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Top-down Influences on Crowding: The Word Superiority Effect and Attentional Cuing

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ABSTRACT

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The goal of the current studies was to examine the influence of top-down mechanisms on the crowding effect. Crowding refers to the reduced ability to identify an object, typically a letter, when other objects in the periphery surround it spatially. We used crowding as a tool to examine the semantic contribution to word superiority effect and investigate the role that attentional cuing plays in both the crowding effect and the word superiority effect. In Experiments 2 and 3, we used a secondary task of either a lexical decision task or an additional letter identification task to assess priming from related crowded items, and found that semantics do not play a role in the word superiority effect. By controlling for letter sequence familiarity we found that words and pronounceable non-words produced comparable priming effects, suggesting that the word superiority effect results from pattern familiarity. In Experiments 4 and 5, we examined whether attentional cuing of crowded stimuli produces target enhancement, distracter suppression effects, or both. We found that neither endogenous nor exogenous cues produced distracter suppressions effects, but there was evidence for signal enhancement effects especially with word stimuli. The evidence suggests that exogenously and endogenously orienting attention interact with the word superiority effect such that they enhance the effect of context for words, but do so in different ways.

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Table of Contents

List of Figures

List of Tables

Introduction

Our analysis of the world is influenced by top-down mechanisms. This is true of all cognitive processes. In perception, there is the process of filling-in that allows us to process shapes as wholes even when they are occluded. Attention acts to facilitate processing of some items at the expense of others via top-down mechanisms. Memory is reconstructive in nature based on prior experiences. Language has filling-in in the form of the phonemic restoration effect, and the list goes on. The influence of top-down mechanisms is important for the ways we represent the world, and therefore our understanding of these mechanisms is important for our understanding of how the brain and cognitive processes operate.

Crowding

The purpose of the present studies was to investigate the influence of top-down processes, specifically attentional cuing and context, on the crowding effect. We did not manipulate crowding effects, but rather we used crowding as a tool to examine the semantic contribution to the word superiority effect and attentional cuing effects on crowded word and non-word stimuli. Crowding occurs when identification of a peripheral target stimulus decreases as nearby distracters are added. It has been shown that as items become more eccentric, their discriminability decreases due to a decrease in acuity in the periphery compared to the fovea. However, if an item is flanked by distracters as in crowding, there is a much sharper decrease in discriminability as eccentricity increases (Bouma, 1970). The crowding effect depends on the spacing of the distracters from the target. As the distance between the distracters and the target increases, the discriminability of the target increases. Specifically, the distracters need to be approximately 0.5 x eccentricity degrees away from the target for performance to mimic the single letter condition at the same eccentricity (Bouma, 1970). For example, at an eccentricity of 10 degrees the distracters need to be 5 degrees away from the target for it to be as perceptible as when presented alone.

This phenomenon has commonly been known as *crowding* in the vision literature and *lateral masking* in the psychological literature. There is still controversy regarding the similarities and differences between the two and when to use each label appropriately (c.f. Huckauf & Heller, 2004; Pelli, Palomares, & Majaj, 2004). Both crowding and lateral masking involve the pooling of information over time and/or over space, and this pooling of information results in a less perceptible target. However, recent findings suggest that they are two distinct phenomenon. Lateral masking is the disruption in stimulus awareness due to the presence of surrounding items, and is said to occur as a result of lateral inhibitory interactions between neurons in primary visual cortex. The research below describing adaptation has shown that the crowding phenomenon occurs at a later stage of processing, thus arguing for a distinction between the two phenomenon. Crowding results from a disruption in identification of the stimuli while feature processing in primary visual cortex is preserved. Crowding only affects proper identification, while leaving detection intact (Pelli, et al., 2004).

Feature integration is used to recognize the center letter of the crowded item. Feature integration allows for the individual elements that form an object to be joined, and excludes those elements that do not belong to the object (Treisman & Gelade, 1980; Pelli, et al., 2004). This feature integration process has been likened to attentional selection, where attention needs to resolve what features correspond to each item for selection. In the case of crowding, feature integration needs to parse the elements that belong to the distracter items from those that belong to the central target. Thus, the elements need to be properly conjoined and then categorized or identified as some familiar item (e.g. an A vs. a B), in order to report the identity of the target. Tyler and Likova (2007) propose that this occurs via a mechanism called a "comparator." The feature integration mechanism or the "comparator" mechanism breaks down in some manner under crowded conditions, the extent to which has not yet been resolved in the literature. Both of the steps in this process, the parsing of the elements and the identification have been shown to contribute to crowding. A deficit in parsing can be seen in "location errors," or errors in which the subject reports a distracter item (most often an adjacent distracter). A deficit in identification can be seen in "item errors," or errors occurring when a subject reports an item not present in the display (Huckauf & Heller, 2002). Location errors might occur because in a crowded letter identification task when subjects are unsure of the target they are generally told to guess, and if there is a distracter that appears more visible than the target, then they guess that letter.

Huckauf and Heller (2002) had subjects report the center letter of a crowded display in a partial report procedure, as well as every item in the display in a whole report procedure. They found that correct identification of the center letter was higher in the whole report procedure than in the partial report procedure. They also found that the item on the left (in the right and left visual field) was reported correctly most often, suggesting that subjects were using a reading process to scan the items. This top-down reading process might have facilitated the processing of the center item in the whole report condition. Further, it might be true that when the letters form a word (not tested by

Huckauf and Heller, 2002), the letters' positional information is less affected by crowding leading to greater accuracy in reporting the center letter.

The phenomenological experience of a crowded item has been reported to be a graying out of the feature or an inability to resolve what the features are (Pelli, et al., 2004). The distracter items are visible and tend to be identifiable, although this varies with the number of distracters present, and those distracters presented foveally to the target (closer to the fovea) are generally perceived better that those presented parafoveally to a target (Chastain, 1983). Distracters presented to the left of the target (independent of visual field) are also more likely to be reported in the case of a location error, presumably because we read left to right (Huckauf & Heller, 2002).

The graying out of the central letter maps nicely onto a theory that the receptive fields in areas V2 and V3 (that have receptive fields large enough to encompass a target and distracter item) are producing inhibition of neighboring receptive fields thus producing this graying phenomenon for items in the center of two receptive fields (Tyler & Likova, 2007). For example, for the letter sequence A B C, if one receptive field encompasses A and part of B, while another encompasses C and part of B, all the while inhibiting each other, the mutual receptive field inhibition is going to impair perception of the B because each half is being inhibited by the other receptive field. Such an explanation locates the source of the crowding to be at a level higher than V1, where the receptive fields are too small and would not extend beyond the borders of one item.

Other research has shown that crowding occurs at a higher level than V1. This research (He, Cavanagh, & Intriligator, 1996; He, Cavanagh, & Intriligator, 1997; Montaser-Kouhsari & Rajimehr, 2005) has shown that adaptation is immune to crowding.

In an adaptation procedure a certain stimulus (i.e., a vertical grating) is presented for an extended duration during which time the neurons that respond to that particular feature (i.e., vertical orientation selective cells) decrease their firing rate. This adaptation phase is then followed by a test phase in which the same or a different test feature is presented (i.e., a vertical or horizontal grating) and performance to the test stimulus is measured. Adaptation occurs when performance is better on the non-adapted stimulus then on the adapted stimulus, because the adapted neurons are no longer firing at the same level as the non-adapted neurons. Adaptation has been shown to occur in early visual areas (V1 neurons), and thus if such orientation adaptation is immune to crowding then crowding must occur at some higher level. This also offers support for the claim that crowding results from a breakdown of the feature integration mechanism or the "comparator" mechanism, which operates after orientation (feature) processing.

Additionally, the crowding phenomenon is greater in the upper visual field compared to the lower visual field (He, et al., 1996). This is in contrast to the neural representation of space in primary visual cortex, which is equal across the visual fields, providing further evidence that the crowding effect occurs at a level higher than V1.

If the crowding effect results from a breakdown of the feature integration mechanism, or the attentional selection mechanism, then this would suggest that it is the processing resolution of attention that limits the identification of the crowded target. Support for this hypothesis comes from a study by He, et al. (1996) who hypothesized that if crowding is related to attentional resolution then tasks requiring more attention should be performed better when presented in the lower visual field (because crowding is reduced in the lower visual field) while a task requiring little attention should not show an asymmetry. They presented crowded stimuli in which the target was a feature or a conjunction of features, which they hypothesized would tap performance requiring less attention and more attention, respectively. Their results fully supported their hypothesis, with only the conjunction condition showing better performance in the lower visual field. These findings show that attentional manipulations influence the extent of crowding and support their hypothesis that crowding is limited by attentional resolution. A possible neural explanation for this effect comes from the asymmetry of dorsal stream projections from early visual areas into the parietal lobe that are highly involved with attention (Posner & Petersen, 1990). These projections are more numerous from the lower visual field than the upper visual field (Maunsell & Newsome, 1987).

However, there are others who disagree with He, et al. (1996). These researchers argue instead that crowding results from the pooling of information across an inappropriately large area, which occurs preattentively and is independent of attentional resolution (Pelli, et al., 2004; Freeman & Pelli, 2007). The representation of the target includes features from the distracters, which degrades identification. This is the main reason why the spacing of target to distracters (called critical spacing) is important in crowding, because as the spacing increases the likelihood of target and distracter feature pooling decreases. Pelli, et al. (2004) claim that the brain uses "integration fields" over which to integrate information. These fields vary in size from very small in the fovea, to large in the periphery. They are inappropriately large for identification of individual elements in the periphery, resulting in crowding.

Single unit recording studies in primary visual cortex have shown that the response of a given cell to an item in its receptive field is modulated by presenting information in adjacent receptive fields (Kapadia, Ito, Gilbert, & Westheimer, 1995; Zipser, Lamme, & Shiller, 1996). The modulation appears to be maximal when the additional item (in the adjacent receptive field) is collinear to and of the same orientation as the item in that cells' receptive field. The modulatory response decreases as these properties deviate from the collinear orientation. The modulatory response varies in a given area, with some cells showing facilitation (increased firing rate) to the additional item, while others show an inhibitory response. These findings show that surrounding information (context) modulates the responses of cells. The target is visible when presented alone, but the context of surrounding information modulates the response of the cell to the target.

Logan's (1996) CODE theory offers a modeling view as to how information from the visual scene might be selected for processing. Logan proposes that all items are represented in a bottom up manner by (normal) distributions on a spatial surface, with additional top-down mechanisms that can set a threshold for perceptual grouping of individual items. The threshold can be varied, but a threshold defined as the local minimum, set as the lowest threshold for which an item's distribution can be separated from other distributions, can account for the decrease in accuracy seen in identifying a crowded item. It can account for the hypothesis that the decrease in identification of a crowded item results from the inability to parse and conjoin all appropriate features for that item. The model proposes that when items are closely spaced to one another the distributions of the items are close, and the local minimum threshold would be set higher than when the items are farther away and the distributions more widely spaced. When the items are close to each other the distributions will overlap with each other more than when they are farther apart, and thus when a region is sampled for processing, the chances of sampling a portion of the distribution that overlaps with another item is high. Thus, it is harder to distinguish the properties that belong to one item from the properties that belong to an adjacent item. The model might account for the hypothesis that information is pooled over a wide area in the periphery by decreasing the spacing between the distributions of individual items (compared to when they appear in the fovea), making it less likely that a regional sample will contain only information from one item. The model might also vary the threshold (resolution) level, making it higher for information appearing in the periphery, such that as the threshold is increased the sampling of a given region would contain information from a larger number of distributions. This model does not specifically address between-item interactions nor does it address the processing of information in the periphery; thus, the application of the model to the phenomenon of crowding cannot be done without making some assumptions or modifications. However, the properties of the distribution(s), of sampling, and of thresholding in this model do allow the model to account for the decreased ability to resolve the center item in a multi-item display.

Top-Down Influences on Crowding

Attentional orienting and the word superiority effect are both top-down phenomenon that have been shown to influence crowding. In the section below, there will be a description of attentional cuing effects in general, followed by a discussion of attentional cuing effects on crowding. This will be followed by a discussion of findings related to the word superiority effect in general and then as they relate to crowding.

Endogenous vs. exogenous cuing effects

Covert attention affords us the ability to orient our attention in the absence of eye movements. When attempting to orient attention to a given location, researchers use either a central cue, such as an arrow that points in the direction of the most likely target location or a peripheral cue, such as a flash of light that appears very briefly near the target location. These two different cue types have been shown to draw on different attentional mechanisms, an endogenous and exogenous mechanism, respectively. The two systems have been shown to have different signature characteristics (Posner & Cohen, 1984; Jonides, 1981; Muller & Rabbit, 1989), with endogenous cuing employing a voluntary orienting system which is slower to respond (usually ~250 ms post-cue) and shows faster responses in the presence of a valid cue, regardless of the cue target SOA (lacks inhibition of return). Whereas exogenous cuing utilizes the reflexive orienting system, responds very rapidly (optimal ~150 ms cue-target interval), with short lasting facilitation effects, and displays inhibition of return with long cue-target intervals. Inhibition of return refers to the slowed response to a target that appears at a location that has been exogenously cued approximately 400 ms prior to the appearance of the target. It is as if attention, having been drawn reflexively to a location at which a target failed to occur, is inhibited from returning to that location for a brief period of time.

Attentional enhancement vs. suppression

Researchers use visual cues to direct attention to a given location or object, which typically results in either faster reaction times or greater accuracy compared to a condition with no attentional manipulation. Once attention is oriented, the mechanism by which attention brings items into the center of mental focus is still unknown. However, there are two main hypotheses that are now believed to be the most plausible. First, the signal enhancement hypothesis proposes that attention acts to enhance the representation of the item in the attentional "spotlight," thus enhancing processing of this item to the exclusion of other items. Second, the external noise reduction hypothesis states that attention acts to suppress the "noise" that is surrounding an item thus allowing the system to focus its processing resources on that item in the "spotlight." For example, when attention is cued to one location in a display, attention can act to enhance the signal of the target at that location and/or suppress the input from surrounding distracters that might interfere with the processing of the target item. Important to both of these models is the fact that attention is a limited-capacity resource. If attention had unlimited capacity it would not need to enhance some signals and not others, or suppress distracter interference. Studies of attentional orienting have revealed that when attention needs to be divided among multiple locations, precuing can aid in reducing the effective number of locations, leading to benefits in processing at the cued location.

When we refer to external noise reduction in this paper we are referring to the idea that attention reduces the effects of noise or distracters in the location of or near the target. Some authors have used the term "noise reduction" or "spatial uncertainty reduction" to indicate a decrease in the location uncertainty of the target (as in a large array). This is not the definition we are employing here. Lu, Lesmes, and Dosher (2002) nicely dissociated the two by performing a "contingency" analysis on whether responses to a target depended on (or were "contingent" on) the signal in four other possible locations. They found no contingency in the precued condition nor in the simultaneous onset condition, suggesting that even in the simultaneous condition the cue eliminated any contribution from the other locations (i.e., reduced spatial uncertainty). This suggests that any precuing effects are in addition to the location uncertainty effects and reflect noise reduction at the target location.

There currently is evidence both for the signal enhancement and the external noise reduction hypotheses. In support of the signal enhancement hypothesis, Carrasco, Ling, and Read (2004) used an uninformative peripheral cue, presented subjects with tilted Gabor[1] patches, and asked subjects to judge the orientation of the Gabor that appeared higher in contrast. They kept the contrast of one Gabor constant and varied the contrast of the other to obtain a point of subjective equality, for cued and uncued Gabor patches. They found that attentional cuing enhanced the perceived contrast of the Gabors by about 2.5 percentage points. For example, a 6% contrast Gabor appeared as an 8.5% contrast Gabor when its location was validly cued. This was true across a wide range of stimulus contrasts and revealed that attentional cuing can act to enhance the appearance of the grating, making it appear as though there were more contrast in the stimulus than was actually present. They argued that attention is acting to enhance the strength of the stimulus by enhancing the contrast saliency.

We now turn to the evidence in support of the noise reduction hypothesis. Implied in its name, in order for there to be external noise reduction there must be distracters ("noise") in the display that attention might act to suppress. Support for this claim comes from the finding that cuing effects are greater in multiple-item displays than in single-item displays. Grindley and Townsend (1968) found that when subjects had to identify the orientation of a 'T' presented in one of four locations, a 100% valid precue produced significant benefits when distracter items accompanied the target, but no benefits when

[1] See Note at the end of the document for a description and image of a Gabor patch.

the target was presented alone. Further support can be seen in the "pop-out" effect, in which a target item is easily detected when it is surrounded by other items differing in their features. In this case, the distracter items are perfectly discriminable from the target such that they do not pose confusion in target processing, and thus attention to the target drawn by a precue yields no additional aid in processing. Also, Shiu and Pashler (1994) found that precuing produced no benefit in a single-item display unless there were post-masks in irrelevant locations. This implies that when there is a blank field with only one item and one mask, attention does not need to allocate or divide resources and thus there is no benefit from precuing. Precuing improves performance in multi-item displays by reducing the noise from post-masks and from distracter stimuli in other locations.

There are generally two types of external noise that co-occur in the same spatial location as a target item: superimposed noise and post-masks. In the case of superimposed noise, Lu and Dosher used temporal summation to add their noise to the target display. That is, they present one display with just the target stimuli and at one display refresh following present the noise display, such that the two appear to be superimposed due to the temporal processing limitations of the visual system. Masking is a form of added noise, and is very similar to the above in that a target display is presented and followed at some interval by the masking noise display. Some researchers have used target-mask intervals as short as two display refreshes (Breitmeyer, 1984). Therefore, the addition of external noise and the use of post masks are very similar, under some circumstances. This is relevant here because crowding is a form of spatial masking, and although different from the temporal masking described above, both lead to reduced perceptibility and/or discriminability of the target.

Dosher and Lu (2000a; 2000b; Lu & Dosher, 2000; Lu, Lesmes, & Dosher, 2002) have argued that the primary mechanism of attention is external noise reduction, based on the findings that endogenous cues do not show an advantage unless there is high external noise, while exogenous cues also do not show an advantage unless there is high external noise and show minimal benefits in the absence of noise. In other words, endogenous cues improve performance via external noise reduction while exogenous cues improve performance via external noise reduction and signal enhancement. This is explained below.

