger than the well-known Stroop effect (a masked color word followed by a color patch). Hence any failure to obtain priming with repetition primes would be especially noteworthy. Of course, repetition priming could, in principle, occur at a letter or feature level, before identification of the word; however, this fact simply makes a failure to find repetition priming an even stronger demonstration of attentional filtering. Second, primes were presented at a location fairly close to the target (about 1° above). As noted above, it has been argued that leakage is limited to a small area around an attended location (although the data supporting this claim could argue instead that slippage to a nearby object is more likely than slippage to a distant object). Third, in Experiments 1, 2, and 5, primes occurred alone (without other words on the screen). Thus, arguably, the perceptual load was at a minimum.

To summarize the logic of these experiments, we aimed to determine whether unattended prime words can be identified (leakage) and thereby prime a lexical decision on a subsequently presented target word. To ensure that the prime word really was unattended, we encouraged a sharp focus of attention on a different location and presented the prime for a duration too brief to permit a shift of attention. To maximize sensitivity to leakage, we used repetition primes presented close to the target location, with a minimal perceptual load. Under these conditions, a priming effect would provide strong evidence for identification without attention (leakage).

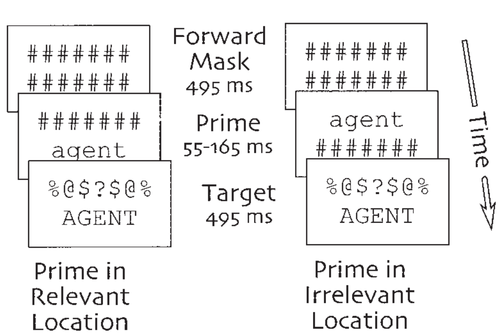

Figure 1. Examples of trials from Experiment 1.

Experiment 1

In this experiment, the target stimulus always appeared in the lower of two locations. Participants were encouraged to attend to this location only. The prime words could be presented in one of two possible locations: the relevant location (i.e., the bottom location, where the target always occurred) or the irrelevant location (one line above the target). To facilitate a precise, narrow focus of attention, we presented forward masks (a row of hash

[4] When looking for a prime, participants are certainly aware that something appears before the target. Even under these conditions, however, they are not consistently aware of what the prime is. Tests of awareness for stimuli similar to ours were carried out by K. I. Forster and Davis (1984) and K. I. Forster et al. (1987). The forward mask, prime, and target were all on the same line. The participants' attention was specifically directed to the masked prime, and their task was to decide whether it was the same as the subsequently presented target item. With a 60-ms duration, the error rate was 41% when the prime was either the same as the target or differed at all letter positions (K. I. Forster & Davis, 1984) and 48.5% when the prime was either the same or differed by one letter from the target (K. I. Forster et al., 1987). Note that guessing would produce an error rate of 50%. Participants in the earlier experiment were also asked to decide whether the prime was a word or not, and the error rate here was 50%. None of these participants reported being able to identify the prime. At most, they reported occasionally seeing a letter or a letter fragment.

marks) in both the relevant and the irrelevant stimulus locations prior to each trial.

Of critical interest were conditions in which the primes were presented briefly (55 ms) before being masked, because only under such circumstances can we be confident that attention did not shift to primes in the irrelevant location (prior to being masked). Also included in this experiment were conditions in which the primes were presented for 110 ms and 165 ms. These conditions allow us to examine what happens when there is sufficient time for participants to allocate their spatial attention to primes in the irrelevant location (attentional slippage), as in most previous studies. There would appear to be little incentive for participants to attend to the prime. However, because they are looking for the target letter string, their attention might be involuntarily captured by the onset of the similar looking prime word (see Folk et al., 1992, 1994). Note that even at these longer prime durations there is still insufficient time for participants to actually move their eyes toward the prime words (Carpenter, 1977; Saslow, 1967; Westheimer, 1954a, 1954b). Thus any differences in priming between the 55-ms duration conditions and the longer duration conditions cannot be attributed to differences in eye position.

Method

Participants

One hundred and twenty students at the University of Arizona participated in partial fulfillment of a course requirement.

Design

We manipulated three factors: (a) whether the prime and target words were the same or unrelated, (b) whether the prime occurred in the relevant location (where the target occurred) or in an irrelevant location (one line above the target), and (c) the duration of the prime (55, 110, or 165 ms). In addition, there were two random factors (participants and items). Because the task was lexical decision, nonword target items were also included. All primes, however, were words (thus the primes were uninformative as to the correct response). Data from nonword targets were used only in assessing participants' overall accuracy.

Stimuli and Procedures

Stimuli like those shown in Figure 1 were presented using a Pentium PC running the Win32-based DMDX experimental control software developed by K. I. Forster and J. C. Forster (2003). Participants were instructed to make a word–nonword judgment on the uppercase letter string as quickly as possible without making many mistakes.

Participants were placed in individual booths. The experiment began with 12 practice trials followed by 240 experimental trials; an experimenter observed the first few trials to make sure the participant understood the instructions. All stimuli were presented in black letters centered on a white background. Participants initiated each trial by pressing a foot pedal. Each trial began with a frame consisting of two rows of hash marks (i.e., #######), one directly above the other, presented for 495 ms. The bottom row of hash marks was located at the location of the upcoming target, and the top row was located just above the target location. These hash marks served three purposes. First, they acted as a warning that the trial was beginning. Second, they precisely cued the location of the relevant and irrelevant objects and gave the participant an object on which to focus attention. Finally, they acted as a forward mask. In the second frame, a lowercase prime word was presented in either the top or bottom row (the other row still contained the hash marks). The prime was presented for 55, 110, or 165 ms. In the third and final frame, the top row was replaced with the string *%@$?$@%*, and the bottom row was replaced by an uppercase letter string (i.e., the target). These stimuli remained on the screen for 495 ms.

Participants were to decide whether the target formed a word. Note that the lower location always contained the target and thus was the only location from which the participant ever needed to extract information. Participants were informed that they would see brief lowercase words, which they should try to ignore. All characters were presented in New Courier, a fixed-width font. The uppercase letters were approximately 4.5 mm high and 4.5 mm wide. The center to center distance was 8 mm. No constraints were placed on head position, so it is not possible to give exact retinal sizes; however, we judged 46 cm to be a comfortable viewing distance, and participants seemed to sit at about this distance from the screen. At 46 cm, 8 mm corresponds to 1° of visual angle.

Materials

All words (targets and primes) were five or six letters long with frequencies between 20 and 70 per million (Kučera & Francis, 1967). We first selected 360 words to serve in this experiment. Of these, 120 were selected at random to serve as word targets (each target word was presented only once to each participant), with the remaining 240 serving as primes. Nonword targets were five- or six-character pronounceable strings that were orthographically legal in English.

Twelve stimulus lists were formed as follows, with the same 120 word targets and 120 nonword targets. First, each of these targets (both words and nonwords) was paired with an unrelated prime chosen at random (without replacement) from the 240 prime words.[5] The 120 word targets were assigned to the 12 experimental conditions (3 Prime Durations × Repeated–Unrelated × Prime in Relevant–Irrelevant Location), so that, across the 12 lists, each word target appeared exactly once in every condition. Thus within each list 10 target words were assigned to each condition. In the repeated conditions, the target word also served as a prime, whereas in the unrelated conditions, the unrelated prime served as the prime. The 120 nonword targets were also assigned to different durations and locations (20 to each combination of duration and location; because all primes were words, there were no repeated nonword trials); however, they were fixed across lists. In addition to these 240 experimental trials, 12 representative practice items were created by using the same method. All participants saw the same practice items in a random order before the experimental trials began.

Each participant was assigned to one of the 12 lists (10 participants per list). The order of presentation of trials was randomized for each participant.