Dosher and Lu (2000a) used endogenous cues with Gabor stimuli to examine the external noise reduction hypothesis. They had subjects discriminate the orientation of a Gabor grating that had varying amounts of noise superimposed. They found that as the amount of noise increased the impact of cuing increased, such that cuing had maximal influence under conditions of high noise and minimal or no impact when no additional noise was added. In addition they found that under conditions of high noise, cuing reduced the contrast discrimination threshold (by as much as 24%), but had no effect when there was no additional noise. This latter finding is interesting in that it appears to contradict the findings of Carrasco, Ling, and Read (2004) who found that attentional cuing enhanced perceived Gabor contrast. However, one important difference between the studies is that the Carrasco, et al. (2004) experiment used near-threshold stimuli that needed to be discriminated from the background, while Dosher and Lu (2000a) used suprathreshold stimuli that needed to be discriminated from the noise. It might be that the different task demands produced differing demands on attention, such that when the stimuli are near threshold attention must boost the signal to enhance discriminability, whereas when stimuli need to be discriminated from noise, attention must diminish the influence of that external noise.

This hypothesis gains support from Lu and Dosher's Perceptual Template Model (Lu & Dosher, 2000b; Lu & Dosher, 1998). They propose that signal enhancement occurs because the system turns up the gain on the stimulus (i.e., sensory perceptual facilitation), which occurs under low external noise conditions. External noise reduction involves changing the perceptual filter or task template (fine tuning) that occurs under conditions of high external noise, when there is external noise to diminish. Another difference between the two experiments concerns the different cue types. Carrasco, et al. (2004) used peripheral (exogenous) cues while Dosher and Lu (2000a) used central endogenous cues. Dosher and Lu (2000a; 2000b; Lu & Dosher, 2000; Lu, Lesmes, & Dosher, 2002) have shown that endogenous cues improve performance by reducing external noise while exogenous cues improve performance by both external noise reduction and signal enhancement.

Dosher and Lu (2000b) had subjects perform an orientation discrimination task under conditions of no added noise or high levels of added noise, with set sizes of 2 – 8 Gabors. The location of the target Gabor was validly cued with a central arrow (endogenous cuing) on 62.5% of trials. They found that the cuing effect depended on the set size of the display, with improved performance under conditions of high noise, for set sizes of 4 and 8, but not for set size 2. They attributed this effect to the external noise reduction mechanism of attention. Under conditions of high noise, attention improves discrimination performance by diminishing the influence of the noise. Supporting a lack of signal enhancement mechanisms with endogenous cuing, they also found that there was no cuing effect under conditions of no external noise for set sizes 2 and 4, but a small effect for set size 8. They attribute this small cuing effect under conditions of no noise for set size 8, or stimulus enhancement, to crowding mechanisms. This suggests that when there is the addition of noise spatially (spatial masking via crowding) that cuing attention can produce a facilitation effect. They did not expand on this effect so it is still unclear whether attention was acting to enhance the signal with a set size of 8, or diminish the influence of the distracter noise. Overall, they argued that attention can exclude the impact of external noise by tuning or focusing the perceptual template (a spatial frequency filter) to search for only possible target orientations.

Lu and Dosher (2000) used endogenous and exogenous cues to examine attentional cuing effects under different levels of added noise. They used a central arrow or a peripheral cue to precue a target Gabor that could appear in one of four possible locations. They also varied the amount of superimposed noise that was added, from no noise to high levels of noise. Similar to their past experiments, they found that the endogenous arrow cue lowered contrast discrimination thresholds with high levels of added noise (average 16.2% reduction), but had no effect at low levels of added noise. However, the exogenous peripheral cues produced reductions in the contrast discrimination threshold under all noise levels. The reduction in contrast threshold was similar for the low and high levels of noise, with an 11% reduction for low levels and a 17.5% reduction for high levels. In support of their Perceptual Template Model, the endogenous attention mechanism was involved in diminishing the impact of external noise when the added noise level was high, but had no effect when the noise level was low, whereas the exogenous attention mechanism was involved in diminishing the impact of external noise when the added noise level was high and enhancing the signal when the added noise level was low.

Research has shown that attentional cuing can diminish the effectiveness of a post-mask on the perceptibility of a preceding target (Boyer & Ro, 2007). If a cue precedes a target and a post mask, target detection performance is better than when the cue is not presented. This might be because the cue enhances the target signal before the mask has the opportunity to suppress it, or it might be that the cue diminishes the impact of the post-mask by excluding that external noise source. This is an open question, but the Perceptual Template Model would suggest that both are possible and that the determining factor would be the type of attentional mechanism deployed (endogenous vs. exogenous).

Attention might utilize both the signal enhancement and noise reduction mechanisms together or differentially depending on the circumstances. Carrasco, et al. (2004) showed that attentional cuing can enhance the signal when a stimulus is presented on a blank field and contrast is low, while Dosher and Lu (2000a; 2000b; Lu & Dosher, 2000; Lu, Lesmes, & Dosher, 2002) have shown that attentional cuing can diminish external noise. In the case of crowding, in order to identify the center item the visual system must distinguish the center letter from its surrounding letters, which might require suppressing the input from the surrounding letters (i.e., diminishing their distraction). Under these conditions attention might act primarily to diminish external noise (i.e., suppress the distracter processing) as it does with temporal masking. The noise reduction mechanism of attention could be a way to reduce crowding. The current paradigms examined whether attention utilizes both of these effects under conditions known to lead to crowding.

Attention and crowding

Several studies have found that attention impacts crowding (Van der Lubbe & Keuss, 2001; Montaser-Kouhsari & Rajimehr, 2005; Strasburger, 2005; Freeman & Pelli, 2007), while others have failed to show an effect (Nazir, 1992; Wilkinson, Wilson, & Ellemberg, 1997). These studies used different paradigms that will be described below. It is important to understand *how* attention modulates the crowding effect. Understanding such modulations might bring us closer to understanding aspects of the phenomenon itself.

Strasburger (2005) examined the effects of attentional cuing on crowding. He presented a ring around the center (to be crowded) letter's location 150 ms prior to the onset of stimulus presentation. The ring disappeared as soon as the stimuli were presented. The cue was 100% valid. Strasburger used different target eccentricities of 1, 2, and 4 degrees of visual angle, and found that there was a cuing effect (increase in target identification) at 1 and 2 degrees that disappeared at 4 degrees. This effect is difficult to understand in light of other cuing studies that have found effects at this and greater eccentricities (Van der Lubbe & Keuss, 2001). Strasburger's work suggests that exogenous cuing can improve identification of crowded items, but the finding that the effect disappeared at increasing eccentricity poses a problem that requires further investigation.

Strasburger (2005) examined the occurrence of localization errors (reporting a distracter more often than predicted by chance) in the cued and no cue conditions and found no difference between the two conditions. He interpreted these results as indicating that while there was an enhancement of the center letter (as seen with better identification in the cued condition), there was no attentional suppression of the distracter items. However, he only found an enhancement of the center letter in the 1 and 2-degree eccentricity conditions, and not the 4-degree condition, but collapsed across eccentricity condition for the analysis of localization errors. Therefore, we do not know if there was a facilitation of the center letter without the suppression of distracters overall, or whether the lack of suppression effect was driven by the 4 degree condition that did not show a cuing enhancement. The other problem with this study was that Strasburger analyzed the localization error rates post hoc and did not employ manipulations to test for such a suppression effect.

Montaser-Kouhsari and Rajimehr (2005) adapted subjects to a row of illusory contours under full (covertly oriented) and poor (dual-task) attentional conditions, and found that there was an adaptation effect under full attentional conditions, but there was no effect under poor attention. They also performed a control experiment to assess whether a given contour was crowded by the others in the row (same procedure without an adaptation test stimulus), and found that orientation discrimination performance was at chance in this case even under full attention conditions. Therefore, they argued that perception of the adaptation stimulus in the main experiment was degraded due to crowding (as shown in the control experiment) and that attention did not act to differentiate the stimuli. Thus, they concluded that attention must have been enhancing the adaptation process subliminally, outside of conscious attentional selection. This shows that attention can modulate target adaptation even when that target is crowded.

This study makes an exciting contribution to the crowding literature because most studies examining the identification of the center letter use some dependent variable that requires attention to respond (e.g., percent correct, stimulus threshold, etc) muddling the debate as to whether attention is necessary for crowding to occur (i.e., whether attention operates independently of crowding and just modulates the effect, Pelli et al., 2004, or whether the crowding effect results directly from attention; that it is the result of inadequate attentional resolution, He et al., 1996). In contrast, Montaser-Kouhsari and Rajimehr (2005) showed that attention is involved in crowding, without requiring conscious report.

One of the factors critical to producing crowding is the spacing between the target and the distracters. Close spacing produces the most crowding, and the effect decreases with increasing spacing. This is called the critical spacing effect. Van der Lubbe and Keuss (2001) examined the effect of precuing on the crowding effect by varying inter item spacing. They used linear arrays in which four items were presented to each side of fixation. The distracter items were x's and the target was an x with a missing arm. The subjects were to report whether the target pointed to the left or the right. The spacing of the items was varied, and either the target was precued using a bar under the item or the whole row of items was precued. They also used an array of the same stimuli that were arranged in a half circle on each side of fixation. In both cases they found that precuing the target position improved reaction times and reduced errors, compared to precuing the entire row. This cuing effect was larger for closely spaced items than for more widely spaced items. It is interesting to note that the effects only occurred at the largest eccentricity they tested, which was 3.81 degrees. Smaller eccentricities did not show an effect of cuing attention. This suggests that cuing attention can reduce the influence of distracters as the crowding effect increases.

Freeman and Pelli (2007) examined this critical spacing effect with and without a peripheral precue in a change detection task. They used two low-spacing conditions in which all the letters were closely spaced and presented in a curve above fixation, and a high spacing condition in which the same number of letter were spread in a circle around fixation. The letters were presented 6 degrees from fixation. They presented the letters in an on-off fashion, with one of the letters changing on 50% of trials. The subject's task was to report if they detected the change or not. On half of the trials a peripheral precue was presented in the blank interim field and when present was 100% valid in indicating the location of the changing letter, if there was one. They found the typical spacing effect in the no-cue condition, with better performance for the more distantly spaced letters than for the closely spaced letters. However, in the precue condition this effect was eliminated. When a precue was presented performance in the most tightly spaced condition was the same as in the loosely spaced condition. All of the prior studies we have discussed regarding attentional cuing and crowding have shown that attentional cuing diminishes the crowding effect, but this is the first to show that attentional cuing can eliminate the crowding effect. The Freeman and Pelli (2007) study is different than most traditional crowding studies in that the subjects simply had to detect a change in the letters, but not report the identity of the letter. An explanation for their results might be that attentional cuing enhances the ability to discern changes in the features. They themselves conclude, "this is an escape from crowding, although the crowding itself is unrelieved" (p. 9). In fact, when they had one subject perform the task and identify the target letter, attentional cuing did not eliminate the spacing effect. The precue condition for identification showed better performance for widely-spaced items compared to closely-spaced items. Thus, when an identification task is cued, attentional cuing diminished the crowding effect but did not eliminate it. Freeman and Pelli use memory to explain their results in the attentional cuing condition. They claim that crowded items are less familiar than non-crowded items so they require long mental representations and thus take up more space in memory. When a precue is present the subject need only remember that one cued item, so the task becomes easier and memory limits are not an issue in this case.

Scolari, Kohnen, Barton, and Awh (2007) also examined whether directing attention to a crowded target could reduce the critical spacing effect. They predicted that if cuing could reduce the critical spacing then in a valid precue condition the target should be identified (at a certain accuracy level) at a smaller distracter spacing distance than in an invalid or neutral condition. They found that cuing increased response accuracy at each distracter spacing used, but it did not affect the critical spacing effect (the valid, invalid, and neutral conditions reached 90% asymptote at the same spacing). Interestingly, when the distracters were presented on either side of fixation at the start of the trial and then a precue indicated the location the target would appear, the cue operated to decrease the critical spacing effect, compared to the condition in which there was still a cue, but the distracters appeared at the same time as the target. They also tested pop-out by making the color of the target and distracters different. Target identification was increased when it appeared in a different color, and the critical spacing effect was decreased. Taken together, these results indicate that different attentional manipulations (in conjunction with display features) have different effects on critical spacing. A precue alone did not reduce critical spacing, while presenting the context on the screen before the cue and using a display that elicits pop-out of the target (or makes it highly salient) did reduce the critical spacing. The latter result is not surprising given that crowding decreases with decreases in target-distracter similarity (Nazir, 1992). In the pop-out display the target differs in color from the surround making it highly salient and thus easier to differentiate that item. In the case of distracter preview, this might afford the opportunity to set a filter on these items and prevent their processing, and thus their interference, when the target is later presented. Presenting a cue aided in orienting attention to the location of the target resulting in better performance than without a cue (under limited time constraints), and with the distracter filter already in place to block distracter processing, the target could be processed more efficiently. The authors argue that distracter preview and pop-out act to decrease target-distracter confusion or integration. The preview might allow for separate grouping of distracter items and target items, such as is true when the items differ in color as in the pop-out display.

A comparison of the simple cuing condition with the pop-out condition also speaks to the signal enhancement vs. distracter inhibition operations of attention. Performance is improved in the pop-out condition because the target is more salient than the distracters. If precuing attention acts in a facilitatory (enhancing) manner on the target then you would expect this facilitation to lead to a benefit in performance, which it did not in the Scolari, et al. (2007) study. This suggests that attention might not operate to *enhance* the signal in a crowded display. Although the work of Van der Lubbe and Keuss (2001) and Freeman and Pelli (2007) found that attention improves identification of crowded items, their studies cannot parse signal enhancement from distracter suppression effects. Further work is required in this area.

In a related study, Poder (2006) examined the influence of target saliency on crowding. He used varying numbers of horizontal or vertical bars, with a target that differed in color from the distracters. With a small number of distracter items, he found the typical crowding effect, in which identifying the orientation of the target was reduced compared to the no-distracter condition. However, in a paradoxical finding, as the number of distracters increased the crowding effect was reduced. He also replicated the effect with more complex shapes such as "X" and "O" in a letter identification task. Poder hypothesized that there might be some type of neuronal filter being used to selectively process only the items of a certain color (like a spatial frequency filter might be used to only process items of a given spatial frequency). Therefore, Poder attempted to distinguish the effect of color from orientation by placing a colored circle around the bars, with the target's surrounding circle being a different color from the others and keeping all the bars black. In fact, Poder found the same result as the first study. Therefore, it was unlikely there was a color based filter in place that was only selecting the item of a certain color (since he separated the color and orientation), but rather it was the salience of the color that facilitated processing in that spatial location. Poder concluded that this color facilitation effect could be due to the salience itself or to some exogenous attention mechanism, which could not be ruled out given that others have found an effect of exogenous cuing on crowding (Van der Lubbe & Keuss, 2001; Strasberger, 2005). The reason the effect increases as the number of distracters is increased is because the distracters act to inhibit one another. With a single ring of distracters the crowding is high, but when more distracters are added, they act to inhibit each other leaving the target without inhibition; thus, the crowding effect diminishes.

There have been two published studies that have failed to show an effect of cuing on crowding (Nazir, 1992; Wilkinson, Wilson, & Ellemberg, 1997). Nazir (1992) examined the effect of precuing on the crowding effect using a gap resolution task with varying shape distracters. The target and distracters appeared 2 degrees away from fixation in a randomly determined location on an invisible ring around fixation. The location of the display was cued 100 ms prior to its arrival (ISI = 0ms). The distracters were either similar in size, shape, or dissimilar to the target item. The subject's task was to locate the gap on the central target square as being on the top, right, bottom, or left. He found that performance was best for the target in isolation, then for the small, dissimilar distracters, then for the equivalent size, dissimilar distracters, and worst for the equivalent size, similar distracters. This indicates that similar distracters produce a larger crowding effect than dissimilar distracters. Interestingly, he found no precuing effect for any of the conditions. Base on these findings we cannot claim that cuing failed to diminish crowding, because the precuing did not have any effect even when the target was presented in isolation. This suggests that either the cue did not properly orient attention to the stimulus set, or less likely, that it did orient attention but the task of resolving the gap location was not aided by attention. The other study that failed to find an effect of cuing on crowding by Wilkinson, Wilson, and Ellemberg (1997) also failed to find any attentional orienting effect, so any results related to crowding cannot be interpreted.

To summarize, Strasburger (2005) found that attentional cuing affected crowding at near but not far eccentricities, Van der Lubbe and Keuss (2001) and Freeman and Pelli

(2007) found that cuing enhances identification of closely-spaced items and reduces the critical spacing effect, and Scolari, Kohnen, Barton, and Awh (2007) and Poder (2006) found that attentional salience diminishes crowding.

Word superiority effect

Reicher (1969) performed an experiment almost 40 years ago that has become a classic in psychology. In this experiment he presented subjects with either a four-letter word, a four-letter non-word, or a single letter, a mask, and then a one-letter probe. For example, he would present 'WORD', a mask, and then ask if a 'D' or 'K' was presented (the 'K' could also form the word 'WORK'), or in the critical comparison condition he would present the letter 'D' and ask if a 'D' or 'K' was presented. He found that subjects were approximately 8% more accurate in identifying the letter when it was presented in the context of a word than when presented in isolation. This phenomenon was coined the *word superiority effect*, as there is superior identification of letters that form a word. Wheeler (1970) replicated this effect, with more controls for things like serial position, the relation to fixation, word-probe delay, and word frequency, and found the same result. There was a 10% increase in letter identification accuracy when the letter was presented within a word than when it was presented in isolation. This effect has been shown to occur independently of some visual characteristics of the word, such as case, but interacts with contrast such that high contrast stimuli produce the greatest word superiority effect and the effect diminishes with low contrast stimuli. The effect is dependent on the presence of a post-mask (Johnston & McClelland, 1973; McClelland & Rumelhart, 1981).

The word superiority effect is a top-down effect that results from context. It is the context of the surrounding letters that make up a word that leads to greater accuracy in identifying the target letter. The implications are that letters of a word are not processed in isolation in a letter-by-letter format, but rather, they are processed in interaction with their surroundings. Johnston and McClelland (1974) manipulated attention to the individual letter or to the whole word in the Reicher (1969) task. They found that even though they directed attention to the critical letter, performance was better when attending to the global word level than to the individual letter level. This was not true of non-words, which showed a benefit from attending to the individual letter in the context of other letters. This shows that there is a global context effect for words that influences performance. Perhaps when attending to one letter, there is a decrease in the influence of the other letters in the display.

Reber, Zimmermann, and Wurtz (2004) examined perceptual judgments associated with the word superiority effect. They found that words appeared to be presented for longer durations, appeared in higher contrast, and appeared to be of larger size than non-words. They concluded that it is the greater perceptual fluency with the words than with non-words that can explain these effects. Perceptual fluency is one dimension of familiarity and is defined by the ease with which incoming information is processed (Reber, et al., 2004). Therefore, it is the familiarity with the letter sequencing of words (i.e., their probable combinations) that leads to these perceptual advantages over non-words. It is interesting to note that these perceptual advantages parallel some of those seen with attentional processing. Attention has been shown to enhance the contrast of items within its "spotlight" (Carrasco, et al., 2004), and to make stimuli appear larger than they actually are. There are mirror effects seen in these two phenomenon, although their actual relationship is still unknown. The word superiority effect results from a top-down enhancement (as a result of experience) while one mechanism of attention is top-down enhancement. It seems probable that some bottom-up trigger from the letter sequence making up a word signals a top-down mechanism, leading to enhanced processing compared to non-words. This top-down mechanism acts in ways like attention, although it need not be attention per se that is responsible for these effects. In the current studies we will be examining both the word superiority effect and the effects of attentional orienting in one experiment, which will allow us to examine the relationship between the two phenomenon. They might act in isolation even when combined in one task, or they make interact with one another to produce effects not otherwise seen.

Interactive Activation Model

McClelland and Rumelhart (1981; Rumelhart & McClelland, 1982) have developed an Interactive Activation Model to account for letter and word processing in vision. Their model has three basic levels with nodes operating at each, as well as other higher levels that might influence the word level, such as memory. There is a feature level, a letter level, and a word level. The features of the entire word can be taken in and processed in parallel (unless visually degraded somehow), and the nodes at the feature level produce possible features that might make up a letter, such as a vertical line 'l', or the top of a 'T', etc. Features are activated in a present(excitatory)/absent(inhibitory) manner immediately when the word is displayed. The nodes at the letter level contain letters of the alphabet and the nodes at the word level contain words one has encountered in the past.

Excitatory and inhibitory activations/influences in this model flow in a bottom-up, feed-forward manner as well as in a top-down, feedback manner. This allows for information at the word level to influence processing at the letter level. Nodes become activated based on the likelihood that that node is in the input, on their resting level of activation, and based on the feedback from other levels. Active nodes excite other related nodes and inhibit unrelated nodes. For example, the feature "|" would activate letters containing that feature, such as "L", "T", "I", etc, but inhibit "O", "G", etc. The more active one node at a given level becomes (via excitatory inputs) the less active other nodes become (via inhibitory inputs) until one node crosses some critical activation threshold, indicating the most likely item.

In this cycle, all letters are activated based on congruent featural activation, and features are assumed to be activated directly from the visual input. Active letters then activate words with letters in a given serial position and inhibit other words. The word level sends feedback to the letter level to activate letters consistent with the word. This loop continues until a letter has been selected as the most active (for report), or a mask appears thereby disrupting the process. When a mask is presented, and the subject must determine the most likely letter mid-process, the model has the assumption that the subject learned through practice to choose the letter at some optimal time in the process.

The model accounts for the word superiority effect by claiming that the letters that form a word become more perceptible because they receive feedback activation from the word level. The letters do not receive this additional feedback activation when the other letters in the sequence do not form a word or the letters are presented in isolation.

Johnson and McClelland (1973) found that there is a 15% word advantage for letters presented in high contrast followed by a post mask, while there is a 5% word advantage for letters presented in low contrast with no post mask. In accounting for these contrast effects on word superiority results, the visual inputs to the model had to be severely degraded when no mask was present to reach 75% correct performance. When a mask is present, it interferes with the time to process the inputs, but the letter receiving the greatest activation prior to the presentation of the mask is chosen as the best candidate. The model was accurately able to mimic the word superiority effect of 15% under masked conditions, but overestimated the effect when no mask was present. The model delivered a 10% word superiority effect with no mask, while Johnson and McClelland (1973) had a 5% effect under these conditions.

Rumelhart and McClelland (1982) varied the temporal interval between the presentation of the context in a word and the target letter to be identified in that word. For example, for the word "WORK", if the "K" was the to-be-identified letter the letters "WOR" were presented both before and after the presentation of the "K". They found that when the "K" was presented prior to the context, performance was worse than when the context was presented prior. They also replicated this finding in the Interactive Activation model. When the context is presented first, the other letters have time to activate related or possible words which can then feed back down and activate possible letters, resulting in an increased activity level when the letter is actually presented (a priming effect). When the letter is presented after its context, its activity reaches a high level faster than if the context had not been presented. They also looked at the contribution of each of the letters in the word context and found that the outer letters had a stronger enhancement effect on target letter performance than the inner letters. In the case of the crowded stimuli, the increased discriminability of the outer letters might be acting in a similar manner to create a feedback loop such that the most likely letter to appear in that context is the one chosen as the response. This would imply that the response is determined based purely on letter sequence familiarity and not on a word reading effect; that is, not on the meaning of the word.

An interesting characteristic of this Interactive Activation model is that the baseline activation level is dependent on the frequency of the word, or in model terms, the number of times the model has encountered that word. This is a basic familiarity effect. The model has no semantic information or word-related knowledge at the word node other than the frequency of the word, and it still can account for the word superiority effect. This would argue that the word superiority effect might simply result from the familiarity with the word sequencing, and not from the semantics of the item. In other words, it is a form of pattern recognition. The familiarity with the pattern of the letters increases the probability of identifying the parts of the pattern. It is analogous to a case where if one identifies an object as a dog, this would lead to a greater likelihood of reporting that the dog has an eye, than if the pattern were unfamiliar or severely degraded. It is important to point out that this familiarity effect is a second-order abstract form of familiarity or pattern matching. The visual system is not performing pattern matching on the exact visual representation (that changes with font, case, etc.), but rather is matching the abstract form of the word to an abstract template for that word.

Further evidence for the familiarity hypothesis comes from the finding that pronounceable pseudowords (non-words) show better letter recognition rates than random letter strings or letters presented alone (McClelland & Rumelhart, 1981), and sometimes the identification rates do not differ from those of words[2] (Baron & Thurston, 1973). Baron and Thurston (1973) have argued that the fact that words and pronounceable pseudowords can produce comparable identification rates suggests that the word superiority effect does not result from the semantics of the word or the words frequency, because if these factors influenced performance identification rates would always be better for words. Baron and Thurston (1973) attempted to address whether the word superiority effect results from letter sequence familiarity by examining a superiority effect for the correct presentation of a chemical formula (e.g. NaCL) vs. a misordered presentation (CLNa), and indeed they found such an effect. However, whether or not words are processed like chemical formulas is an open question, but the finding offers some evidence in support of co-occurrence familiarity.

The Interactive Activation model was also able to model this pronounceable effect because pronounceable pseudowords share two or three letters in common with a real four-letter word, while a random letter string does not. Therefore, the 2-3 letters activate words that are similar to the pseudoword, which leads to feed-back activation from the word level to the letter level, resulting in higher activation levels for related letters. For example, the word "MAVE" would receive feed-back activations at the letter level from words like "SAVE", "HAVE", "MOVE", "MALE", etc., each leading to increased activation of the letters in "MAVE" over what would occur in a random letter

2 Although in the Baron and Thurston (1973) study, the pronounceable non-word group contained words.

string that would receive no word level feed-back. Relatedly, they found that pseudowords with high letter-to-letter probabilities (the sequence has a high probability of being encountered in the English language) showed marginally higher letter identification rates than pseudowords with low letter-to-letter probabilities (which was also accurately modeled by the Interactive Activation model). A word will always result in stronger activations than a pseudoword because a word will activate the node corresponding to it, and inhibit other nodes. The resulting interactive loops produce a stronger activation when all letters match (as in a word) and thus the word advantage over pseudowords. Again, word and pseudoword activity can all be explained by letter sequence familiarity.

Word Superiority Effect, Attention, and Crowding

Previous research has shown that the relationship between the center letter and its flankers impacts the magnitude of crowding. Some of the variables that have been shown to influence this relationship include distance, position, and physical similarity (Bouma, 1970; Nazir, 1992; Pelli, et al., 2004). In some very important research, Elizabeth Fine (2001; 2004) investigated whether there was a linguistic relationship between the crowded letters by manipulating whether a three-letter string formed a word or a non-word. She hypothesized that letters that formed a word would be better recognized (reported) than letters that formed a non-word, based on the word superiority effect. She presented 3 letter trigrams for 150 ms, 10 degrees to the left or right of fixation and had subjects report the center letter of the trigram (Fine, 2001). Non-words were created by substituting the middle letter of the corresponding word stimulus with another letter that would make the trigram a non-word (see Appendix A). She found that across two experiments the letters that formed a word were identified more accurately than the letters that formed a non-word, and that this word superiority effect ranged from a 9% to a 22% increase in accuracy. In a later study, Fine (2004) investigated the word superiority effect of crowded stimuli using a stimulus threshold duration method and found that crowded letters (presented 10 degrees from fixation) that formed words had a mean stimulus duration threshold of 148.8 ms and letters that formed non-words had a mean stimulus duration threshold of 193.3 ms. The stimulus duration threshold was defined as the exposure duration necessary to achieve 78% correct identification accuracy. These results show that letters that make up a word received heightened processing, and specifically that identification of a letter within a word is easier and requires shorter presentation times to achieve the same performance criterion as compared to a letter within a non-word. These results indicate that there is an advantage in identifying letters in the context of a word, however it does not indicate the reason for this advantage. Fine argues that it is due to the semantics of the items, but her experiments do not speak to the reason for the effect, only that the effect is present. One could argue that the facilitation of letter identification in the context of a word is due to the familiarity effect: that experienced readers are more familiar with the letter sequencing of words than the letter sequencing of non-words. For example, we might be better able to judge that "a" is the center letter when presented with "cat" merely because we are more familiar with that letter sequencing than the letter sequencing of "cwt." Therefore, it can be argued that when the perception of the sequence is degraded due to crowding and a judgment has to be made as to the identity of a letter, subjects are merely judging the probability of co-occurrence of the three letters and reporting the most probable case, rather than actually producing a facilitation in processing of that center letter.

This hypothesis would be supported by the findings of the Interactive Activation model. It has also been shown that visual duration thresholds for words decrease with increasing word frequency (Howes & Solomon, 1951), from which one could predict that the visual duration thresholds for words would be less than for non-words simply because words are more frequent. However, it is also possible that presenting the letter in the context of the word is providing a special top-down facilitation, leading to better processing of that item, and thus better identification, than when the same letter is presented in a non-word trigram. This is still an empirical question, one that the current study attempts to answer.

In the crowding phenomenon the flanker items are critical to the reduction in discriminability because performance without the flankers is unimpaired. The word superiority effect for crowded stimuli also suggests that the flankers play a special role in the identification of the center crowded item. Classic evidence for this comes from the Eriksen flanker task (Eriksen & Eriksen, 1974), in which subjects are presented with a target letter that always appeared in the same location (0.5 degree visual angle above fixation) with the task of determining its identity. Critically, the target letter was flanked on each side by three letters that were either the same as the target, different from the target but required the same response, different from the target and required a different response, or were all different from one another. They found that flankers that required a different response from the target interfered with performance more so that any other type of distracters, leading then to conclude that the distracter information is processed even when it is task irrelevant (non search task) and that this distracter processing interferes with performance at the level of the response.

More recent evidence suggests that attention to these flankers might be critical in producing a distracter effect. Freeman, Sagi, and Driver (2001) manipulated attention to a subset of flankers appearing at imaginary corners of a square around a target (in central vision). The flanker Gabor patches could be either the same orientation or an orthogonal orientation to the center Gabor patch. They manipulated attention to the congruent or orthogonal flankers by having subjects perform an additional Vernier acuity task on those flankers. They found that when flankers of a congruent orientation were attended, contrast sensitivity thresholds were lower for the central target, but when ignored, performance was the same as when they were not present in the display. This suggests that attending to the distracters is critical to producing effects on performance. Therefore, in the case of the word superiority effect, the presence of congruent or relevant flankers might be producing a benefit in performance due to attention to the distracter items.

Priming

One way to distinguish whether the crowded items are being identified based on familiarity with the letter sequence (a familiarity effect) or based on the meaning of the word (a semantic effect) in Fine's (2001; 2004) word condition, is to examine whether or not that word can lead to priming in another task. To investigate priming, most researchers use masked presentations with identification/discrimination tasks, as well as stem completion tasks or lexical decision tasks to examine the extent of processing of an item that was not consciously perceived (i.e., not available for later report) or might have been minimally perceived (due to degradation or masking). In a stem completion task, subjects are presented with a list of words to remember and then in a later test phase are given the first few letters of a word and asked to complete the word. Priming is said to occur when subjects are faster and more accurate at completing stems for items that were in the list they learned than for items that were not in the list. In a lexical decision task, a letter string might be presented with another letter string and the subject is to decide if both are words (Meyer & Schvaneveldt, 1971), or more commonly, a word is presented, masked, and the subject makes a word/non-word decision to a following letter string (Neely, 1991). Priming is shown when subjects are faster and more accurate when the two letter strings are the same or related words. Also, the magnitude of priming has been shown to be larger when the items are from the same semantic category (e.g. bread and butter), than when they are from unrelated categories (e.g. doctor and butter; Neely, 1991). This priming occurs independently of conscious recollection or perception of the items. For example, depth of encoding is known to affect the ability consciously to recall studied items, however, it does not affect the magnitude of priming. Priming is the same regardless of the depth of encoding. Priming also occurs regardless of whether the item was ever perceived, that is, priming still occurs when items are masked and never enter conscious awareness (Marcel, 1983). Marcel (1983) showed that the magnitude of priming was the same regardless of whether the item was perceived or not, indicating that conscious awareness is not necessary for performance and no gain is accrued by it. This is applicable to this research because crowded targets are degraded and the whole might not be available for report. However, the priming literature suggests that even if they are not fully available for report, or the subject reports them but is purely guessing, the semantics of the item might still be processed and can influence behavior.

In typical masking paradigms the masked item has the ability to prime a later response. This might be due to the fact that the item is processed unconsciously or that components/features of the item might be processed consciously, but not fully enough to allow for accurate conscious report. With crowded stimuli the items can be presented for an unlimited amount of time, and still no conscious identification comes about for the central item. This form of masking allows us to assess the processing of information knowing it is out of awareness.

Words have been shown to act as a type of cue in improving performance. Patients with damage to the right parietal lobe show deficits in attention, specifically attending to information on the left side of space. When given a line bisection task, these patients will bisect the line to the right of true center because they are failing to attend to the left half of the line. Cuing the patients to the left side of space prior to performing the task reduces this effect, because the patient can now orient to the region of space previously neglected. The effect is also diminished when a sequence of letters forming a word are used, compared to a random letter string, presumably because the word is acting in some fashion like a cue (Sieroff, Pollatsek, & Posner, 1988; Posner & Petersen, 1990). The word processing is not influenced by cuing per se, because a later study showed that cuing the words in normal subjects produced no benefit above and beyond presenting the word vs. the letter string (Sieroff & Posner, 1988).

Rumelhart (unpublished, cited in Rumelhart & McClelland, 1982) examined priming in the word superiority effect paradigm. He presented a prime word followed by two related words that differed by a one letter (e.g. "WAR" followed by "ARMS-ARMY"), and subjects made a forced choice response to the differing letter. He found that the prime did not improve performance relative to a control condition with an unrelated prime. The experiment was unpublished and described very briefly in a related paper, so it is hard to make any conclusions without knowing the details of the methods, but the study tentatively suggest that semantics are not important in producing the word superiority effect. The conclusion requires further investigation.

Description of Current Research

Fine (2001; 2004) has shown that crowded letters presented in the context of a word trigram are identified better than letters presented in a non-word trigram. She has attributed this facilitation to the word superiority effect. However, in her studies she made no attempt to control for familiarity and therefore it remains to be determined whether or not this facilitation is the result of letter sequence familiarity with words or whether it is the result of semantics. One could argue that the facilitation of letter identification in the context of a word is due to the fact that experienced readers are more familiar with the letter sequencing of words than the letter sequencing of non-words. For example, we might be better able to judge that "a" is the center letter when presented with "cat" merely because we are more familiar with that letter sequencing than the letter sequencing of "cwt" (c.f. Reber, et al. 2004). Therefore, it can be argued that when the perception of the sequence is degraded due to crowding and a judgment has to be made as to the identity of a letter, subjects are merely judging the probability of co-occurrence of the three letters and reporting the most probable case, rather than actually producing a facilitation in the processing of that center letter. However, it is also possible that when presenting the letter in the context of the word, the letter/word might receive facilitation from the meaning of the word, leading to better processing of that item, and thus better identification, than when the same letter is presented in a non-word trigram. This is still an empirical question, which the current study attempts to answer.

It is hard to imagine that meaning is not involved in the word superiority effect. If the effect results from familiarity with the letter sequence, one must consider that each instance of experience with that letter sequence was also paired with the semantics of the word. When we read or speak we do so for the purpose of comprehension, either by ourselves or for others. The notion of comprehension inherently encompasses semantics. Therefore, it seems likely that in order for there to be a familiarity effect with a word, there must also be a semantic component, although this remains to be determined.