Results and Discussion

Participants who made more than 20% errors ($n = 4$) were replaced. In this and all subsequent experiments, RTs that deviated from a participant's mean (across all word trials) by more than two standard deviations were replaced by a value equal to two standard deviations from the mean. An average for each participant in each condition was then calculated. The resulting means and standard errors are displayed in Table 1 along with a similar analysis for

[5] The average orthographic overlap between unrelated primes and targets for the critical items was less than 0.5 letters in each of the experiments described here.

Table 1
Mean Lexical Decision Response Times (RTs) and Error Rates in Experiment 1

Prime type and location	Prime duration: 55 ms RT in ms	55 ms % errors	110 ms RT in ms	110 ms % errors	165 ms RT in ms	165 ms % errors
Unrelated						
Relevant	629 (10)	9.3 (0.9)	623 (10)	9.0 (1.0)	618 (12)	5.4 (0.8)
Irrelevant	632 (11)	7.6 (0.8)	644 (11)	7.8 (0.8)	639 (11)	11.9 (0.9)
Repeated						
Relevant	591 (10)	6.2 (0.8)	574 (11)	3.6 (0.5)	541 (11)	3.6 (0.6)
Irrelevant	630 (11)	8.1 (0.8)	602 (11)	5.5 (0.6)	583 (11)	5.8 (0.8)
Priming (unrelated–repeated)						
Relevant	39 (6)	3.1 (1.2)	50 (6)	5.4 (1.1)	76 (7)	1.8 (0.9)
Irrelevant	1 (7)	−0.5 (1.3)	42 (7)	2.3 (0.9)	57 (6)	6.2 (1.1)

Note. Standard errors are shown in parentheses.

error rates.[6] An item analysis, in which averages were obtained across words (rather than across participants), was also conducted. The main purpose of the item analysis is to ensure that the observed effects were not generated by a small number of unusual words (Clark, 1973).

When the prime appeared in the relevant location (and thus presumably was attended), we observed strong priming effects at all prime durations, ranging in size from 39 ms to 76 ms. These effects were highly reliable: by participants, $t(108) > 7$, $p < .001$, for all conditions; by items, $t(108) > 6$, $p < .001$, for all conditions. The strong repetition priming observed with the 55-ms prime duration (39 ms) indicates that participants generally had sufficient time to identify even these short duration primes. Strong priming (greater than 40 ms), ts(108) > 6, ps $< .001$, was also observed when the prime was in the irrelevant location, but only when presented long enough to permit a shift of attention to it (110 or 165 ms). This indicates that participants had sufficient acuity to perceive the primes in that location.

Of primary interest was whether repetition priming would occur for 55-ms primes in the irrelevant location. In this condition, participants (presumably) initially focused their attention on the relevant location, and there was insufficient time for participants to shift their attention to the prime word before it was masked. Hence, we believe that these prime words were unattended. This condition produced essentially no repetition priming (only 1 ms, on average), ts(108) < 1, whereas the corresponding condition with the prime in the relevant location produced 39 ms of priming. These results argue that unattended words were not processed enough to result in priming. In particular, there appears to have been no lexical or semantic leakage outside the focus of attention.

The pattern seen in the RTs was repeated in the error data. Priming effects were significant for the relevant/55-ms condition—by participants, $t(108) = 2.64$, $p < .01$; by items, $t(108) = 2.72$, $p < .01$—the relevant/110-ms condition—by participants, $t(108) = 5.16$, $p < .001$; by items, $t(108) = 5.01$, $p < .001$—the irrelevant/110-ms condition—by participants, $t(108) = 2.56$, $p < .05$; by items, $t(108) = 2.46$, $p < .05$—and the irrelevant/165-ms condition—by participants, $t(108) = 5.83$, $p < .001$; by items, $t(108) = 3.37$, $p < .005$. The relevant/165-ms condition was significant by items, $t(108) = 2.30$, $p < .05$, but only approached significance by participants, $t(108) = 1.97$, $.05 < p < .10$. It is important to note that when the prime appeared in the irrelevant location for only 55 ms, there was no priming, ts(108) < 1; in fact, the trend was for control words to have slightly fewer errors.

Although short-duration prime words in the irrelevant location produced very little priming, longer duration primes in the irrelevant location produced significant priming effects (though always less than primes of the same duration presented in the relevant location). We attribute this priming at longer exposures to attentional slippage: Prime words in the irrelevant location can capture attention. If attention arrives before the prime word has been masked, then the prime word can be processed sufficiently to produce priming. According to one very simple slippage model, the lexical and semantic processing of the unattended stimulus is delayed by the amount of time required to shift attention (see Johnston et al., 1995, for a similar model). On this view, the amount of priming from stimuli in the relevant and irrelevant locations can be equated simply by increasing the exposure duration of the stimulus in the irrelevant location by an amount equal to the shift time. It is interesting to note that this simple model fits the data from the present experiment extremely well, with an approximate attention-shift time of 55 ms (notice the horizontal shift of about 55 ms between the two curves in Figure 2). For instance, a 110-ms prime in the irrelevant location produces about as much priming as a 55-ms prime in the relevant location. Likewise, a 165-ms prime in the irrelevant location produces about as much priming as a 110-ms prime in the relevant location. It is interesting to note that this estimate of the shift time (55 ms) is very close to the estimates provided by previous research (e.g., Tsal, 1983).

The excellent fit of this simple model suggests that it deserves further investigation. However, it should be noted that the model is overly simplistic. For example, the primes in the irrelevant location were more eccentric than those in the relevant location; the

[6] Note that in statistical analyses and calculation of standard errors, the mean for each condition on each list was subtracted from each participant or item score in that condition. This procedure has the effect of eliminating list variance from estimates of within-condition variance.

increased eccentricity might have reduced the priming effect (though, as we show in Experiment 5, this effect must be rather modest). In addition, it is unrealistic to expect primes in the irrelevant location to always capture attention after exactly 55 ms, yet any variance in this value is not captured by the model. Furthermore, this model does not address the issue of whether attention capture by primes in the irrelevant location necessarily means that attention has left the target location. Alternatively, attention might spread to cover both locations, as suggested by the fact that prime location has little effect on absolute RTs in the control conditions.

Experiment 2

We propose that the 55-ms primes in the irrelevant location produce little or no repetition priming because they were unattended and because unattended words are not identified. However, it is logically possible that these primes were identified, but there was insufficient time for this processing to influence lexical decisions to the target. One particular hypothesis worth considering is that unattended prime words are identified, but for some reason it takes longer for the unattended primes to produce an effect on the target (see Broadbent & Gathercole, 1990; Gathercole & Broadbent, 1987). For example, Carrasco and McElree (2001) found that inattention not only reduced asymptotic performance but also slowed processing of stimuli. To explain the data from Experiment 1, this delay would need to be about 55 ms. On this view, we should be able to roughly compensate for the delay in the effect of an unattended prime simply by inserting a 55-ms delay between prime offset and target onset. In other words, an unattended prime with a 55-ms delay before the target should produce roughly the same amount of repetition priming as an attended prime without the delay. This prediction was tested in Experiments 2A and 2B. In Experiment 2A, there was no delay between the prime and the target, just as in Experiment 1. The only way in which this experiment differed from Experiment 1 is that we eliminated the 110- and 165-ms prime durations to concentrate more data in the condition of primary interest (the 55-ms condition). Experiment 2B was similar, except that there was a 55-ms delay between the offset of the prime and the onset of the target, as shown in Figure 3.

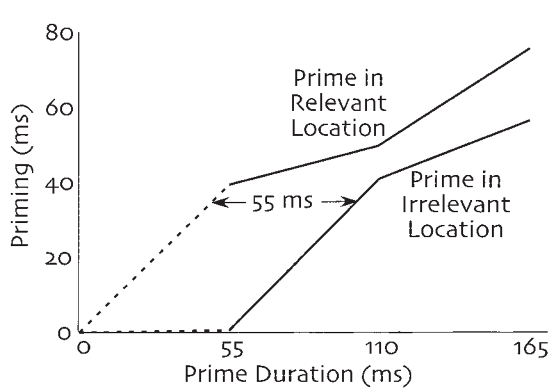

Figure 2. Priming as a function of stimulus onset asynchrony.

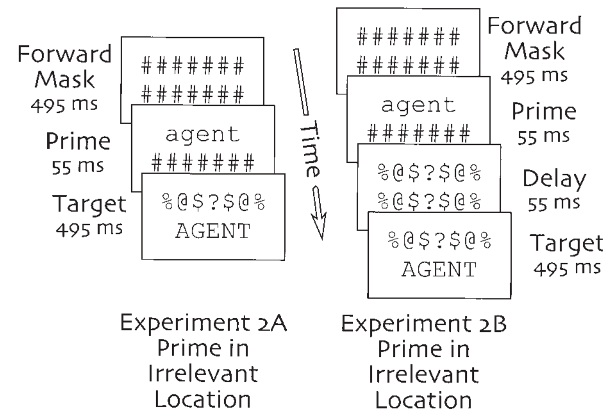

Figure 3. Examples of stimuli from Experiments 2A and 2B.

Method

Participants

Eighty students (40 in Experiment 2A and 40 in Experiment 2B) at the University of Arizona participated in partial fulfillment of a course requirement.

Design

Prime–target SOA was manipulated between the two experiments (2A and 2B). There were two additional experimental factors of interest within each experiment: (a) whether the prime and target were the same or different and (b) whether the prime occurred in the relevant location (i.e., the target location) or in the irrelevant location. In addition, there were two random factors (participants and items).

Stimuli, Materials, and Procedure

Stimuli and materials were the same as those used in Experiment 1 except as follows: In both experiments (2A and 2B), the prime duration remained constant at 55 ms. Notice that at 55 ms the primes were too short to be seen consciously by participants and thus most participants were unaware that they were present. In Experiment 2A, the number of trials per condition was 18, with an additional 12 practice trials. Words with frequencies from 30 to 70 per million were used. Because participants were, in general, unaware of the primes, reference to them was omitted from the instructions. In Experiment 2B, the number of trials per condition was 20, with an additional 16 practice trials. Words with frequencies from 20 to 70 per million were used. A 55-ms backward mask was introduced between the prime and the target (see Figure 3). This mask served the purposes of extending the prime–target SOA without increasing the duration of the prime and roughly equating the masking of the prime in all conditions. Like Experiment 1, but unlike Experiment 2A, participants were told that they might see lowercase words and to ignore them.

Results

Experiment 2A (No Break Between Prime and Target)

Analysis procedures were similar to Experiment 1. Participants who made more than 20% errors were replaced ($n = 4$). The mean RTs and error rates are displayed in Table 2.

As in Experiment 1, the priming effect was much larger when the prime was in the relevant location (51 ms) than when it was in

Table 2
Mean Lexical Decision Response Times (RTs) and Error Rates in Experiment 2

Prime type and location	Experiment 2A RT in ms	Experiment 2A % errors	Experiment 2B RT in ms	Experiment 2B % errors
Unrelated				
Relevant	590 (17)	7.9 (1.2)	574 (15)	10.1 (1.3)
Irrelevant	588 (19)	7.5 (1.2)	564 (14)	11.1 (1.4)
Repeated				
Relevant	539 (17)	3.9 (0.7)	522 (12)	5.4 (1.0)
Irrelevant	578 (17)	5.7 (0.8)	548 (10)	9.9 (1.3)
Priming (unrelated–repeated)				
Relevant	51 (6)	4.0 (1.2)	51 (7)	4.8 (1.3)
Irrelevant	11 (7)	1.8 (1.2)	16 (7)	1.2 (1.2)

Note. Standard errors are shown in parentheses.

the irrelevant location (11 ms): by participants, $t(36) = 6.39$, $p <$ .001; by items, $t(68) = 4.14$, $p < .001$. For attended primes, the priming effect was significant: by participants, $t(36) = 8.54$, $p <$ .001; by items, $t(68) = 8.40$, $p < .001$. For unattended primes, the priming effect was not significant by participants, $t(36) = 1.55$, $p > .10$, but was significant when analyzed by items, $t(68) = 2.16$, $p < .05$.

The error data show similar effects. With primes in the relevant location, participants made less than half as many errors on repeated trials as on unrelated trials: by participants, $t(36) = 3.55$, $p < .01$; by items, $t(68) = 3.40$, $p < .01$. In contrast, there was no significant difference in error rate between the repeated and unrelated prime conditions when the primes were in the irrelevant location. The difference between priming with primes in the relevant and irrelevant locations was not significant by participants, $t(36) = 1.59$, $p >.10$, although it approached significance by items, $t(68) = 1.67$, $.05 < p < .10$.

Experiment 2B (55-ms Delay Between Prime and Target)

Participants who made more than 20% errors were replaced ($n = 3$). The mean RTs and error rates are displayed in Table 2.

As in Experiment 1, the priming effect was much larger when the prime was in the relevant location (51 ms) than when it was in the irrelevant location (16 ms): by participants, $t(36) = 5.28$, $p <$ .001; by items, $t(76) = 4.51$, $p < .001$. For attended primes, the priming effect was significant: by participants, $t(36) = 7.02$, $p <$ .001; by items, $t(76) = 8.46$, $p < .001$. For unattended primes, the priming effect was significant when analyzed by participants, $t(36) = 2.46$, $p > .05$, and by items, $t(76) = 3.01$, $p < .005$.

These effects were mirrored in the error data. When primes were in the relevant location, participants made about half as many errors on repeated trials as unrelated trials: by participants, $t(36) =$ 3.66, $p < .001$; by items, $t(76) = 3.80$, $p < .001$. In contrast, the effect of prime type when the primes were in the irrelevant location was not significant. This interaction was significant by participants, $t(36) = 2.07$, $p < .05$, although not by items, $t(76) =$ 1.52, $p > .10$.

Between-participants analyses were carried out to compare priming in Experiments 2A and 2B. The differences did not approach significance for either attended or unattended primes, $ts(78) < 1$.

Discussion

Experiments 2A and 2B examined the possibility that unattended primes are identified just as rapidly as attended primes but that they are delayed in influencing responses to the target. According to this explanation of our results from Experiment 1, identification of both the attended and unattended primes occurs in roughly the first 50 ms; however, extra time (~50 ms) is required to link the identity of unattended words to response processes. If this explanation were true, increasing the SOA between the prime and target by an additional 55 ms (even without increasing prime duration) should greatly increase the observed priming from primes in the irrelevant location, so that it is approximately as large as the priming effect from an attended 55-ms prime. Contrary to this expectation, the addition of the 55-ms break between prime and target in Experiment 2B had very little effect. These data argue against the hypothesis that unattended primes are identified as quickly as attended primes but it takes more time for them to influence RTs to the target. The most parsimonious explanation of these data is that processing of the unattended primes was sharply attenuated.