The main goal of these studies is to examine the influence of top-down mechanisms on the crowding effect. We will use crowding as a tool to examine how semantics contribute to the word superiority effect, and investigate the role attentional cuing plays in both the crowding effect and the word superiority effect. Cuing might act on non-words (or ordinary crowded items) such that it enhances the identification/discrimination of letters in a non-word. However, the role of attention in the word superiority effect is another matter. Attentional cuing might suppress the processing of the distracters such that they have less influence on the center letter resulting in increased discriminablity. However, if cuing strips the target letter of its context we should find that words and non-words should produce similar results. Thus, we should observe a decrease in the word superiority effect when attention is manipulated. Alternatively, cuing might enhance processing of the center letter leading to better discriminability of the center letter, while leaving the distracters unaffected. This would manifest as increased identification for the word and non-word conditions, but not affect the difference between the two (the word superiority effect). It is also possible that the word superiority effect might be enhancing letter processing to the maximum allowed in a crowded display, and that orienting attention will not enhance letter processing. These studies will provide us with a better understanding of the mechanisms of attention and how attentional cuing and the word superiority effect interact in a crowded display.

Assessing the Semantics of Crowded Stimuli

In Experiment 2 and 3, we will present a secondary[3] semantic task/item, along with the initial crowded stimulus to assess whether subjects are reading the crowded letters as words. If subjects are reading the crowded items and deriving semantic information from them, then this semantic information might influence performance in another task/item (as in priming). In Experiment 2, we presented a lexical decision task at fixation as the secondary task. If the crowded letter appears within a word such as "cat," the lexical decision word is "dog," and the semantics are being derived from the crowded word, then performance on the lexical decision task should be better than the condition in which the crowded item is unrelated or is a non-word. In Experiment 3, we presented an initial crowded item followed by an additional crowded item that could be related to the first. As with the lexical decision task, if the semantics are being derived from the first crowded word, then performance on the second crowded word should be better when the two are related than when they are unrelated or the second is a non-word. This secondary task, the lexical decision task or the second crowded item, allows us to asses whether or not subjects are reading the crowded word and semantics are being derived to assist in the identification of the center letter. If there is no improvement in the secondary task when a

[3] Secondary in time, not in importance.

semantically-related word is the initial crowded item, then it seems more plausible that semantics are not contributing to the facilitation of performance for the crowded letter within a word, but rather a basic probability or familiarity effect might be causing the facilitation. The two experiments are intended to build upon one another and offer converging evidence as to the contribution of semantics to the word superiority effect. However, in Experiment 2, the additional task of requiring subjects to perform a lexical decision (LD) task might, 1) lower overall performance rates due to the attentionally demanding nature of the dual task paradigm and/or 2) change the subjects' task set (relative to the pilot study) such that they are more inclined to pay attention to words than they would be if they were not required to perform the word/non-word task. The first factor is expected but the second factor requires an additional study to assess whether or not the addition of this LD task is altering subjects attentional set. If the addition of the LD task induces subjects to pay more attention to words then non-words, this might manifest as an increase in the word superiority effect for the crowded stimuli because words are receiving heightened processing. If Experiment 2 reveals a much larger word superiority effect than in Experiment 1 this would suggest that subjects are paying more attention to the words, and validate the claim that there is a change of attentional set. If the magnitude of the word superiority effect stays the same as in Experiment 1, this suggests that the addition of the LD task did not change performance on the crowded letter identification task. Therefore, whether subjects are changing their attentional set is an empirical question.

Fine (2001) blocked the presentation of crowded words and non-words and found that when the stimuli were blocked identification of letters within words was 16.7%

better than when stimuli were random, while non-words were only 2.5% better when blocked. She also had subjects report whether the stimulus was a word or a non-word and found that overall when the center letter formed a word, identification was better than when it formed a non-word. Additionally, there was no difference in subject's ability to identify the words vs. the non-words, but that when the word type was correctly identified, identification of the center letter was better when it formed a word than a non-word. This suggests that the additional task of requiring subjects to report whether the item as a word or non-word favored the identification of letters within words. However, in the current studies we don't know if subjects adopt the strategy of identifying words. In the Fine study, she instructed subjects to pay attention to whether the letters formed a word or not (explicitly and by blocking), making it part of their task. This is in contrast to the current studies that are not asking subjects to perform a word/non-word identification task, but rather might be doing this on their own due to the presence of the LD task. Therefore, doing Experiment 3 in addition to Experiment 2 provides better insight as to the semantic influences on the word superiority effect.

In these experiments we are using priming performance to infer the level of processing that is occurring on the first crowded stimulus. Therefore, it is important for us to distinguish clearly between the two processes we are discussing. There is a word superiority effect possible for the first crowded item and a word superiority effect *and* priming effect possible for the second item (either the second crowded item or the lexical decision item). The word superiority effect for the first crowded item represents how well the center letter can be identified in the word and in the non-word. The word superiority effect for the second item represents the same information, but the priming effect represents how well the center letter can be identified in addition to the level of processing that occurred on the first crowded item (and inherently the second item). If the first crowded item is processed to the level of semantics there is no way to infer this based solely on the word superiority effect for this item. The second task with the priming effect is needed to assess semantic processing. However, the processing of the first item to the level of semantics can influence the word superiority effect for the second item, in that if priming facilitates the processing of the second item then center letter identification is improved. However, the word superiority effect for the second item includes performance for the unrelated words as well as the related words (overall response to words) so it is not a pure measure of priming (semantic processing) as the two effects are confounded. We must look at the word superiority and priming effect in the related word condition to assess the contribution of semantics. Thus, the word superiority effect for the first item represents the depth of processing of the item, but the related priming effect for the second item manifests that depth.

We used a manipulation of second item relatedness to examine the priming effect that might occur when semantic information is accessed. However, another approach would be to control, as well as possible, the letter co-occurrence (sequence) probability differences between words and non-words. Words contain legal bigram combinations that are familiar to readers, but non-words can be created such that they also contain legal bigrams and can be pronounced like words. These pronounceable non-words are similar to words in their bigram frequency and are thus similar in their letter sequence familiarity. By comparing performance when the non-words are pronounceable to when they are not (do not contain legal bigrams) we can control for the letter sequence familiarity effect as best as is possible and determine whether or not words, which contain semantic information in their repertoire, would produce a priming effect that differs from pronounceable non-words. This approach differs from past experiments (Baron & Thurston, 1973) examining the effect of pronounceability on the word superiority effect in that we are testing whether or not semantics are accessed in a word superiority task by assessing their influence on later performance. Past studies (Baron & Thurston, 1973) have used the logic that if controlling for bigram frequency explains performance than there must not be any other processing involved. This is post hoc, deductive reasoning, and it could be argued that we still do not know if all the premises are true. Instead of using this subtraction method (word performance - pronounceable non-word performance = 0), the current study will use a more standard approach to assessing the influence of meaning by employing a priming task.

It is important to determine whether semantics plays a role in the word superiority effect because 1) an understanding of the mechanisms of the phenomenon are important and 2) the finding might shed light onto any attentional cuing effects that emerge in the following experiments. For example, if the word superiority effect is simply a result of pattern familiarity then attentional cuing could completely abolish such an effect. However, if it is the result of higher-order processes such as semantics, then cuing might not be able to abolish such effects completely. It is important to note that we cannot experimentally manipulate whether or not the word superiority effect is based on pattern familiarity or semantics. Therefore, we cannot compare the attentional cuing effects separately for familiarity versus semantics, but the conclusions about the role of cuing might be influenced by the outcome of this experiment.

Cuing effects on Crowded Letter Identification

An implication of the finding of better identification of a crowded letter within a word is that the subject is actually utilizing the distracter stimuli to facilitate performance. This contrasts with the typical distracting or inhibitory effect produced by distracter items. We will investigate the effects of cuing on target identification in these contexts. That is, we will examine whether or not cuing operates to enhance the signal at the location of interest or whether it might operate to suppress the surrounding distracters. These two effects might not be exclusive, but there is still controversy as to the operations of each. In this paradigm, if we were to cue the center letter and attentional cuing acted to facilitate (enhance) processing in that location then identification of that letter should improve, regardless of condition (see Figure 1). If attentional cuing is acting to suppress the influence of the distracters then we should see a *reduction* in the word superiority effect. Because attentional cuing is acting to suppress the processing of the surrounding context, it is thus suppressing the processing of the word as a whole, making it more like a non-word condition. This manifests as an increase in performance in the non-word condition because the distracter influence is suppressed (diminished crowding), but the word condition falls to the level of the non-word because there is no longer a word context present to produce facilitation.

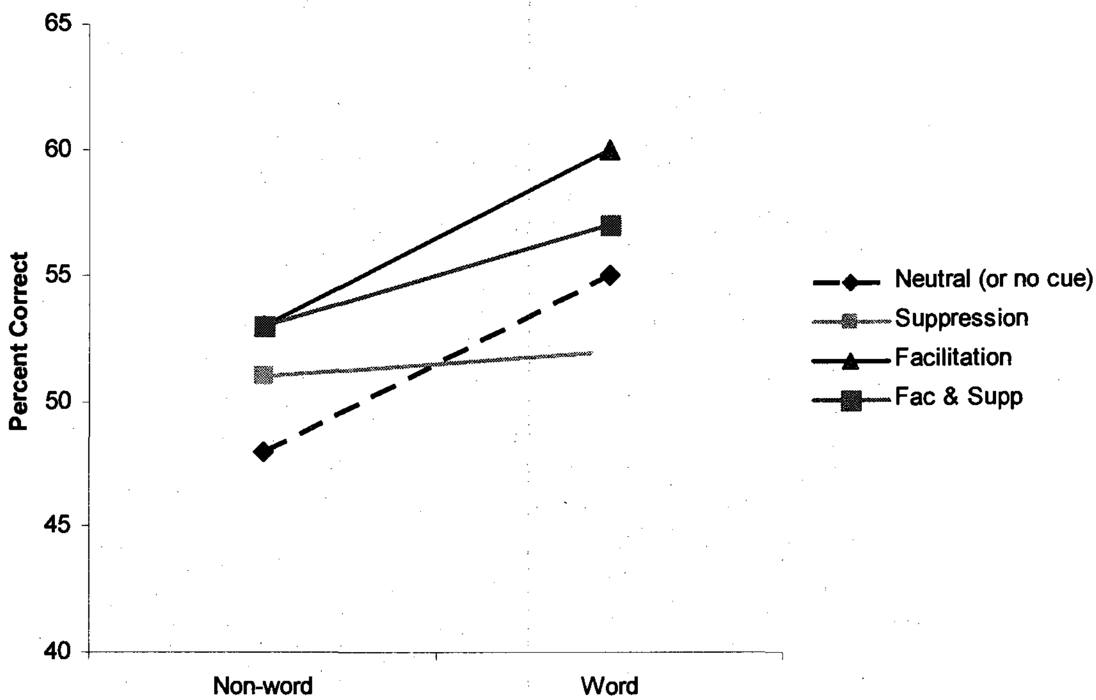

Figure 1. The predicted attentional cuing effects on the word superiority effect for crowded stimuli.

Previous research has shown that endogenous and exogenous cuing operate differently and can have different effects on performance. We want to extend these findings to determine how these different cue types will affect the word superiority effect seen with crowded stimuli. In exogenous cuing the exact location of the central letter can be cued, and thus we can assess the facilitation of identification seen with this type of cuing. In endogenous cuing, the arrow points in the direction of the entire word/trigram. Therefore, it is not clear whether endogenous attentional cuing would facilitate just the center letter, as a result of the task demands, or whether it would facilitate the entire row of letters. Also, based on the work of Carrasco et al. (2004) and Dosher and Lu (2000a;

2000b) we would predict that exogenous cuing would lead to signal enhancement of the center letter, while endogenous cuing would lead to distracter suppression.

In Experiment 4 we assess the individual effects of endogenous and exogenous cuing and compare their effects. In one block, we cue the center letter endogenously while in another block, we cue it exogenously.

We will attempt to determine whether exogenous and/or endogenous orienting a) facilitate processing of just the center letter, b) whether they facilitate processing of the whole row, and thus increase the word superiority effect, or c) whether they suppress the processing of distracters. Exogenous cuing might facilitate performance only in the location cued and not facilitate processing of the distracters, as would be predicted based on its spatial precision and signal enhancement effects (Carrasco, et al., 2004). With endogenous attentional cuing, the facilitatory cuing effect is presumed to be more global (it cues a general area) so it might facilitate processing of the entire row of letters. Endogenous cuing also has a noise suppression effect so it might suppress processing of the distracters. Thus, it is harder to predict the effects of endogenous cuing on identification of a crowded target.

We predict that if the cue facilitates processing of only the center letter, then identification of that letter should increase both in the word and the non-word conditions. If the cue facilitates processing of the entire row then there should be an advantage when the letters form a word, and the entire word will be facilitated, including the center letter. This would increase the difference between the word and non-word conditions, increasing the word superiority effect. If the cue suppresses processing of the distracters, then there should be little or no difference between the word and non-word conditions because the other letters in the word are being suppressed, which reduces the likelihood that they will be read as a word. It is more likely that exogenous cuing will produce facilitation only at the target location, while endogenous cuing might produce a more global facilitation effect or a distracter inhibition effect. These predictions are based on the previously cited literature

The last question in this series involves examining the relationship or interaction between attentional cuing and the word superiority effect. Both phenomena are top-down effects which facilitate processing. When they are combined in one paradigm do they operate independently or do they interact? To our knowledge, this question has not been asked in the current literature on crowding, attentional cuing, and word superiority. This is the question that we hope to be able to answer with this research. There are four possible combinations: a valid cue with a word stimulus, an invalid cue with a word stimulus, a valid cue with a non-word stimulus, and an invalid cue with a non-word stimulus (see Table 1).

	Valid Cue	**Invalid Cue**
Word	+ Word + Cue	+ Word - Cue
Non-word	- Word + Cue	- Word - Cue

Table 1. The word/non-word and valid/invalid cue matrix.

This matrix will allow us to parse the effects due to cuing from the effects due to word superiority and examine their interaction. The interaction between cuing and the word superiority effect is not clearly defined, given that Johnston and McClelland (1974) found that cuing attention to a letter within a word in a foveal display resulted in poorer performance for that letter compared to when the letter was not cued, while research on attention and crowding (Van der Lubbe & Keuss, 2001; Montaser-Kouhsari & Rajimehr, 2005; Strasburger, 2005; Poder 2006; Freeman & Pelli, 2007; Scolari, Kohnen, Barton, & Awh, 2007) has shown that attention has a facilitatory effect on the identification of a crowded target.

Cuing effects on Crowded Letter Discrimination

In Experiment 5 we used a discrimination task to assess the effects of an attentional manipulation on the crowding effect. This experiment provides a converging approach, allowing us to derive a more general conclusion regarding the effects of attentional cuing. Specifically, this experiment provides another way of determining whether or not attentional cuing suppresses distracter processing. We presented subjects with a crowding stimulus such as "lht," and then asked them (for example) whether "e" was the center letter? The item "e" could have been either a) the center letter, b) one of the surrounding distracters, or c) an item not present. If attentional cuing suppresses processing of the distracter items, then subjects should be equally likely to respond positively to an item that was not presented and to a distracter. If the distracters are not being suppressed, then subjects should be more likely to respond positively to a distracter than to an item not present because the distracter was actually present in the display and could be confused with the center letter. Finally, if the probe was the center letter, then performance should be much better than when the probe was a distracter letter, which in turn should be better than when the probe was a letter not present in the display. Also, if attentional cuing suppresses processing of distracter items then overall identification of the distracters should be worse when attention is manipulated than when there is no cue present (no suppression taking place).

This last experiment differs methodologically from the other experiments by using a probe item to which subjects respond yes/no to indicate whether the probe was the center letter. In the other experiments the subject needs to generate the identity of the center letter on their own in the crowded letter identification task. In this experiment they are simply indicating whether the probe is correct or incorrect in identifying the center letter. This experiment might be easier for subjects when the center letter and the probe are the same item, but it also introduces an element of confusability when a distracter is a probe. In this case, if subjects are not sure of the center item they might be more likely to report that the distracter was the center letter given that it was present in the display. We can therefore examine distracter report (saying yes to a distracter probe) when there is a neutral cue present and attention is not manipulated, and when we cue attention to examine whether attention suppresses distracter input. Specifically, if attentional cuing suppresses the distracters then the percentage of trials in which a subject says yes to a distracter probe (makes an error) will be reduced when attention is validly cued, compared to the neutral or invalid conditions.

Experiment 1: Replication of Fine (2001; 2004)

Method

Participants. Five subjects were recruited from the Rice University community, and voluntarily participated. All subjects had normal or corrected to normal vision, were native English speakers, and provided informed consent.

Stimuli and Apparatus and Procedure. All stimuli were presented on a 40 cm horizontal by 30 cm vertical CRT monitor with a refresh rate of 60 Hz, powered by a Dell PC computer. The subjects placed their head in a chin rest, to ensure that they viewed the screen from a distance of 57cm, such that one cm of the screen corresponded to one degree of visual angle. All stimuli were black presented on a white background. There was a fixation cross in the center of the screen that measured 0.5 x 0.5 degrees of visual angle. The crowded array consisted of three letters, with the center letter positioned 10 degrees to the left or right of the center of fixation (visual field was randomly determined by the computer). The letters were presented in Courier font because it is a monospaced font, making interletter spacing constant. The letters were arranged horizontally on the screen with a 1-degree interletter spacing. The 'x' measured 1.0 x 1.0 degree of visual angle. The letters were presented such that they formed words or non-words (see Appendix A). All the letter sequences were those used by Fine (2004).

Each trial began with a fixation cross in the center of the screen, which stayed on throughout the trial. The subject initiated the trial by pressing the space bar. The three-letter sequence was flashed on the screen for 150 ms, followed by a 500 ms delay period and then a response probe. The response probe said 'Select Center Letter', at which time the subject had 5 seconds to make a response on the keypad (see Figure 2). They were instructed to make the most accurate judgment possible as to the identity of the center letter and if they were unsure, they were told to make their best guess. The 5 seconds response window was imposed to prevent subjects from deliberating over the identity of the letter. After the 5 seconds response window, the 'Select Center Letter' was replaced by a fixation cross, at which time the subject could initiate a new trial.