These results replicated those of Experiment 1 in that the attended primes produced much larger priming effects than did the unattended primes. These results differ somewhat from the results of Experiment 1, however, in that they appear to show slightly larger priming effects for the irrelevant location with a prime duration of 55 ms. These conditions produced about 15 ms of priming in Experiment 2, whereas the equivalent condition of Experiment 1 produced only 1 ms of priming. One clue is that in Experiment 2A, we observed significant priming when the results were analyzed by items but not when analyzed by participants, indicating that the priming effect was not consistent across participants. This result led us to examine the data of individual participants. On such examination, it is immediately apparent that the priming effect is present only for the slowest participants. A very similar pattern was also found in Experiment 2B. Table 3 shows the average amount of priming when the prime occurred in the relevant and irrelevant locations as a function of the participant's overall RT. In Experiments 2A and 2B, clear priming for unattended primes occurs only for participants whose average RT is more than one standard deviation above the mean (cutoffs were 675 ms for Experiment 2A and 630 ms for Experiment 2B).[7]

Notice, in contrast, that slow participants in the 55-ms prime condition of Experiment 1 did not show especially large priming effects. The most salient methodological difference between Experiments 1 and 2 is that Experiment 1 also contained 110- and 165-ms primes, whereas Experiment 2 did not. Although this difference might seem trivial, it is important to note that the 110- and 165-ms primes are generally visible to the participant, whereas the 55-ms primes are not. Consequently, the participants in Ex-

[7] Note that the same basic pattern of results is obtained regardless of whether the participants are classified on the basis of overall RT (as in Table 7) or on the basis of just their RTs in the repeated condition or the unrelated condition.

Table 3
Priming (in Milliseconds) in Experiments 1 and 2 Broken Down by Participants' Overall Response Time (RT)

Relative Mean RT	Prime location: Relevant	Prime location: Irrelevant
Experiment 2A		
Faster than $M - 1SD$ ($n = 5$)	63	11
Between $M - 1SD$ and M ($n = 19$)	44	−2
Between M and $M + 1SD$ ($n = 10$)	53	10
Slower than $M + 1SD$ ($n = 6$)	63	52
Experiment 2B		
Faster than $M - 1SD$ ($n = 5$)	39	−2
Between $M - 1SD$ and M ($n = 19$)	44	2
Between M and $M + 1SD$ ($n = 10$)	51	18
Slower than $M + 1SD$ ($n = 6$)	87	80
Experiment 1		
Faster than $M - 1SD$ ($n = 5$)	34	−12
Between $M - 1SD$ and M ($n = 19$)	47	2
Between M and $M + 1SD$ ($n = 10$)	28	13
Slower than $M + 1SD$ ($n = 6$)	36	−6

periment 1 were much more likely to be aware of the presence of the primes and hence more likely to make an effort to ignore them. In fact, many participants in Experiment 1 offered that their "strategy" was to try to ignore the lowercase (prime) words. Thus we suspect that the inclusion of trials with salient primes increases participants' motivation to precisely focus their spatial attention on the target location and may also increase their motivation to use temporal filtering as well (see Naccache, Blandin, & Dehaene, 2002). Consistent with this hypothesis, Experiment 1 produced less priming from both the attended and unattended primes than did Experiment 2.

Thus it seems very plausible that there was more attentional slippage to primes in the irrelevant location in Experiment 2 than in Experiment 1. Specifically, we suspect that some participants in Experiment 2 might not have focused their attention (prior to the trial), resulting in both the target and the distractor locations being attended to some degree. Note that as far as the participants were aware, no interfering words ever appeared in the irrelevant location. This hypothesis not only explains why we found more priming from primes in the irrelevant location in Experiment 2 than in Experiment 1 but also explains why only the slowest participants showed priming effects. Participants who sometimes allow their attention to slip to the irrelevant location will respond more slowly (because they are not always attending fully to the target) and will also produce larger priming effects from words in the irrelevant location.

The hypothesis that a minority of participants in focused attention experiments may not choose to or be able to focus their attention as closely as others is not novel. Conway et al. (2001) reported that only low-memory span participants noticed their name in the irrelevant channel of a dichotic listening task. They suggested that poor executive control could cause participants to fail both tasks (although they noted that it is also possible that an inability to focus spatial attention might cause poor executive control). Thus, the hypothesis that some participants do not focus their attention as well as the majority can explain not only our data but also that of other studies of focused attention. Although this speculation is interesting and deserves further investigation, it should not distract us from our main finding, which is that most participants showed little evidence of having identified the primes when they were presented in the irrelevant location for only 55 ms.

Experiment 3

Experiments 1 and 2 demonstrated that lexical decisions to a target are influenced by short duration (55 ms) prime words in the relevant location but are little influenced by the same prime words when they appear in the irrelevant location. We attribute this difference to the fact that the primes are attended in one case but not in the other. However, this is not the only possible explanation. The primes in the relevant location happen to always appear in the same location as the target, whereas the primes in the irrelevant location always appear in a different location from the target. Therefore, the critical factor might not be whether the primes are attended, but rather whether the prime and the target appear in the same location (Shiffrin, Diller, & Cohen, 1996). Two items presented in the same location might be more likely to be seen as part of the same object, and it has been shown (at least for unmasked primes) that priming effects are stronger when the prime and target are grouped together as part of the same object (Kahneman, Treisman, & Gibbs, 1992).

The design of Experiments 1 and 2 conflated these two factors (whether the prime is attended vs. whether the prime is in the same location as the target), so it is impossible to determine which factor was critical on the basis of those data. Experiment 3, therefore, was designed to tease apart these two variables. We presented two thirds of the targets in one location and one third in the other location. We refer to these as the *expected* and *unexpected* target locations, respectively. The expected target location was on top for half the participants and on the bottom for the other half. Presumably, participants will primarily attend to the expected location. Note, however, that we would expect this attentional manipulation to be weaker than that of the previous experiments because of reduced certainty regarding the target location (Yantis & Johnston, 1990).

This design permits a factorial manipulation of whether primes appear in the expected location and whether the prime and target appear in the same location. If the critical factor determining priming is whether the prime and target appear as part of the same object, then we should expect to find larger priming effects when the prime and target appear in the same location than when they appear in different locations. It should make little difference whether the prime was in the expected or unexpected location. Meanwhile, if the critical factor is whether the prime is attended, then we would expect to find more priming when the prime appears in the expected location than when it appears in the unexpected location. It should make little difference whether the target does or does not happen to appear in the same location as the prime.

The stimuli in this experiment differ from those of previous experiments in several ways. First, primes were presented simultaneously in both locations (see Figure 4). This design made data

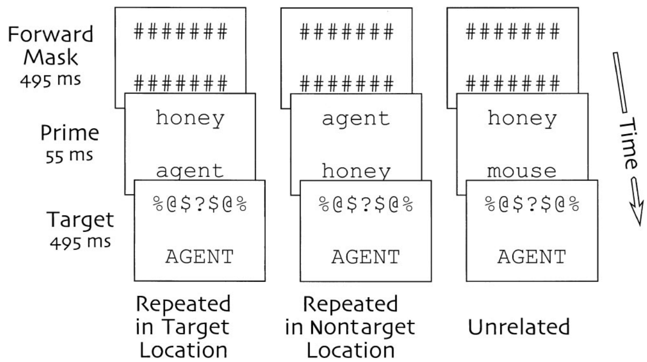

Figure 4. Examples of stimuli from Experiment 3.

collection more efficient because a single unrelated-prime control condition could be used for both repeated-prime conditions (expected location primes and unexpected location primes). Second, the prime duration was 41 ms. Finally, the primes were slightly farther apart (see Figure 4). We felt these last two steps would increase the likelihood of integration of the target and primes occurring in the same location while decreasing the likelihood of integration from two separate locations.

Method

Participants

Sixty students at the University of Arizona participated in partial fulfillment of a course requirement.

Stimuli, Materials, and Design

Stimuli were similar to those used in previous experiments with a few exceptions (see Figure 4). First, lowercase primes appeared in both the top and bottom locations on every trial. Second, the two possible stimulus locations were twice as far apart (17 mm rather than 8 mm). Finally, the primes were presented for 41 ms rather than 55 ms. All words (targets and primes) were five or six letters long with frequencies between 30 and 70 per million (Kučera & Francis, 1967).

Two factors were manipulated within participants: target location and type of prime (repeated/target location as the target, repeated/nontarget location from the target, or unrelated). Participants completed 12 trials in each condition. In addition, the expected location (top vs. bottom) was counterbalanced across participants. To reduce the number of different lists required, we assigned each target word to either the top or bottom location. (Thus, an item analysis is not possible for comparisons between top and bottom target locations.)

The design described in the previous paragraph contained equal numbers of expected and unexpected trials (72). Therefore, to achieve the proper ratio (2:1) of expected to unexpected, we added 72 *biasing* trials in which the target appeared in the expected location. These biasing trials were not analyzed, except to determine the overall percentage correct. The primes in these trials were never identical to the target. In addition, there were 18 practice trials, which were also biased in a 2:1 ratio.

Results and Discussion

Participants who made more than 20% errors were replaced (n = 10). The results appear in Table 4, shown separately for participants who expected the target to appear in the top location and participants who expected the target to appear in the bottom location. The most striking aspect of these results is that when we collapse across the locus of attention, it makes little difference whether the repeated prime and target appear in the same location. The difference in mean response time (3 ms) was nonsignificant: by participants, $t(54) < 1$; by items, $t(66) < 1$. This outcome makes it clear that the relative location of the prime and target was not primarily responsible for the pattern of data found in Experiments 1 and 2.

There was a trend for participants who were biased to the bottom location to produce larger priming effects than those who were biased to the top location: by participants, $t(54) = 2.80$, $p < .01$. However, this effect was not replicated in Experiment 4 and was not significant by items, $t(66) = 1.46$, $p > .10$. Furthermore, this effect did not interact with priming effects, which were the focus of these studies.

Once again, the pattern found in error rates closely mirrors that found in RTs. There was no overall difference between priming in the same location and different location conditions. In fact, there was a trend toward participants being more accurate in the repeated/nontarget location conditions than in the repeated/target location conditions (by participants: 0.9%, SE = 1.1%).

Table 5 presents a different breakdown of the data, so that we can determine whether primes in the expected location (which

Table 4
Mean Lexical Decision Response Times (RTs) and Error Rates in Experiment 3 Broken Down by Prime Location Relative to Actual Target Location

	Expected target location					
	Bottom		Top		Average	
Prime type and location	RT in ms	% errors	RT in ms	% errors	RT in ms	% errors
Unrelated	690 (32)	8.6 (1.3)	664 (18)	8.1 (1.7)	677 (18)	8.3 (1.1)
Repeated						
Target	658 (25)	8.3 (1.3)	649 (20)	7.4 (1.5)	654 (16)	7.8 (1.0)
Nontarget	661 (28)	6.7 (1.5)	652 (18)	7.2 (1.3)	656 (17)	6.9 (1.0)
Priming (unrelated–repeated)						
Target	31 (12)	0.3 (1.2)	15 (7)	0.7 (2.1)	23 (7)	0.5 (1.1)
Nontarget	29 (10)	1.9 (1.2)	13 (6)	0.8 (1.5)	21 (6)	1.4 (1.0)

Note. Standard errors are shown in parentheses.

Table 5
Mean Lexical Decision Response Times (RTs) and Error Rates in Experiment 3 Broken Down by Prime Location Relative to Expected Target Location

	Expected target location					
	Bottom		Top		Average	
Prime type and location	RT in ms	% errors	RT in ms	% errors	RT in ms	% errors
Unrelated	690 (32)	8.6 (1.3)	664 (18)	8.1 (1.7)	677 (18)	8.3 (1.1)
Repeated						
Expected	655 (26)	6.4 (1.4)	645 (20)	5.6 (1.1)	650 (16)	6.0 (0.9)
Unexpected	664 (27)	8.6 (1.4)	656 (18)	9.0 (1.5)	660 (16)	8.8 (1.0)
Priming (unrelated–repeated)						
Expected	35 (11)	2.2 (1.2)	20 (7)	2.5 (1.7)	27 (7)	2.4 (1.1)
Unexpected	25 (10)	0.0 (1.4)	8 (6)	−1.0 (1.8)	17 (6)	−0.5 (1.1)

Note. Standard errors are shown in parentheses.

presumably were usually attended) produced more priming than those in the unexpected location (which presumably were usually unattended). The difference in priming between primes in the expected and unexpected locations (11 ms) was significant by participants, $t(54) = 2.13$, $p < .05$, and marginally significant by items, $t(66) = 1.93$, $.05 < p < .10$. This experiment differs from the previous two in that there is relatively strong priming even when the prime is in the location where fewer primes appeared. Presumably this effect occurred because the target appeared there on one third of the trials, leading participants to attend that location some of the time. This could have been accomplished either by attending to both locations at once (a diffuse mode of attention) or by attending to just one at a time with probability matching across trials. Probability matching involves attending to each location with a probability equal to the probability that that location is the target; in this case, participants would attend to the less likely location on about one third of the trials. It has been shown that both people and animals tend to probability match even when it is a suboptimal strategy (e.g., Gardner, 1957; Grant et al., 1951; van der Heijden, 1989; Voss et al., 1959). Equivalently, participants might have continued to attend to the location of the target on the previous trial, a strategy several participants claimed to have used. Of interest, the probability-matching strategy predicts that the amount of priming from the less likely target location should be half that from the more likely location. This prediction matches the observed data fairly well. Note that this probability-matching hypothesis not only explains why we found more priming from unattended primes relative to Experiment 1 but also explains why we appear to have found less priming from attended primes. As we show below, Experiment 4 is consistent with this hypothesis.

The error data show priming when the prime appeared in the expected location but not when the prime appeared in the unexpected location. The difference between the expected and unexpected conditions (2.8%) was again significant: by participants, $t(54) = 2.70$, $p < .01$; by items, $t(66) = 2.79$, $p < .01$.

Experiment 4

Experiment 3 indicated that priming depends on the degree to which participants attend to the prime, not on whether the prime and target appear in the same location. However, primes in the less relevant location did produce a significant amount of priming. We proposed that this priming occurred because participants adopted a probability-matching strategy (or something equivalent), whereby they attended the unexpected location on a substantial proportion of trials (about one third). Alternatively, the effectiveness of primes in the less relevant location in Experiment 3 might indicate that there is a modest amount of leakage from unattended primes.

The goal of Experiment 4 was to verify, by using the methods of Experiment 3, that primes in the unattended location produce much less priming when that location is always unattended (as in Experiment 1). The design replicated that of Experiment 3, therefore, in all respects except that the target always appeared in the expected location and never in the unexpected location.

Method

Participants

Twenty-four students at the University of Arizona participated in partial fulfillment of a course requirement.

Stimuli, Materials, and Design

Stimuli were the same as those used in Experiment 3 except that for each participant, targets appeared only in one location (top or bottom) and the biasing items were removed. Each participant saw 24 trials in each combination of target lexicality (word or nonword) and type of prime (same location as target, different location from target, or control).

Results

Results are shown in Table 6. Once again, the priming effect was much larger when the repeated prime appeared in the expected–relevant location (41 ms) rather than in the unexpected–irrelevant location (0 ms): by participants, $t(18) = 5.62$, $p < .001$; by items, $t(66) = 5.39$, $p < .001$. For repeated primes in the relevant location, the priming effect was significant: by participants, $t(18) = 7.70$, $p < .001$; by items, $t(66) = 6.24$, $p < .001$. When repeated primes were in the irrelevant location, however, the priming effect did not approach significance: by participants, $t(18) < 1$; by items, $t(66) < 1$.