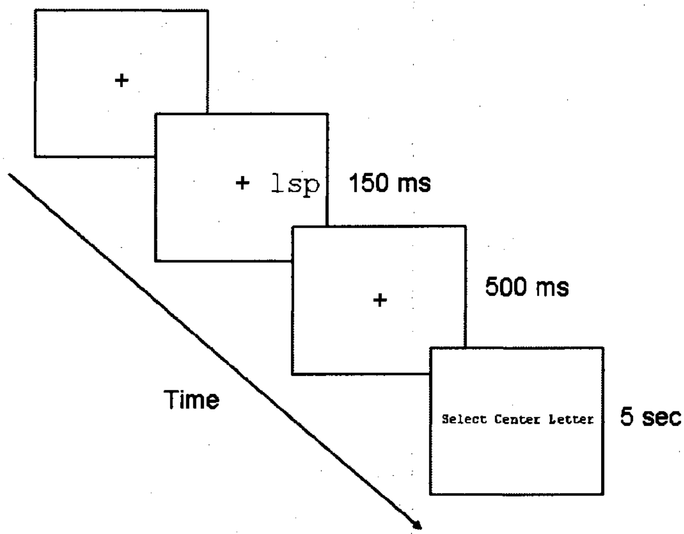

Figure 2. The sequence of events on any given trial in Experiment 1, examining the word superiority effect for crowded stimuli.

Each session began with 12 practice trials, which were not included in the analysis. There were 114 trials with stimuli presented to the left visual field and 114 trials to the right visual field included in the analysis. Half of each (57 trials) were words and the other half were non-words. There were a total of 240 (including practice) trials in each session, lasting about 20 minutes in duration. The subjects could take a break at any time during the experiment by not initiating a new trial.

Design. The independent variable in this study was crowded item type (word, non-word) and the dependent variable was accuracy in identifying the center letter of the crowded item.

Results and Discussion

We calculated the mean percent correct for letter identification when the letter was presented within a word and when it was presented within a non-word, and then performed a paired samples t-test on the two percentages from each subject. Our results support the word superiority effect for crowded stimuli. Identification of the center letter was greater when presented within a word (M = 54.35%), than when presented within a non-word (M = 48.96%; $t(4) = 3.08$, $p = .037$, two-tailed).

In order to be certain that we could replicate Fine's (2001; 2004) results, we computed the effect size for our word/non-word mean difference. Our effect size was 1.38, which is larger than the effect size we calculated for Fine (2001) of 0.82 when the dependent measure was percent correct, but is comparable to the value in Fine (2004) of 1.37 when the dependent measure was stimulus threshold duration. Given that our effect size using percent correct was greater than her effect size using percent correct and comparable to her effect size using stimulus threshold duration, we have decided to use percent correct as the dependent measure in the future studies of this document. It should be noted that this is a large effect size. This is helpful in testing the various hypotheses in the following studies because some of the effects might be smaller and simply modulate this basic effect size.

Experiment 2: Assessing Semantics - Lexical Decision

Method

Participants. Twelve subjects were recruited from the Rice University Psychology Department research pool (9 females; mean age of 21 years; two left handed subjects). All subjects had normal or corrected to normal vision, were native English speakers, and participated only after providing informed consent.

Stimuli and Apparatus and Procedure. All display parameters were the same as Experiment 1, except where noted.

The center stimulus for the lexical decision task was a word or non-word trigram. The words were either related or not related to a crowded word, or a non-word (see Appendix B). Therefore, there were three lexical decision items for every crowded item. They were scaled such that they were the same perceptual size as the crowded stimuli. The lexical decision item was presented in 10-point font ("o" measured 0.35 x 0.35 degrees), and the crowded item was presented in 38-point font ("o" measured 1.30 x 1.30 degrees). The crowded stimuli, and their parameters, were the same as those used in Experiment 1, except that they were presented in Courier New font and the size changed such that an 'o' measured 1.30 x 1.30 degrees.

The words related to the (crowded) word prime were chosen from the Edinburgh Associative Thesaurus; a free-association database. They were the words that subjects reported most frequently when given a word and asked to report the first word that comes to mind. For example, when subjects were given the word "ink" they reported the word "pen" as the first word that came to mind. After selecting a related word for each one of the prime words in our list (see Appendix B), these words were put into a group called "word set 1." To select the unrelated words, words were chosen that contained the same number of letters as the related word that had been previously chosen to match that word. The unrelated words were chosen randomly from list of words of that letter length. The unrelated words could not be related to any of the words that subjects gave as a free associate or to the word prime. After all of the unrelated words were chosen, they were grouped into "word set 2." The non-words were chosen from the ARC nonword database (Rastle, Harrington, & Coltheart, 2002), and matched in word length to the related and unrelated words chosen for each word prime.

To scale the eccentric items to be the same size as the central item we used the method from Rousselet, Husk, Bennett, and Sekuler (2005). Here is what they did:

> "To determine the amount an image should be magnified on the screen so that it stimulates a constant cortical area, the ratio of cortical magnification (*M*) at fixation versus magnification at eccentricity *E* needs to be determined. To do so we used the following formula (Horton & Hoyt, 1991): $M_{linear}=A/(E+e2)$, with *E* the eccentricity in degrees, *A* the cortical scaling factor in mm, and *e*2 the eccentricity in degrees at which a stimulus subtends half the cortical distance that it subtends at the fovea. We used A=29.2 mm and $e2$=3.67° based on a recent report of the cortical magnification factor in V1 (Dougherty et al., 2003. For a stimulus presented at fixation, E=0° and M=29.2/3.67=7.96. For a stimulus presented at 5° from fixation, E=5 and M=29.2/(5+3.67)=3.37. So, the image at fixation stimulates a cortical surface area that is 7.96/3.37=2.36 times larger than the surface stimulated by the same image when it is presented at 5°. Therefore, the image size had to be multiplied by 2.36 to compensate for the magnification factor when the image was presented at 5°. Finally, for a stimulus presented at 10° from fixation, E=10 and M=29.2/(10+3.67)=2.14. By the same reasoning, image size had to be

multiplied by 7.96/2.14=3.72 when the image was presented at 10°." p. 757

After scaling the items we noticed that the letters in Courier font changed their shape and become jagged when scaled. Therefore, for this and all future studies we choose to use a different monospaced font: Courier New. Figure 3 shows a comparison between the two fonts.

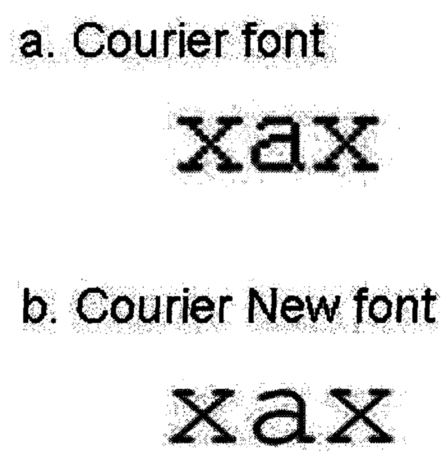

Figure 3. This figure shows the difference between Courier and Courier New font as would appear when scaled to one degree of visual angle. The Courier New font preserves the line segments and doesn't distort the letters, as the Courier font does, so this font was chosen for this and future experiments.

Each trial began with a fixation cross in the center of the screen, which stayed on throughout the trial. The subject initiated the trial by pressing the SPACE bar. The three-letter sequence was flashed on the screen for 150 ms, followed by a 500 ms delay period to allow attention to re-orient to the fixation and then a lexical decision item was presented at fixation for 150 ms (see Figure 4). The central item was followed by a mask which was present for 2 seconds. While the mask was present on the screen the subject responded word or non-word on the keypad. There was no need to mask the crowded prime items as normal priming studies would, as the crowding acts as a mask itself. A response probe was then presented that said 'Select Center Letter' for a response on the crowded letter identification task. The subject had 2 seconds to make their response on the keypad. They were instructed to make the most accurate judgment possible as to the identity of the center letter and if they were unsure, they were told to make their best guess. This response period was shorted compared to the other studies, as it was found that due to the presence of the first response, the second was much faster. The response window was also decreased in an attempt to make a very long experiment shorter. The response screen was then replaced by a fixation cross, at which time the subject could initiate a new trial.

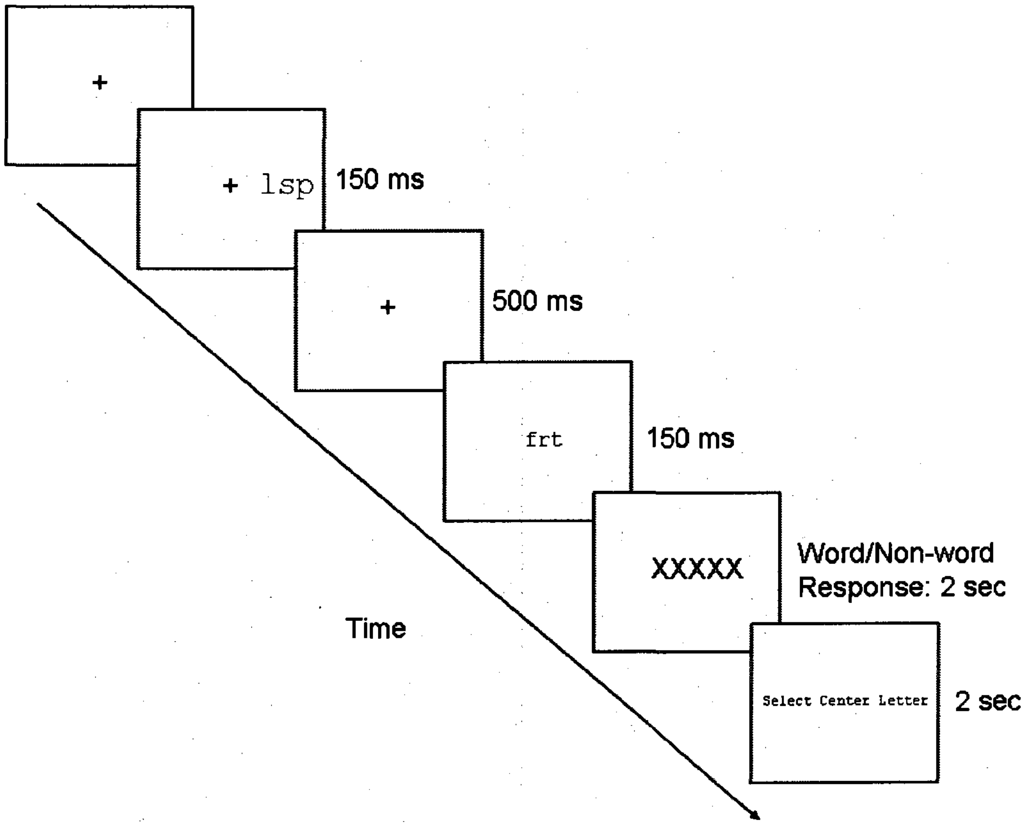

Figure 4. The sequence of events on any given trial in Experiment 2, examining the semantics of the word superiority effect for crowded stimuli.

We measured reaction times to the lexical decision item, and recorded the number of letters correctly identified in the center letter identification task.

Each session began with 12 practice trials, which were not included in the analysis. There were 318 trials with stimuli presented to the left visual field and 318 trials to the right visual field included in the analysis. Half of each (159 trials) were crowded words, of which one third had corresponding lexical decision words related to their meanings, one third had lexical decision words unrelated to their meanings, and one third had lexical decision non-words (see Appendix B). The other half were non-words, with the same lexical decision division. The non-words were generated by Fine (2001) by changing the center letter of a word. Therefore, the same lexical decision words matched with words were matched with that words corresponding non-words. There were a total of 648 (including 12 practice) trials in each session, lasting approximately 75-90 minutes in duration. The subjects could take a break at any time during the experiment by not initiating a new trial.

Design. The independent variables in this study were crowded prime type (word, non-word), whether each words corresponding non-word prime was pronounceable or not: pronounceability ([word and] pronounceable non-word group, [word and] non-pronounceable non-word group), the visual field of the crowded item (left, right), and lexical decision word set (non-word, word set 1 [contained items related to the word prime], and word set 2 [contained items unrelated to the word prime]). Subjects responded to the lexical decision item and the crowded item. Therefore, the dependent variables were accuracy in identifying the center letter of the crowded item, accuracy in identifying the lexical decision item as a word or non-word, and lexical decision response time.

Results and Discussion

The trials in which response times to the lexical decision task were less than 250 ms or greater than 2000 ms were excluded from the analysis. This lead to the exclusion of less than 2% of trials. Separate analyses were performed on the mean percent of center letters correctly identified in the crowded letter identification task, the mean percent correct on the lexical decision task, and the mean response times for the correct lexical decision responses. Each dependent variable was subject to a 2 (crowded prime type: non-word, word) by 2 (the crowded items visual field: left, right), by 2 (for the latter two analyses; word set of the lexical decision (relatedness to the word prime; non-word, word set 1 [containing words related to the word prime], word set 2 [containing words unrelated to the word prime]) within subjects ANOVA. A relatedness effect can only be present in the lexical decision task as relatedness refers to the relationship between the crowded word and the lexical decision item. Any significant findings or *a priori* hypotheses were further investigated with simple effects analyses and/or t-tests. Only significant finding are reported unless a finding was of specific interest to the hypothesis.

An ANOVA on the mean percent of center letters correctly identified in the crowded letter identification task revealed a word superiority effect ($F(1, 11) = 43.06$, $p < .001$), with greater center letter identification rates for letters within words ($M = 72.13\%$) than within non-words ($M = 58.83\%$; see Figure 5). There was also a main effect of visual field ($F(1, 11) = 14.91$, $p = .003$), such that center letter identification rates were higher when stimuli were presented to the right visual field ($M = 71.88\%$) than to the left visual field ($M = 59.08\%$).

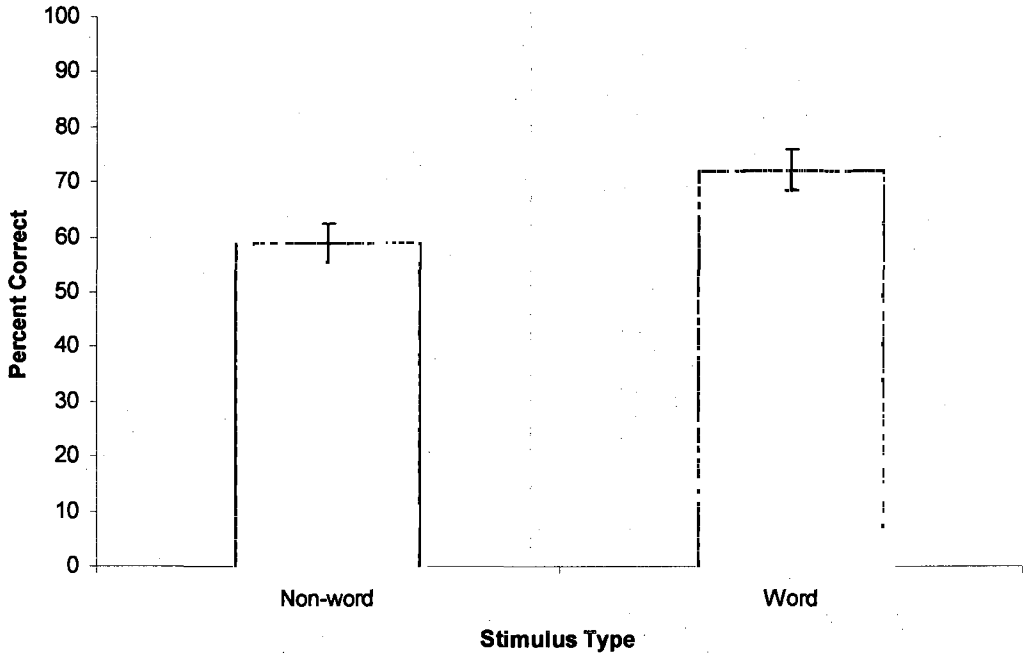

Figure 5. The mean center letter identification rates for letters within a word and within a non-word. A word superiority effect is shown. Error bars represent the standard error of the mean.

An ANOVA on the mean percent correct on the lexical decision task revealed no significant main effects or interactions (see Figure 6). However, to investigate our predictions about the effects of relatedness, post hoc tests were performed. As Figure 7 shows, subjects were less accurate in their responses when the item was preceded by a related (word set 1) prime word ($M = 95.16\%$) than by an unrelated (word set 2) prime word ($M = 96.96\%$; $t(11) = 2.56, p = .026$), indicating that a related prime *interferes* with performance.

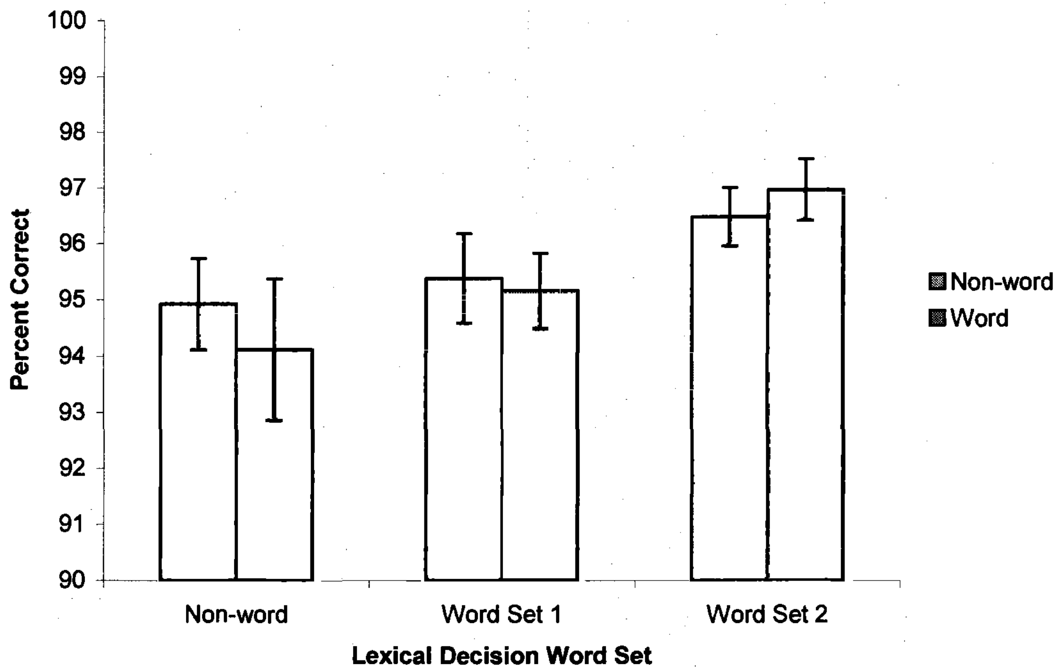

Figure 6. Performance on the lexical decision task, as a function of the prime type. Word set 1 contained words that were related to the prime word and word set 2 contained words that were unrelated to the prime word. Error bars represent the standard error of the mean. Note that the scale starts at 90% correct.