Table 6
Mean Lexical Decision Response Times (RTs) and Error Rates in Experiment 4 Broken Down by Prime Location Relative to Expected Target Location

	Expected target location					
	Bottom		Top		Average	
Prime type and location	RT in ms	% errors	RT in ms	% errors	RT in ms	% errors
Unrelated	560 (19)	5.9 (1.7)	581 (28)	6.3 (1.9)	571 (17)	6.1 (1.3)
Repeated						
Expected	516 (14)	4.2 (1.5)	542 (28)	2.4 (1.0)	529 (16)	3.3 (0.9)
Unexpected	556 (24)	7.6 (1.9)	585 (28)	5.9 (1.4)	571 (18)	6.8 (1.2)
Priming (unrelated–repeated)						
Expected	43 (9)	1.7 (1.8)	39 (6)	3.8 (2.1)	41 (5)	2.8 (1.4)
Unexpected	4 (7)	−1.7 (1.4)	−4 (7)	0.3 (2.1)	0 (5)	−0.7 (1.3)

Note. Standard errors are shown in parentheses.

The same pattern was seen in the error data. There was a significantly larger priming effect when the repeated prime was in the relevant location than when it was in the irrelevant location: by participants, $t(18) = 2.67$, $p < .05$; by items, $t(66) = 2.75$, $p < .01$. There was a marginally significant priming effect when the repeated prime was in the relevant location: by participants, $t(18) = 1.99$, $.05 < p < .10$; by items, $t(66) = 1.83$, $.05 < p < .10$. There was no such effect when the prime was in the irrelevant location: by participants, $t(18) < 1$; by items, $t(66) < 1$.

Discussion

Unlike the present experiment, Experiment 3 presented targets in the expected location on two thirds of the trials and in the unexpected location on one third of the trials. In that experiment, we observed small but significant priming effects from the unexpected location, which we attributed to a probability-matching strategy (or something equivalent). Experiment 4 discouraged probability matching by presenting the targets in the expected location on every trial. As predicted, we found no evidence of priming from words in the unexpected–irrelevant location. The results therefore closely resemble those of Experiment 1 with the somewhat different display conditions of Experiment 3.

Experiment 5

In Experiments 1–4, we observed substantial priming from masked words presented in a relevant and presumably attended location, even when they were presented for as little as 41 ms. However, when the same words were presented in an irrelevant and presumably unattended location, we found essentially no priming. Our interpretation of these findings is that when the irrelevant words are unattended they are not identified. Another possible explanation of these findings, however, is that the irrelevant words were not identified simply because they were presented too far from fixation. In Experiments 1, 2, and 4, participants presumably fixated their eyes near the location where the target always appeared. Primes in the other location were not only unattended but also eccentric.

The purpose of Experiment 5 was to determine whether the lack of priming from words in the irrelevant location is due to a lack of spatial attention or to the eccentricity. The basic approach was to vary the locus of attention without varying the eccentricity of the prime word. To accomplish this goal, we presented an exogenous cue just prior to the onset of the prime, as shown in Figure 5. This cue consisted of a series of three different nonwords presented for 27.5 ms each followed by a row of hash marks presented for 27.5 ms (for a total duration of 110 ms). We believed that this cue would capture spatial attention for the same reason we believed that prime words captured attention in Experiment 1: When participants are looking for a target word, the appearance of another wordlike object is likely to capture attention. Although we assume that this cue will capture attention, note that the cue duration is too short (110 ms) to permit participants to move their eyes to the top location before a 55-ms prime has been masked. Furthermore, because the target word always appears at the bottom location, it seems unlikely that participants would move their eyes to a cue in another location, even if they had time to do so.

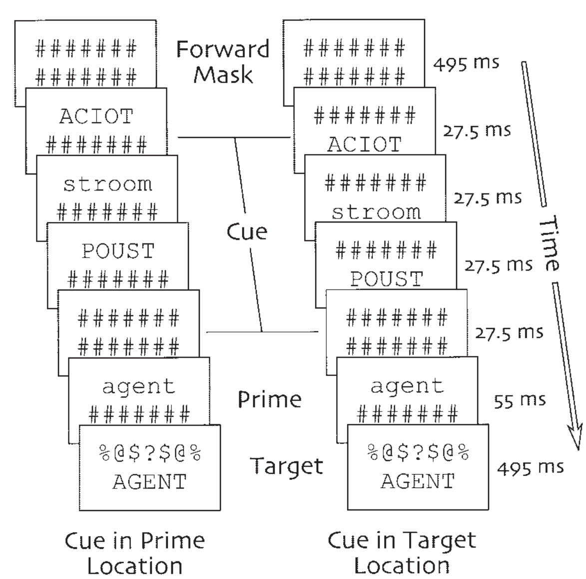

Figure 5. Examples of stimuli from Experiment 5.

In this experiment, the target always appeared in the bottom location (just as in Experiments 1 and 2). We presume, therefore, that participants fixated their eyes near this location. The prime words were always presented for 55 ms in the top (irrelevant) location and therefore were just as eccentric as in the irrelevant location conditions of Experiments 1 and 2. On half of the trials, the cue appeared in the bottom location; because the prime word appeared in the other (top) location, it presumably was unattended. On the other half of the trials, the cue appeared in the top location; because this cue is presumed to capture attention (at least sometimes), the prime word should be attended in this condition. Thus, we manipulated attention while holding prime eccentricity constant.

If words are identified only when attended, then the irrelevant prime words (always in the top location) should produce priming when the cue is on the top but not when the cue is on the bottom. Note that even if some participants do not always attend strictly to the bottom location at the beginning of each trial (as we argued was happening in Experiment 2), the cue in the bottom location will serve to redirect attention to that location. In other words, both endogenous and exogenous attention cuing are working together in this condition. Thus, this condition would appear to provide an even cleaner test of whether unattended words are identified.

Alternatively, if eccentricity rather than spatial attention is the key factor, then the irrelevant words should not produce priming in either condition. In both of our conditions, the prime words appeared in the top (eccentric) location, whereas the target word appeared in the bottom location (where participants will presumably fixate).

Method

Participants

Thirty-two students at the University of Arizona participated in partial fulfillment of a course requirement.

Stimuli, Materials, and Design

Stimuli were similar to those used in Experiments 1 and 2 with the following exceptions (see Figure 5). First, primes appeared only in the top location. Second, the 55-ms prime was preceded by a cue. This cue consisted of three nonwords (drawn at random from the same set of nonwords used for the nonword targets) followed by the same row of hash marks used as premasks in Experiments 1–4. Each of these nonwords (and the row of hash marks) was presented for 27.5 ms so that this cue lasted a total of 110 ms. The cue could appear in either the location of the prime (the top location) or the location of the target (the bottom location).

Several different considerations went into the selection of this particular cue. The reason to use nonwords, rather than words, in the cue was to minimize the involvement of lexical mechanisms, reducing possible inhibition of the following prime. Similarly, because various models of word recognition allow a "winner" to shut out competitors (e.g., McClelland & Rumelhart, 1981), we used brief exposures of each nonword (27.5 ms) to decrease the likelihood that any particular representation of the cue would be "settled" on. We added the row of hash marks to the end of the cue so that the stimulus immediately preceding the prime word would always be the same (i.e., whether cued or uncued); this served to roughly equalize the level of premasking of the prime between conditions. The total duration of the cue (110 ms) was short enough to ensure that participants could not fixate the prime with their eyes but long enough to ensure that covert spatial attention would have time to move to the top location. Earlier, we estimated that attention might be reallocated in as little as 55 ms, on average; however, on individual trials this reallocation may take longer (or shorter). Therefore, to allow for random variation in the time to shift attention and for any misestimation of this time, we used a cue duration of 110 ms.

Immediately following the cue, the prime appeared for 55 ms in the top location. As in the previous experiments (with the exception of Experiment 2B), the prime was immediately followed by an uppercase target word in the bottom location. All words (targets and primes) were five or six letters long with frequencies between 20 and 79 per million (Kučera & Francis, 1967).

Three factors were manipulated within participants: target lexicality, cue location, and type of prime. Participants completed 30 experimental trials in each condition. In addition, there were 16 practice trials, 2 in each of the eight conditions.

Results

Participants who made more than 20% errors were replaced ($n = 4$). The results appear in Table 7.

The exogenous attention cue had a strong influence on the effectiveness of the prime. When the cue appeared in the same location as the target (i.e., a different location from the prime), no evidence of priming was found ($M = -1$ ms): by participants, $t(28) < 1$; by items, $t(116) < 1$. In contrast, when the cue appeared in the same location as the prime, 27 ms of priming was found: by participants, $t(28) = 6.16$, $p < .001$; by items, $t(116) = 4.93$, $p < .001$. This difference was highly significant: by participants, $t(28) = 4.92$, $p < .001$; by items, $t(116) = 4.26$, $p < .001$.

A similar pattern of results was found in the accuracy data. When the cue appeared in the same location as the target, no effect of the prime was found: by participants, $t(28) = 0$; by items, $t(116) = 0$. When the cue appeared in the same location as the prime, participants made fewer errors when the prime was the same as the target: by participants, $t(28) = 2.40$, $p < .05$; by items, $t(116) = 2.36$, $p < .05$. This effect of cue location on priming approached significance by participants, $t(28) = 1.73$, $.05 < p < .10$, but not by items, $t(116) = 1.42$.

Discussion

In this experiment, we manipulated the locus of spatial attention using a cue consisting of a sequence of flickering nonwords, while

Table 7
Mean Lexical Decision Response Times (RTs) and Error Rates in Experiment 5

Prime type and cuing	RT in ms	% errors
Unrelated		
Prime cued	559 (13)	8.2 (1.2)
Target cued	546 (12)	7.8 (1.1)
Repeated		
Prime cued	532 (13)	5.6 (1.0)
Target cued	547 (13)	7.8 (1.0)
Priming (unrelated–repeated)		
Prime cued	27 (4)	2.6 (1.1)
Target cued	−1 (4)	0.0 (1.1)

Note. Standard errors are shown in parentheses. The target always appeared in the bottom location, and the prime always appeared in the top location.

holding the eccentricity of prime words constant. Our theory predicts priming effects when the prime was cued (i.e., attended) but not when the prime was not cued (i.e., unattended). In fact, this is precisely what we found. This finding argues strongly against the suggestion that the lack of priming from irrelevant words in the top location is due to eccentricity.

Although eccentricity cannot explain our results, it is possible that eccentricity plays some role here. Although there was substantial priming when the cue occurred in the location of the prime, there was less priming in this experiment than in Experiments 1, 2, and 4 with the primes in the relevant location. This difference may have been due to a residual effect of eccentricity. However, it is also possible that attention did not always shift to the cued location in Experiment 5 (whereas attention was always allocated to the relevant location in Experiments 1, 2, and 4). Participants were aware that the location where the primes were presented would never be relevant and thus may have partially inhibited attention shifts to that location (Yantis & Jonides, 1990). However, neither of these possibilities takes away from the fact that a substantial priming effect was found under conditions in which the prime was presumably attended but was entirely eliminated under conditions in which the prime was presumably unattended.

Implications of These Experiments

We conducted five experiments to determine whether word identification occurs for unattended stimuli. In each of these experiments, we presented a prime word either at a location that was presumably attended or at a location that was presumably unattended. This prime word could be either identical to or unrelated to a subsequent target stimulus. The primary dependent measure was the degree to which the prime stimulus influenced lexical decisions to the target (the repetition priming effect).

In Experiment 1, priming was much weaker for primes in the presumably unattended location than for primes in the presumably attended location. In fact, when the prime was presented in the unattended location for only 55 ms (so that it disappeared before participants could reallocate attention to it), the amount of priming was essentially zero. By comparison, an attended prime of the same duration produced 39 ms of priming. In Experiment 2, the addition of a delay between the prime and the target produced no apparent increment in the amount of priming for unattended primes. This result argues against the hypothesis that unattended primes are identified but simply take more time to influence the processing of the target stimulus. Experiment 3 showed that priming does not depend on whether the prime and target appear in the same location, and thus appear to comprise the same object. Rather, priming depends on whether the prime is attended. Converging evidence for this conclusion was obtained in Experiment 5, in which the prime and target always appeared in different locations and attention was manipulated with an exogenous cue. Cued (and thus presumably attended) primes were effective, but uncued (and thus presumably unattended) primes were not, again suggesting that attention is required to identify these words. These results provide further evidence against alternative explanations based on the prime's spatial relationship to the target or its distance from fixation. In summary, the data suggest that participants simply do not identify words that are unattended.

We also found evidence that when participants are looking for a target word, prime words can capture attention. Primes presented for longer than the amount of time required to shift attention (the 110- and 165-ms conditions of Experiment 1) in irrelevant locations did produce significant priming effects. We suggested that this priming at longer exposures was due to attentional slippage, in which initially unattended prime words are able to capture attention. The data from Experiment 1 are explained nicely by a (probably overly) simple slippage model, which assumes that (a) primes always capture attention, (b) the resulting shift of attention takes about 55 ms, and (c) the amount of priming observed is a function of how long the prime is attended (see Figure 2). Further evidence that wordlike stimuli can capture attention was found in Experiment 5, in which the onsets of orthographically legal nonwords appear to have drawn attention to their location.

As we noted in the introduction, many studies have reported priming effects from irrelevant material, and such findings are widely interpreted as demonstrating the leakiness of attentional filtering. However, irrelevant stimuli are not necessarily unattended. As von Helmholtz (1910/1925) claimed,

> It is natural for the attention to be distracted from one thing to another. As soon as the interest in one object has been exhausted, and there is no longer anything new in it to be perceived, it is transferred to something else, even against our will. (p. 498)

Thus it should not surprise us that when stimuli are presented for extended periods of time, people shift their attention to them. Our data suggest that irrelevant and initially unattended stimuli do not begin to be identified until they have been presented for more than about 50 ms (enough time for a shift of attention). This is what would be expected from a filter theory that allows no identification without attention (provided that such a model is augmented with a modern understanding of attention capture). However, although our data are compatible with such models, we also need to examine whether they rule out models that incorporate leakage.

Alternative Hypotheses

The dominant view over the past 40 years has been that if an early attentional filter exists at all, it must be leaky, allowing unattended stimuli to be identified (Allport et al., 1985; Deutsch & Deutsch, 1963; Fuentes et al., 1994; Lavie & Tsal, 1994; Miller, 1991; Neely & Kahan, 2001; Treisman, 1960). Here we have described how the results used as evidence for leakage can instead be explained by the slippage of attention to irrelevant items. This alternative explanation undermines the *raison d'être* for the postulation of leakage. Slippage of attention is a very well-documented phenomenon and by itself is capable of explaining why irrelevant items are sometimes identified. Thus, there is really no need to postulate a route to object identification for unattended objects.

We have taken this argument further by providing new empirical evidence that when steps are taken to minimize slippage, irrelevant stimuli are not identified. Our findings further undercut any reason for postulating identification without attention. Nonetheless, many researchers strongly believe that at least some objects are identified without being attended. We do not expect them to relinquish the search for identification without attention. Nor should they. It is not yet clear how our results will generalize to different forms of masking, different attentional manipulations, different stimuli, different tasks, or different measures. Consequentially, our data are open to a number of alternative hypotheses. In this section, we discuss these hypotheses and how new data could be brought to bear on them.

Does Attention Merely Attenuate Signals?