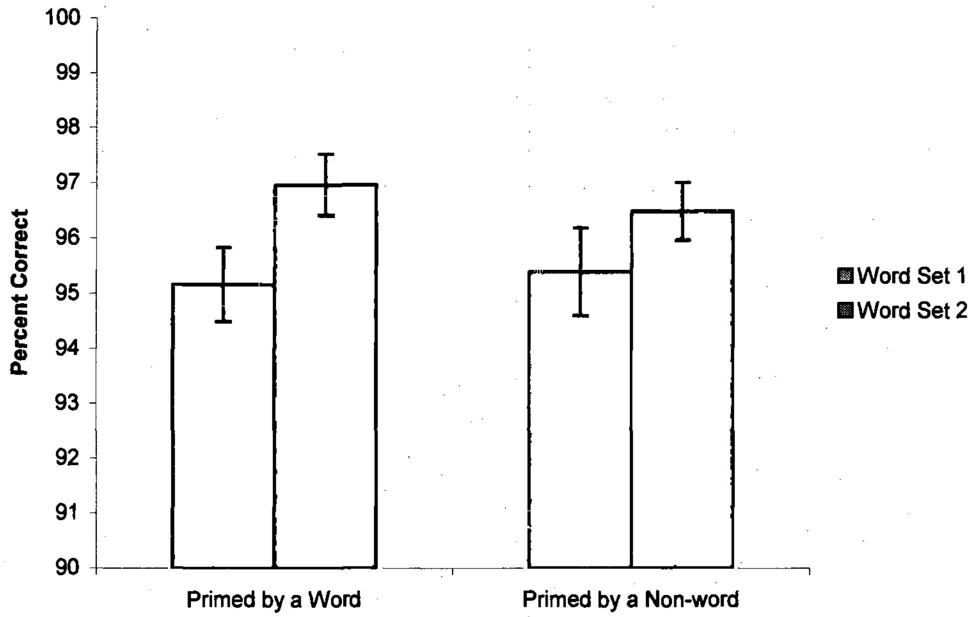

Figure 7. Performance on the lexical decision task, as a function of whether the item was primed by a word from word set 1 or 2. Word set 1 contained words that were related to the prime word and word set 2 contained words that were unrelated to the prime word. Error bars represent the standard error of the mean. Note that the scale starts at 90% correct.

An ANOVA on the mean response times for the correct lexical decision responses revealed a main effect of word set ($F(2, 22) = 4.06, p = .03$), with slower response times to word set 1 (the word prime-related items; $M = 660$ ms) compared to the non-word ($M = 627$ ms) or word set 2 (the word prime-unrelated items; $M = 628$ ms; see Figure 8). There was also a prime type by word set by visual field interaction ($F(2, 22) = 12.91, p < .001$; see Figure 9), such that when there was a non-word prime lexical decision responses were faster when stimuli were presented to the right visual field, with the exception of word set 1 (which showed the opposite pattern), whereas when there was a word prime lexical decision responses were faster when stimuli were presented to the right visual field, with the exception of word set 2.

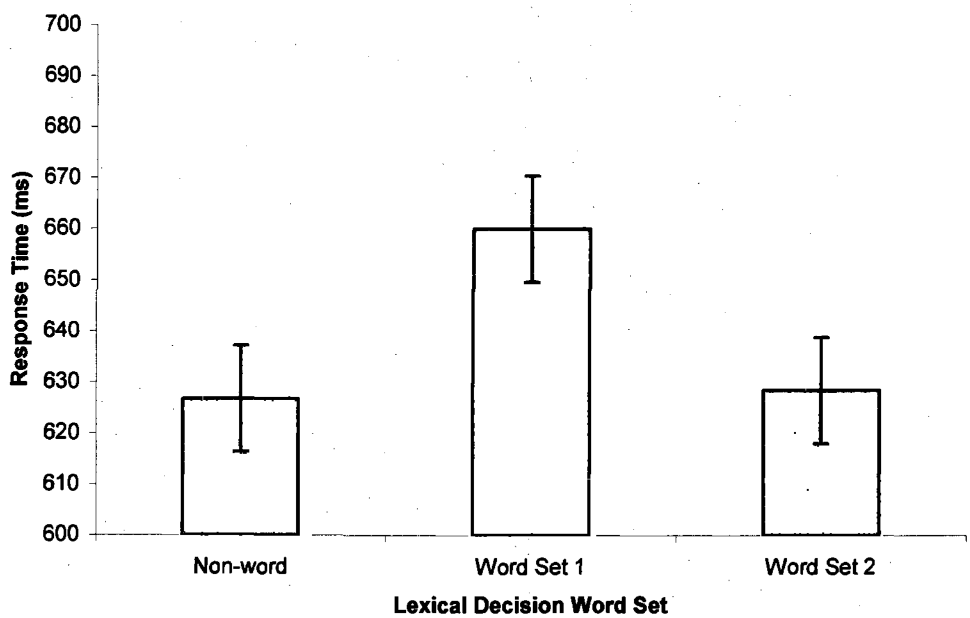

Figure 8. The effect of word set on response times in the lexical decision task. Word set 1 contained words that were related to the prime word and word set 2 contained words that were unrelated to the prime word. Error bars represent the standard error of the mean adjusted for a within subjects design[4]. Note that the scale starts at 600 ms.

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[4] Loftus and Masson (1994) provide an error bar adjustment procedure appropriate for a within subjects design, to allow the differences between the conditions to be seen on a graph. This adjustment was only used on the response time data of this experiment, as the large standard errors in the response times obscured any conditional differences from being seen on the graphs.

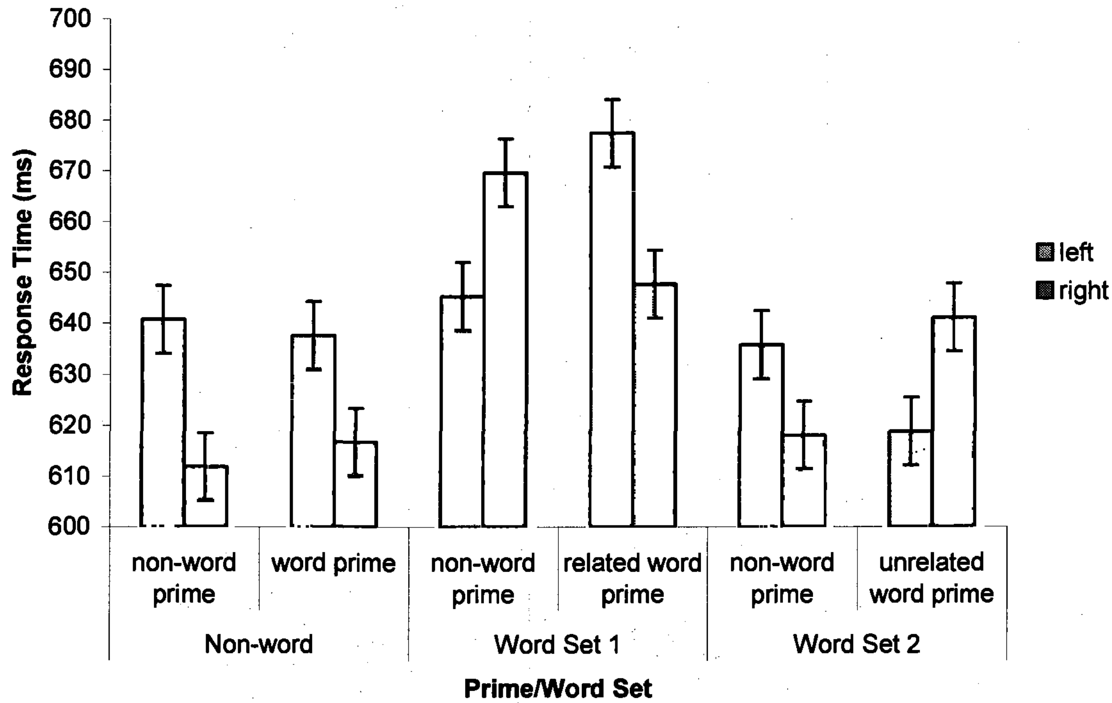

Figure 9. The effect of visual field on the prime-relatedness effect. Word set 1 contained words that were related to the prime word and word set 2 contained words that were unrelated to the prime word. Error bars represent the standard error of the mean adjusted for a within subjects design. Note that the scale starts at 600 ms.

To investigate our predictions about relatedness we conducted follow-up pairwise tests. As seen in Figure 10, response times to a word preceded by a related word were slower than when preceded by an unrelated word ($t(11) = 3.53, p = .005$). However, this effect was also present when those words were preceded by the corresponding non-words ($t(11) = 3.24, p = .008$). This indicates that the interference effects were not exclusive to the word prime, and thus there was no priming effect. Rather, there was an overall advantage for the unrelated words regardless of prime type.

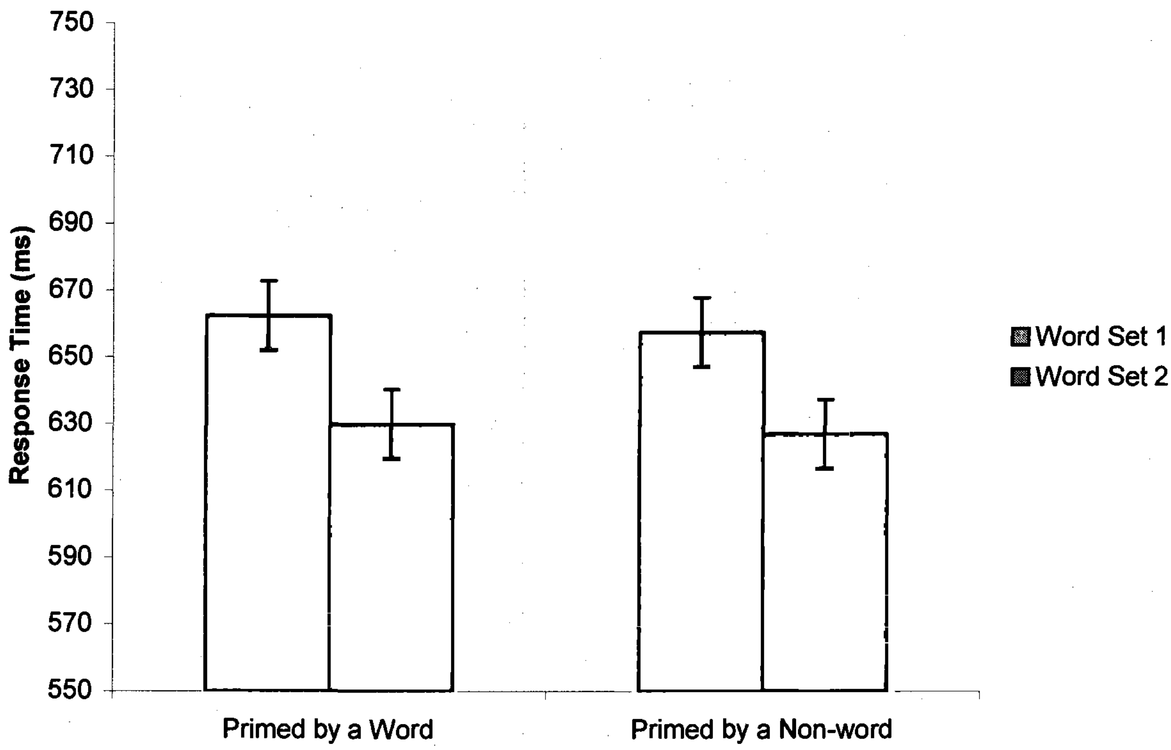

Figure 10. The effect of prime type on word response times in the lexical decision task. Word set 1 contained words that were related to the prime word and word set 2 contained words that were unrelated to the prime word. Error bars represent the standard error of the mean adjusted for a within subjects design. Note that the scale starts at 550 ms.

This lexical decision experiment and the two crowded stimuli experiment were designed to assess whether or not semantics play a role in the word superiority effect. Even though the two experiments attempt to address the same questions, their results produce opposite answers, with the lexical decision experiment showing a semantic interference effect and the two-stimuli experiment showing a priming effect (see below). In order to identify why the experiments produced opposite results, we conducted an item analysis. The item analysis was intended to show which word primes produced priming and which produced interference. As we can see in Table 2, the majority of word primes produced interference effects (slower response times) in the lexical decision task, and some words produced priming effects, but the net result was an interference effect. We can also see from Table 2, that there appears to be no effect of semantic relationship, with a similar number of category/exemplar pairs producing interference and priming. If we extract the words that were used in the two-stimuli experiment and examine whether or not they produced priming or interference effects (see Table 3), the results are mixed, with 5 words producing interference, and 6 words producing priming. However, the net priming effect was larger (+29 ms). Given that the two experiments employed different tasks to assess semantic priming we cannot directly compare the priming effects seen with the subset of words used in the two-stimuli experiment, however, we can say that there was a trend for these words to produce a priming effect, while a larger sample set of words produced a net interference effect.

Crowded Item	Unrelated - Related	Related Relationship
Interference Effects		
act	-49	associate
aft	-121	associate
ago	-209	associate
amp	-116	associate
ape	-14	cat./exemp.
ark	-70	associate
ash	-142	associate
ask	-42	associate
ate	-74	associate
bye	-72	associate
emu	-77	cat./exemp.
hoe	-292	associate

ink	-73	associate
its	-15	associate
lap	-21	associate
lay	-107	associate
net	-31	associate
ode	-156	associate
oft	-116	associate
ore	-55	associate
out	-8	associate
owe	-7	associate
owl	-13	associate
rye	-64	cat./exemp.
sip	-83	associate
spy	-126	associate
sty	-426	associate
thy	-116	associate
two	-42	associate
ump	-166	associate
wag	-258	associate
wok	-0.8	cat./exemp.
wry	-120	associate
Average	**-99**	
Priming Effects		
ace	3	cat./exemp.
ado	4	associate
age	88	cat./exemp.
any	110	associate
apt	10	associate
ego	161	associate
elf	41	associate
gym	19	associate
ice	36	associate
jug	72	associate
old	178	associate
one	103	associate
pin	4	associate
rib	54	cat./exemp.
she	51	associate
sly	60	associate
sum	8	associate
use	7	associate
yet	79	associate
yew	143	cat./exemp.

Average	**61**
Net Effect	**-38**

Table 2. The interference or priming effect (in ms) of each prime on the lexical decision response time. There was a net interference effect of 38 ms.

Crowded Item	Unrelated - Related	Related Relationship
Interference Effects		
ask	-42	associate
ink	-73	associate
its	-15	associate
lap	-21	associate
lay	-107	associate
Average	**-51**	
Priming Effects		
gym	19	associate
old	178	associate
one	103	associate
she	51	associate
sly	60	associate
yet	74	associate
Average	**80**	
Net Effect	**29**	

Table 3. This table shows only the interference or priming effect (in ms) of each prime also used in the two-stimuli experiment (on the lexical decision response time in this experiment). There was a net priming effect of 29 ms.

The item analysis revealed that certain word pairs produced a priming effect while others produced an interference effect, so the words chosen in each experiment lead to either the interference or priming effect that was found. This leads one to believe that the semantic relationship between the prime and the target might contribute to the word superiority effect. However, this hypothesis is premature. We conducted an additional analysis on the pronounceability of each word's corresponding non-word (described below) that revealed a different story.

Several studies have found that pronounceable non-words produce a smaller word superiority effect than non-pronounceable non-words, also called random letter strings (Baron & Thurston, 1973; McClelland & Rumelhart, 1981). Pronounceable non-words are more similar to real words in their bigram frequency than are non-pronounceable non-words[5]. Additionally, non-pronounceable non-words can contain illegal bigram combinations, where as pronounceable non-words cannot. Therefore in comparing pronounceable non-words to real words we might be able to control for some of the letter sequence familiarity differences between words and non-words. Also, it can be argued that the majority of the difference between words and pronounceable non-words is that words contain semantic information. Therefore, a priming effect for words compared to pronounceable non-words would indicate that the semantic system is contributing to the word superiority effect above and beyond that of familiarity[6].

In order to examine this effect of pronounceability, the non-words (and their corresponding words) were grouped by whether the non-words were pronounceable (e.g. ank, sle) or non-pronounceable (e.g. gpm, lsp; see Table 4). The "pronounceable non-word group" contained words and their corresponding pronounceable non-words. The "non-pronounceable non-word group" contained words and non-pronounceable non-words. A 2 (Pronounceability: pronounceable non-word group, non-pronounceable non-

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[5] We are using the term pronounceable here to refer to the fact that some non-words can be pronounced due to the fact that they contain similar bigrams to those that appear in words. We are not using pronounceable to refer to a difference in phonemic representations between pronounceable non-words and non-pronounceable non-words. Phonemic effects are beyond the scope of this paper.

[6] We thank Dr. Randi Martin for helpful discussions on this topic.

word group) x 2 (Prime type: word, non-word) x 2 (Visual field: left, right) within subjects ANOVA was conducted for the center letter identification, and a 2 (Pronounceability: pronounceable non-word group, non-pronounceable non-word group) x 2 (Prime type: word, non-word) x 3 (word set: non-word, word set 1, word set 2) x 2 (Visual field: left, right) within subjects ANOVA was conducted separately for the lexical decision accuracy and lexical decision response time.