Theories of attentional filtering lie along a continuum ranging from those in which unattended objects receive no semantic activation (such as ours) to those in which unattended items receive as much semantic activation as attended ones (such as Deutsch & Deutsch, 1963). We believe that the present data provide strong evidence that the truth lies close to the "no leakage" end of the continuum. Several of our experiments produced no priming at all from unattended primes. However, it is unclear whether it is even possible to determine whether there is actually no leakage or simply very little leakage. Furthermore, it is not clear that the view that there is no leakage is simpler or more intuitive than the view that there is very little leakage.

We suspect that ultimately, some leakage will be demonstrated to occur in some situations. However, it appears to us that current data showing identification of irrelevant stimuli are better explained by postulating slippage than by postulating leakage. If we are correct, current theories that postulate leakage are simply wrong about which mechanisms are responsible for a wide range of behavioral effects.

Is Attention a Facilitator?

In 1976, Neisser attacked filter theories (a term he construed very broadly, including not only Broadbent's theory but its late selection rivals as well) for claiming that attention worked only to suppress processing of certain stimuli. The alternative metaphor Neisser proposed was that attention acted as a facilitator, selecting objects for further processing. In the context of our theory, this view raises two questions. First, does one of these metaphors better capture our (or Broadbent's) view than the other? Second, does one of these metaphors better capture the truth? With respect to the first question, despite Neisser's claims, Broadbent seemed to think of attention more in terms of facilitation than suppression. The name *filter theory* may be permanently attached to Broadbent's model, but he actually refers to attention as a *selective filter*, a term that echoes both the suppression and the facilitation metaphors. In fact, in the summary of his 1958 book (Broadbent, 1958, pp. 297–299), the term *filter* appears only in a diagram (as part of the term *selective filter*). There is no place in this summary where any form of suppression is discussed. The word *select* and its derivatives, in contrast, are used 13 times.

Because this issue is a matter of some controversy and at the same time orthogonal to our interests, we have attempted to state our theory in a way that abstracts out any claim about whether attended stimuli are facilitated or unattended stimuli are suppressed. Our view is that although both of these metaphors are useful, neither should be taken too literally. The truth may be closer to Desimone and Duncan's (1995; Desimone, 1998; Reynolds et al., 1999) biased competition model in which networks representing features of a particular object facilitate each other and inhibit features of other objects, resulting in a competition where the stable states of the system are those in which only one object is represented. Facilitation and suppression interact in complex ways in such a model, and it is not clear that either metaphor captures this interaction. In any case, this issue is beyond the scope of this article.

Does Attention Prevent Processing of Unattended Words Only When the Task Requires Word Processing?

In our experiments, both the target and the prime are words. It is possible that when the primary task is word processing, one must make sure that the functional units devoted to word processing are not overloaded by irrelevant wordlike stimuli (Brown et al., 2002). In contrast, when the primary task is not word processing, as in the Stroop paradigm, word processing mechanisms might be free to pick up this nominally irrelevant information. In an experiment with color-patch targets, for instance, words presented in unattended locations might be routinely identified. This hypothesis could explain the numerous findings of Stroop effects from irrelevant words, even when those words were separated spatially from the color patch (Brown et al., 1995; Kahneman & Chajczyk, 1983). However, as we discussed above, there is reason to doubt that any of these experiments showing Stroop effects involved distractors that were truly unattended. Consequently, at present, we prefer to adopt the parsimonious conclusion that unattended words are not identified, regardless of the task at hand.

Is Attention Needed Only to Process Masked, Eccentric Words?

We have concluded that in our masked priming study, there was no identification without attention. However, one can question the generality of this finding. Do unmasked visual stimuli (e.g., words on the page of a book in good lighting conditions) also require attention to be identified? Because we did not study priming effects from unmasked words, we cannot be certain that the same conclusions would apply. It is certainly possible that masked stimuli have a special need for attentional resources (as noted by an anonymous reviewer). However, we know of no direct evidence supporting this assertion. Furthermore, there is direct evidence from other paradigms that unmasked stimuli also require attention to be identified. In particular, McCann et al. (1992) used a cuing manipulation with unmasked words to address this issue. They provided evidence that when the location of a target word was invalidly cued, attention had to first be redirected toward that word before identification could begin. Thus, their data suggest that our conclusions do indeed generalize beyond the identification of masked words. Nevertheless, this is an important issue and deserves further investigation.

Would a Nonbehavioral Measure Show Evidence of Stimulus Identification?

We took several steps to provide a sensitive test for the identification of unattended words. However, no behavioral measure (such as priming) can prove that unattended primes are not identified. In principle, priming effects could be blocked at several different points. It is conceivable, for instance, that unattended words are identified but are later blocked in such a way that prevents any behavioral consequence. An alternative means of assessing whether unattended words are identified would be to use neuroimaging techniques. Using both fMRI and ERP techniques, Dehaene et al. (2001) have demonstrated that masked words produce activation patterns that differ from those produced by visible words. It is possible that such techniques could demonstrate high-level processing of unattended words, even when such processing has minimal behavioral consequences. In the absence of such data, however, a relatively peripheral blocking of prime processing seems most compatible with the attention literature and with available neurophysiological evidence.

Central Rather Than Peripheral Attention?

It might be possible to explain our findings in terms of central attentional processes rather than in terms of peripheral, spatial attentional processes. For instance, it is possible that the early accumulation of evidence is equal for attended and unattended items, but later decision processes largely ignore the accumulated information about the unattended items. However, this type of explanation leads to several theoretical complications. First, when little time elapses between prime and target (as was the case here), priming effects are usually assumed to be the result of automatic processing (Neely, 1977). If so, allocation of central attention would seem to be irrelevant. Second, it is not clear why central attention should depend so strongly on physical location. After all, the prime in the relevant location is no more relevant to the task than the prime in the irrelevant location. One could argue that when a prime occurs in the same location as the target, it is more likely to be linked to that target by some resource-consuming central operation. However, this account is inconsistent with the present Experiment 3, which showed that unattended primes cause relatively little priming even when the target happens to appear in that same location. Conversely, Experiments 3 and 5 both show that strong priming can be obtained when the prime and target are in different locations. Thus, the effectiveness of the prime depends on whether the prime appears in an attended location, not on whether it appears in the same location as the target. At this point, explaining our data by reference to a spatially selective central mechanism adds unnecessary complexity, given the sufficiency of an early attention model.

This line of argumentation should not be taken to suggest that we do not believe in the existence or importance of central selective mechanisms. Clearly there is strong evidence for such mechanisms (e.g., Johnston et al., 1995; Pashler & Johnston, 1998). Of particular relevance here, the existence of negative priming (Allport et al., 1985; Tipper, 1985; Tipper & Cranston, 1985; also see discussion above) suggests that items that have received peripheral attention can later be inhibited centrally. However, we believe that our effects closely match known properties of peripheral attention and are a poor fit to those of central attention.

CONCLUSION

We have proposed a filter theory of attention that echoes many of the ideas proposed by Broadbent. In particular, we have attempted to resurrect the claim that there is no identification without attention. This hypothesis has long been maligned on the basis of numerous studies showing that irrelevant stimuli are identified. However, a careful review of these studies shows that they failed to control for movements of attention. What has routinely been taken as evidence for leakage through the attentional filter could instead be caused by slips of attention. Given the paucity of studies taking sufficient steps to prevent slippage, we decided to conduct our own study. Despite attempts to maximize the sensitivity of our paradigm, we found no evidence of leakage. This finding is consistent with the general trend in the literature that the more experimenters attempt to prevent nuisance factors such as attentional slippage, the less evidence they find that irrelevant stimuli are identified (e.g., Pashler, 1998, Chapter 2; Ruthruff & Miller, 1995; Yantis & Johnston, 1990). We conclude that Broadbent was correct after all: There is no identification without attention.

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