Words	Pronounceable Non-words	Words	Non-Pronounceable Non-words
ado	afo	ace	aoe
ask	ank	act	aot
ate	abe	aft	aht
emu	ewu	age	aqe
its	jbs	ago	aqo
jug	jeg	amp	awp
ode	ofe	any	auy
old	oid	ape	aje
ore	ove	apt	ajt
owe	oze	ark	avk
she	sle	ash	anh
sum	sem	bye	bpe
thy	tly	ego	eqo
use	une	elf	eif
		gym	gpm
		hoe	hme
		ice	ioe
		ink	iuk
		lap	lsp
		lay	lsy
		net	nct
		oft	oht
		one	oue
		out	oet
		owl	ozl
		pin	ptn
		rib	rtb
		rye	rpe
		sip	stp
		sly	siy
		spy	sjy
		sty	sby
		two	tzo
		ump	uwp
		wag	wsg
		wok	wmk
		wry	wvy
		yet	yct
		yew	ycw

Table 4. The grouping of pronounceable and non-pronounceable non-words, and their corresponding word.

The ANOVA examining center letter performance revealed a main effect of visual field ($F(1, 11) = 15.48, p = .002$), such that center letter identification rates were higher when stimuli were presented to the right ($M = 72.75\%$) vs. the left visual field ($M = 59.46\%$). Additionally, there was a word superiority effect ($F(1, 11) = 32.84, p < .001$), with higher center letter identification rates for letters presented within a word than within a non-word, but interestingly this effect was qualified by the interaction between word type and pronounceablity ($F(1, 11) = 24.98, p < .001$), such that there was only a word superiority effect for the non-pronounceable non-word group but not for the pronounceable non-word group (see Figure 11).

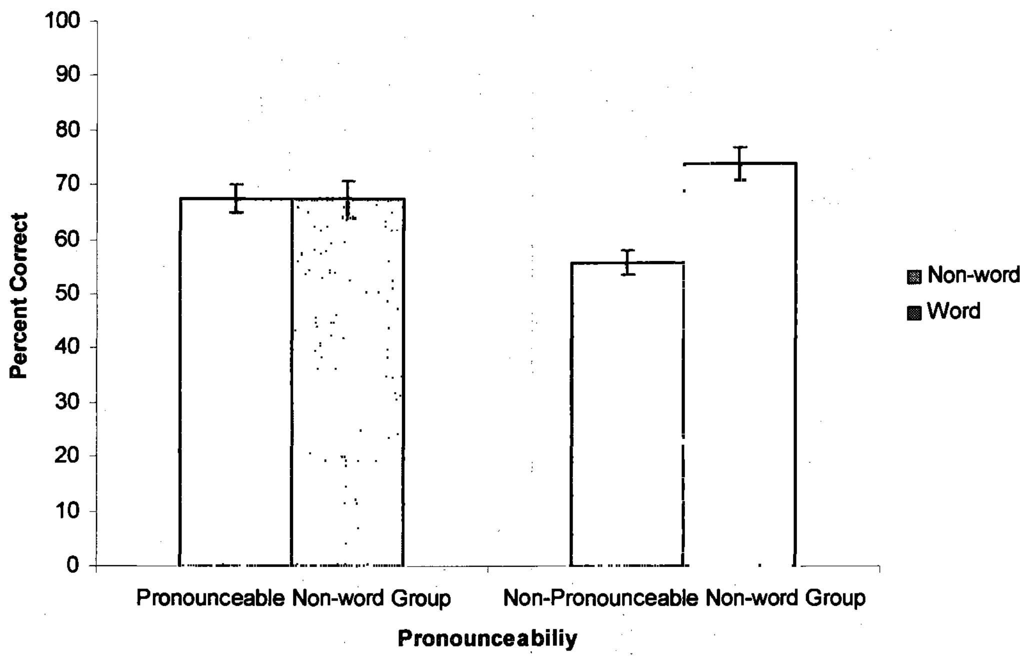


Figure 11. The crowded item word superiority effect for the pronounceable non-word and non-pronounceable non-word groups. The pronounceable non-word group contained words and pronounceable non-words, and the non-pronounceable non-word group contained words and non-pronounceable non-words.

The ANOVA examining lexical decision accuracy revealed an effect of word set, which simply reflected a word superiority effect ($F(2, 22) = 5.03, p = .016$), such that subjects were more accurate when responding to a word ($M_{\text{word set 1}} = 95.92\%$, $M_{\text{word set 2}} = 96.75\%$; see Figure 12) than to a non-word ($M = 93.79\%$; $F(1, 11) = 5.97, p = .03$). There was a pronounceability by relatedness/word set interaction ($F(2, 22) = 9.67, p = .001$; see Figure 13), such that for word set 1, being primed by an item from the pronounceable non-word group produced better performance than when primed by an item from the non-pronounceable non-word group. When we break up the pronounceable prime group variable an examine whether there is an effect on whether subjects were responding to a word or a non-word (see Figure 14) we can see that the pronounceable non-word prime group results in a word superiority effect on the lexical decision task, while the non-pronounceable non-word prime group does not.

To examine the effect of pronounceability on the semantic priming effect we looked at the priming effect of words and pronounceable non-words for word set 1 (word prime - related condition; see Figure 15). This interaction is not significant ($F(2, 22) = 0.67$, $p = .52$), but it shows that responses to items in word set 1 were the not affected by whether they were preceded by non-word primes or related word primes, and this occurs regardless of non-word pronounceability.

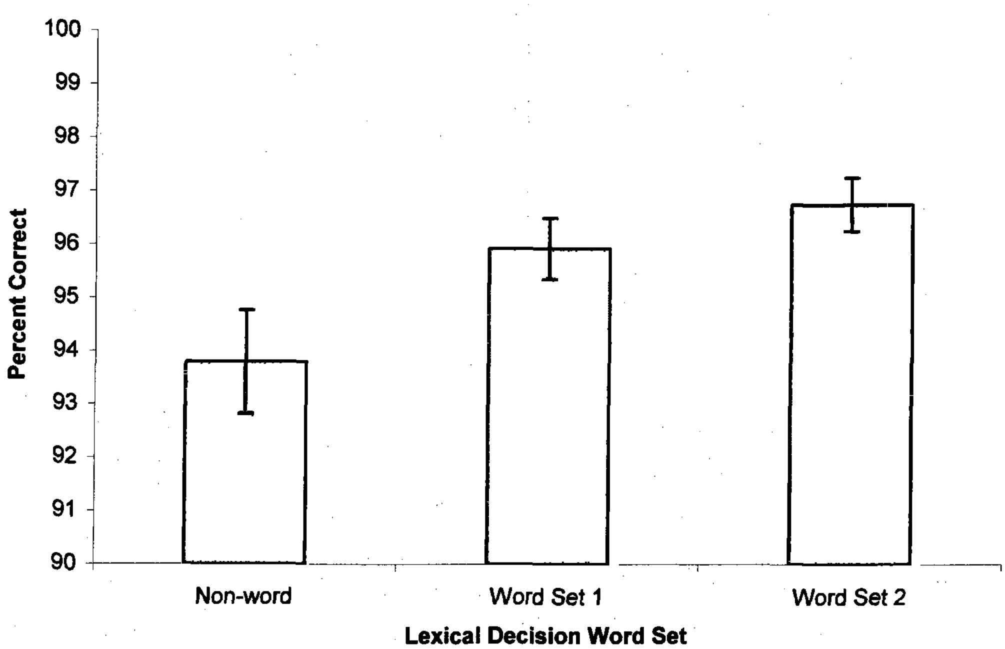


Figure 12. The effect of stimulus type effected lexical decision responses, with greater accuracy for words than for non-words. Note that the scale starts at 90% correct.

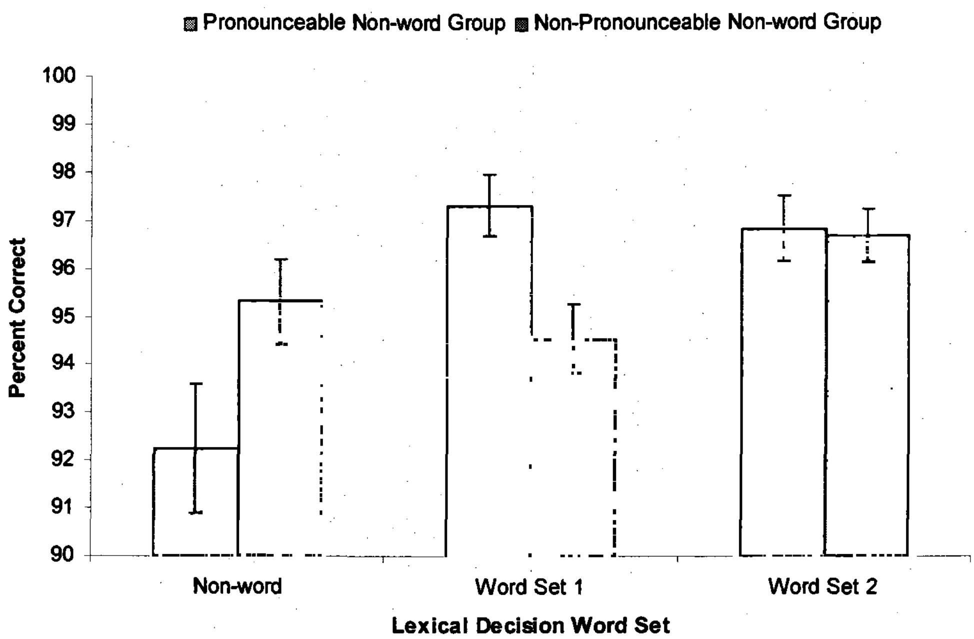


Figure 13. The effect of the pronounceability of the prime on responses for the different word sets. The pronounceable non-word group contained words and pronounceable non-words, and the non-pronounceable non-word group contained words and non-pronounceable non-words. Note that the scale starts at 90% correct.

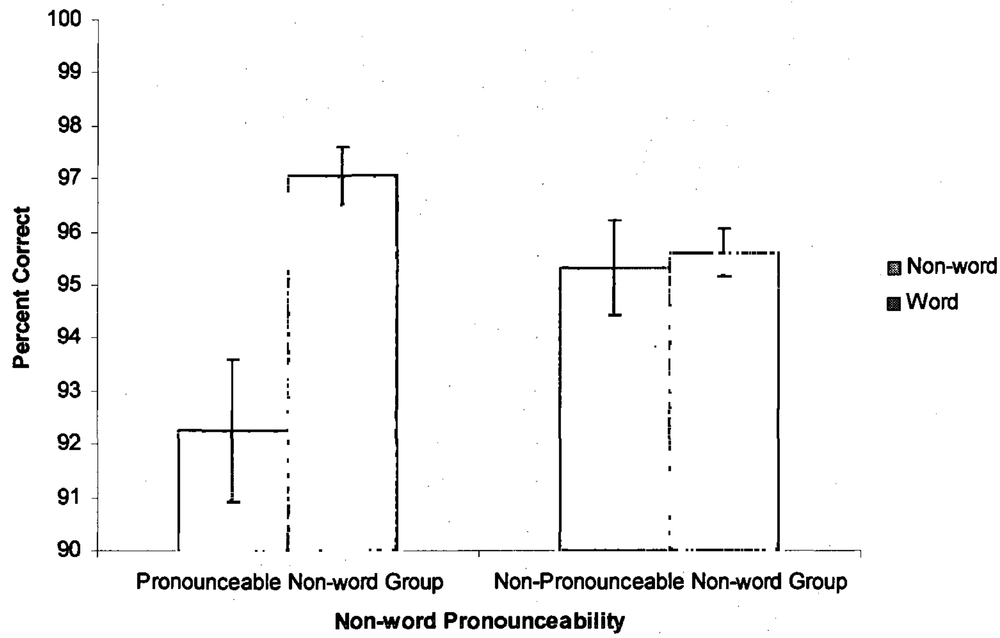
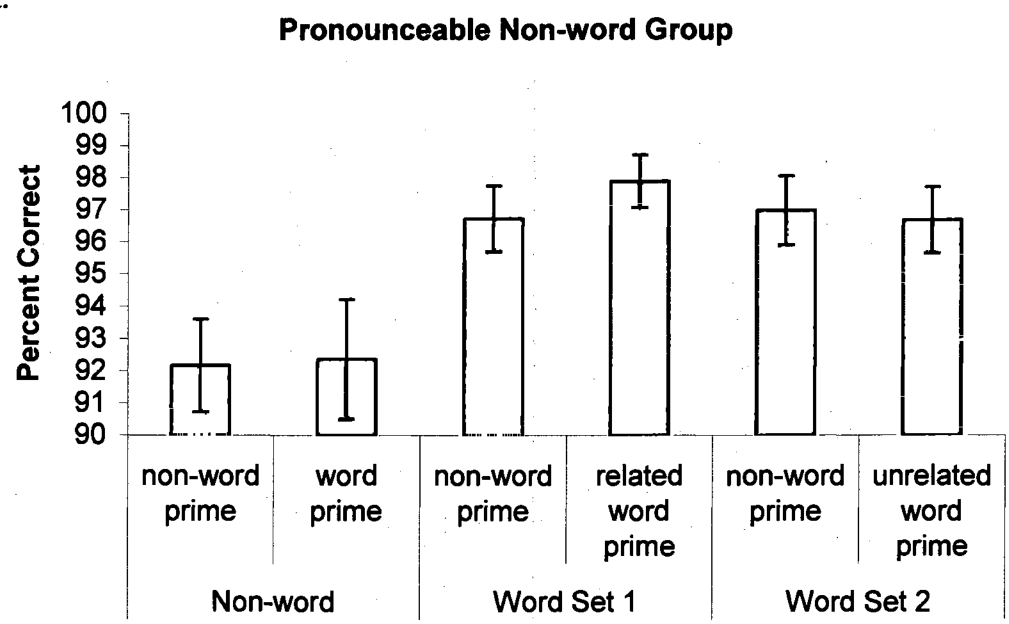


Figure 14. The effect of prime pronounceability on performance in the lexical decision task. The pronounceable non-word prime group produced a word superiority effect, while the non-pronounceable non-word prime group did not. The pronounceable non-word group contained words and pronounceable non-words, and the non-pronounceable non-word group contained words and non-pronounceable non-words. Note that the scale starts at 90% correct.

a.



b.

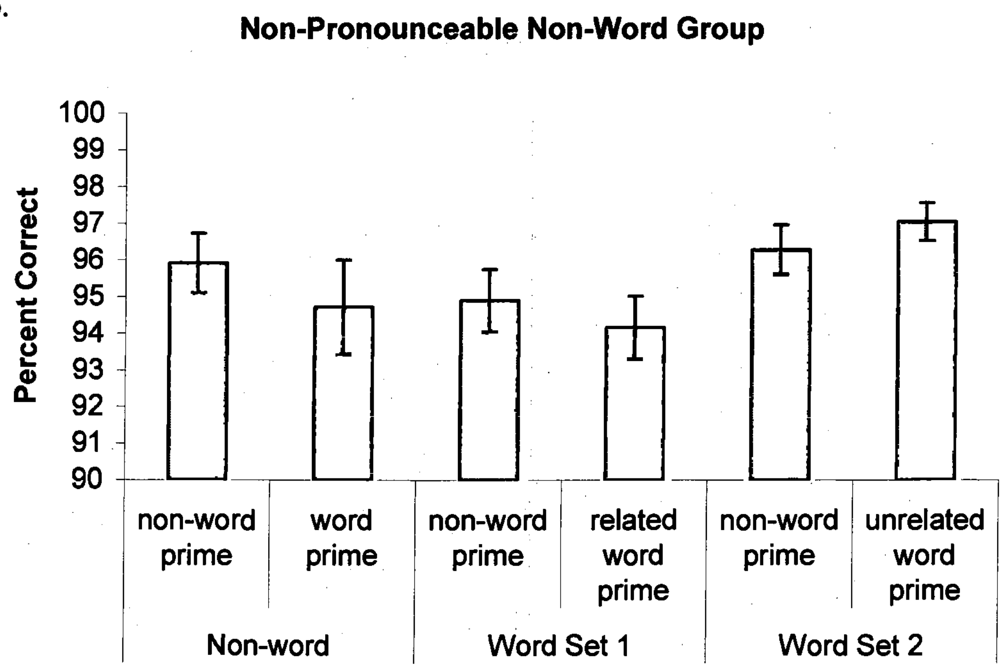


Figure 15. The effect of prime type on lexical decision responses in each word set condition, split by whether the non-word primes were pronounceable (a.) or non-pronounceable (b.). Note that the scale starts at 90% correct.

The ANOVA examining lexical decision response times found no word superiority effect ($F(1, 11) = 1.26, p = .29$; see Figure 16), with subjects responding similarly to a word ($M = 644$ ms) and to a non-word ($M = 625$ ms). There was also no interaction with pronounceability ($F(1, 11) = 0.12, p = .75$), indicating it made no difference whether the item was primed by the pronounceable non-word or non-pronounceable non-word group (see Figure 16).

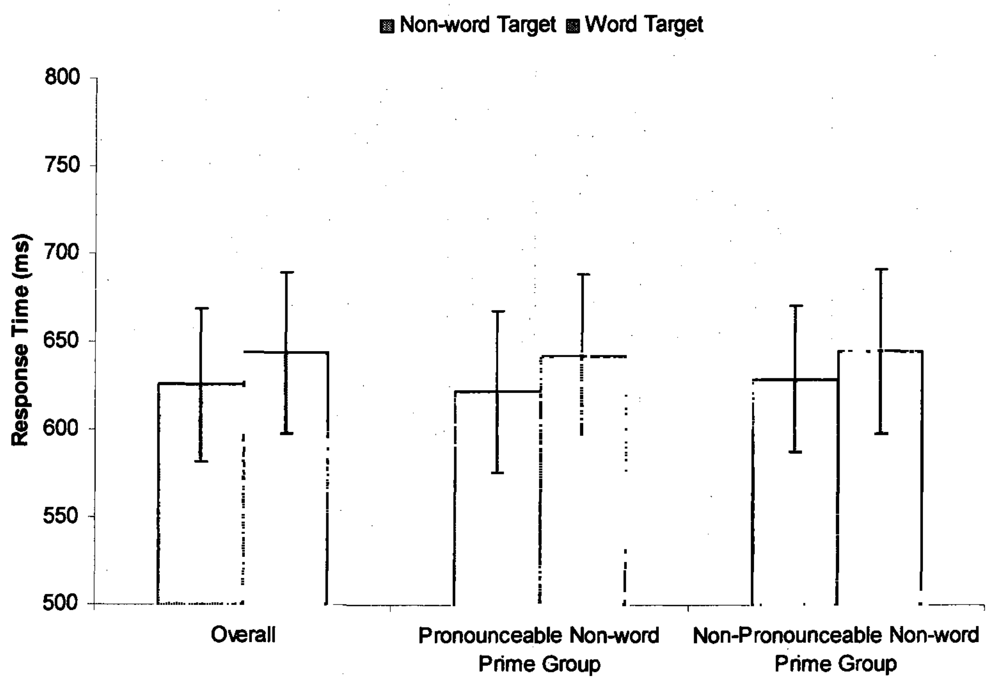


Figure 16. The lack of a word superiority effect in the lexical decision response time data. The pronounceable non-word group contained words and pronounceable non-words, and the non-pronounceable non-word group contained words and non-pronounceable non-words. Note that the scale starts at 500 ms.

There was a main effect of word set ($F(2, 22) = 3.88$, $p = .036$), such that word set 1 (related to word prime; $M = 661$ ms) had slower responses than either word set 2 (unrelated to word prime; $M = 625$ ms) or non-word groups ($M = 625$ ms). There were several interactions with visual field (prime type by visual field, $F(1, 11) = 5.86$, $p = .03$; pronounceability by prime type by visual field, $F(1, 11) = 20.71$, $p = .001$; pronounceability by word set by visual field, $F(2, 22) = 4.70$, $p = .02$; prime type by word set by visual field, $F(2, 22) = 9.30$, $p = .001$; pronounceability by prime type by word set by visual field, $F(2, 22) = 3.32$, $p = .055$), however these are not relevant to the current hypothesis. Of interest is the pronounceability by prime type by word set interaction ($F(2, 22) = 2.94$, $p = .07$; see Figure 17), which shows that there were similar effects for word set 1 (related to word prime) for both the pronounceable non-word and non-pronounceable non-word groups.

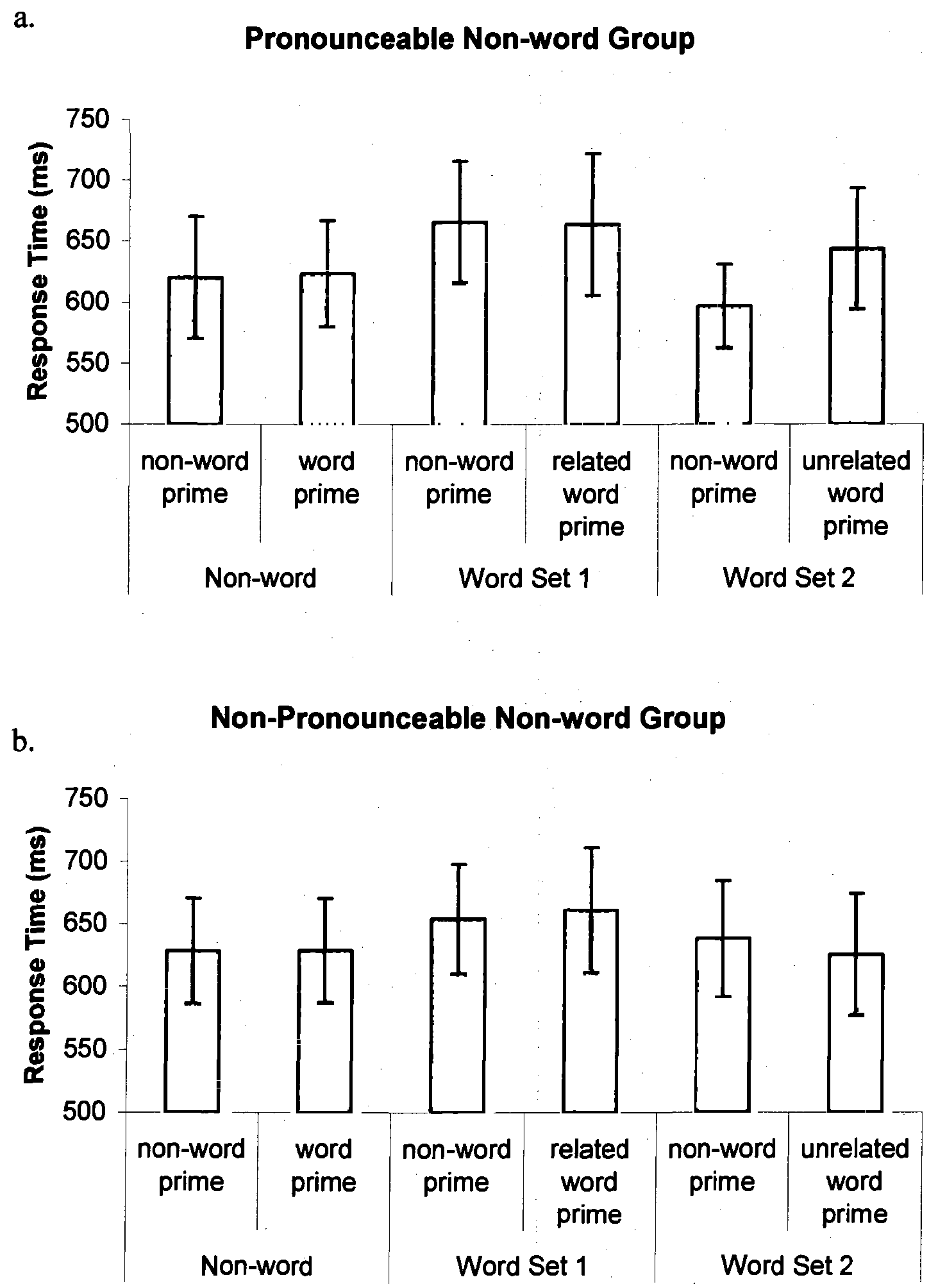


Figure 17. The response times for each word set as a function of prime type, and split by whether the non-word prime was pronounceable (a.) or non-pronounceable (b.). There was no semantic priming in the related word condition (responses to word set 1 with a word prime) for either the pronounceable non-word or non-pronounceable non-word word groups. Note that the scale starts at 500 ms.

As we can see in both the accuracy and response time analysis of pronounceability, the pronounceable non-words produce similar effects to their corresponding words. This suggests that semantics are not playing a role in the word superiority effect, but rather any priming or interference effects we might see can be explained by a simple spreading activation model.

The lexical decision accuracy data show an advantage for words primed by a related word than words primed by and unrelated word, suggesting that there might be an influence of semantic information on lexical decision responses. The item analysis further supports this hypothesis by showing that certain related word pairs produce priming while others produce interference effects and the net result is dependent on how many of each type are present. The current study revealed a net interference effect but if other word pairs were chosen there might have been a net priming effect. However, the pronounceability analysis revealed that the hypothesis that semantic information influences responses was wrong. When dividing the primes into whether or not each words' corresponding non-word was pronounceable (contained legal bigrams) or non-pronounceable (did not contain legal bigrams), we could see that pronounceable non-words produced just as much of an influence on performance as their corresponding words, whereas non-pronounceable non-words did not. Since pronounceable non-words are similar to words in their letter co-occurrence, but differ in that they do not possess semantic information, any similar result must be attributed to the factor they have in common (perceptual familiarity) and cannot be attributed to the factor they do not share (semantics). Thus, it would seem most plausible that a perceptual familiarity effect can explain the similar results between words and pronounceable non-words in this task.

Experiment 3: Assessing Semantics - Two Crowded Items

Method

Participants. Fifteen subjects (1 male, all right handed, mean age of 20 years) were recruited from the Rice University Psychology Department research pool. All subjects had normal or corrected to normal vision, were native English speakers, and participated only after providing informed consent.

Stimuli and Apparatus and Procedure. All display parameters were the same as Experiment 1, except where noted.

For the first six subjects the crowded stimuli, and their parameters, were the same as those used in Experiment 1. Upon changing the font in Experiment 2 to allow for proper scaling, we changed the font in this experiment also. Therefore, the remaining nine subjects were run using Courier New font. Thus the size of the items changed such that an 'o' measured 1.30 x 1.30 degrees. We also added a single word condition to the experiment that only these last nine subjects completed.

For the priming trials, each trial began with a fixation cross in the center of the screen, which stayed on throughout the trial. The subject initiated the trial by pressing the SPACE bar. The first three letter sequence was flashed on the screen for 150 ms, followed by a 500 ms delay period, and then the second three letter sequence was presented for 150 ms (see Figure 18). A response probe was then presented that said either 'First?' or 'Second?' and the subject had 3.5 seconds to key in the center letter of either the first stimulus or the second stimulus, respectively, on the keypad. They were instructed to make the most accurate judgment possible as to the identity of the center letter and if they were unsure, they were told to make their best guess. The response screen was then replaced by a fixation cross, at which time the subject could initiate a new trial.

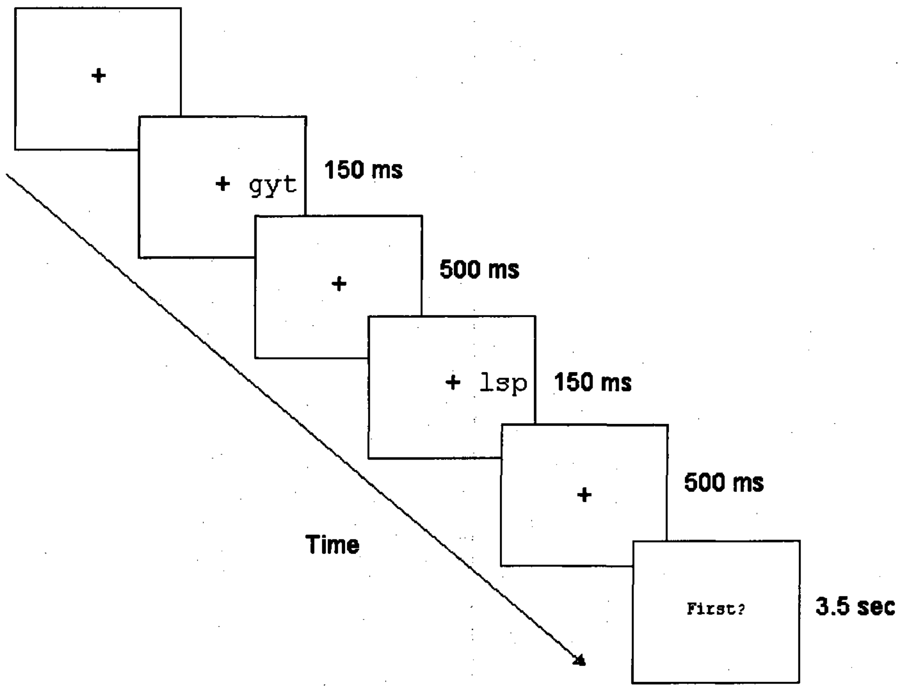


Figure 18. The sequence of events in Experiment 3, assessing semantics with two crowded stimuli.

For the single letter trials, the stimulus properties and sequence of events were the same, except that only single letters were used instead of trigrams. The letters were presented such that the same item never appeared as the first and second stimulus in a trial. All 26 letters of the alphabet were presented, once in each visual field.

Each session began with 12 practice trials, which were not included in the analysis. There were 132 trials with stimuli presented to the left visual field and 132 trials to the right visual field included in the analysis. Half of each (66 trials) were crowded words presented as the first item, of which one third had corresponding second item words related to their meanings, one third had second item words unrelated to their meanings, and one third had second item non-words. The other half were non-words presented as the first item, with the same second item division. This created 6 conditions: word-related/word set 1 (first stimulus-second stimulus), word-unrelated/word set 2, word-non-word, non-word-word set 1, non-word-word set 2, and non-word-non-word. The first item was probed on half the trials (for each condition), and the second item was probed on the other half. The non-words were generated by Fine (2001) by changing the center letter of a word. Only a subset (11) of the words and corresponding non-words created by Fine (2001; and used in Experiment 2) were used. The items were selected such that the crowded word and its matched related, unrelated, and non-word were only three-letter trigrams (see Appendix C). Because both of the items in the trial were to be crowded they all had to be three-letter items. There were a total of 276 (including 12 practice) trials of three letter sequences and 52 trials of single letters in each session, lasting approximately 45 minutes in duration. The subjects could take a break at any time during the experiment by not initiating a new trial. We recorded the number of center letters correctly identified for each trigram in the priming trials and the number of correct letter identifications in the single letter trials.

Design. In order to assess crowding the independent variable was task (letter in isolation, trigram) and the dependent variable was accuracy of response. In order to assess crowding and priming, the independent variables were font type (courier, courier new), visual field (left, right), response probe (first, second), prime type (or first item;

word, non-word), whether the non-word prime was pronounceable or not: pronounceability ([words and] pronounceable non-word group, [words and] non-pronounceable non-word group), word set (non-word, word set 1 [containing words that were related to the word prime], word set 2 [containing words that were unrelated to the word prime]). The dependent variable was accuracy in identifying the center letter of the trigram.

Results and Discussion

The trials for the related (second item) word "add" were removed from the analyses because it is unclear when subjects responded "d" as the center letter whether they were reporting the center letter or the right distracter. This was a bad choice of word and should not have been used. This resulted in the removal of 8 trials per subject.

An initial ANOVA was conducted to test for performance differences between subjects run with Courier font and those run with Courier New font. The 2 (Visual field: left, right) X 2 (Response: first, second) X 2 (Prime type: word, non-word) X 3 (word set: word set 1, word set 2, non-word) X 2 (Font type: Courier, Courier New) mixed ANOVA revealed neither a main effect ($F(1, 13) = 1.89$, $p = .19$) nor any interactions with font type. Therefore, all further analyses were collapsed across this variable.

The mean percent correct center letter identification's when the letter was presented in isolation and when crowded, was calculated separately for each response. Identification rates were higher in the single letter condition ($M = 97.44\%$) than in the crowded letter condition for response 1 ($M = 65.17\%$; $t(8) = -6.35$, $p < .001$) and response 2 ($M_{\text{single}} = 97.86\%$, $M_{\text{crowded}} = 75.57\%$; $t(8) = -7.13$, $p < .001$).

We calculated the mean percent correct center letter identification's when the letter was presented within a word and when it was presented within a non-word, for each response (see Figure 19). There was a word-superiority effect for response 1 ($t(14) = 6.32, p < .001$), and response 2 ($t(14) = 5.79, p < .001$), with higher letter identification rates when the letter was presented within a word ($M_{response1}$ = 72.57%, $M_{response2}$ = 79.07%) than within a non-word ($M_{response1}$ = 48.90%, $M_{response2}$ = 61.67%).

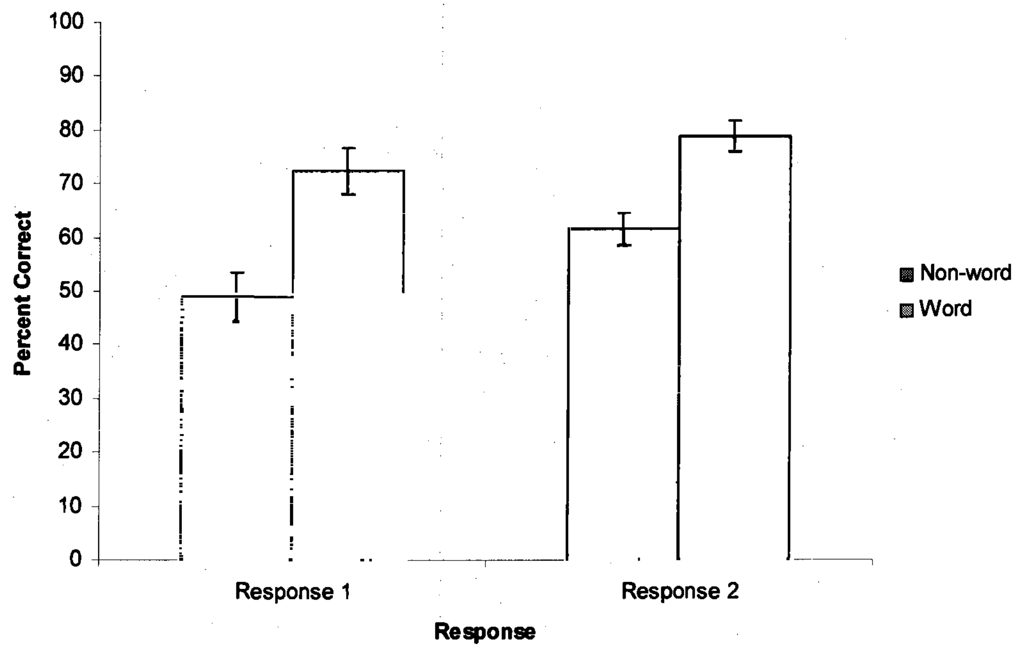


Figure 19. The figure shows a word superiority effect for each response. Error bars represent the standard error of the mean.

To assess whether priming occurred, we conducted a 2 (Visual field: left, right) X 2 (Prime type: word, non-word) X 3 (word set/relatedness: word set 1 [containing words related to the word prime], word set 2 [containing words unrelated to the word prime], non-word) ANOVA, separately for each response. Support for priming would show as a prime type by word set/relatedness interaction for response 2, but not for response 1. A word set/relatedness main effect or interaction would not be expected for response 1, since the relatedness variable refers to the relatedness between the first word and second word. If such an effect did emerge it would mean that the stimulus type of the second item influenced performance on the first item. For response 1, there was a main effect of prime type ($F(1, 14) = 39.97, p < .001$), such that identification rates were higher when the prime was a word ($M = 72.57\%$) than a non-word ($M = 48.91\%$). There was a main effect of visual field ($F(1, 14) = 6.84, p = .02$), such that identification rates were better when stimuli were presented in the right visual field ($M = 64.09\%$) than in the left visual field ($M = 57.39\%$). There was also a prime type x word set x visual field interaction ($F(2, 28) = 4.12, p = .03$). No other effects were significant.

For response 2, there was a main effect of word set ($F(2, 28) = 20.25, p < .001$), such that identification rates were highest for word set 1 (the word prime-related items; $M = 81.08\%$), followed by word set 2 (the word prime-unrelated items; $M = 77.06\%$), and then the non-word items ($M = 61.67\%$). More importantly there was a word set/relatedness by prime type interaction ($F(2, 28) = 7.17, p = .003$; see Figure 20). To test our hypothesis that related words would show the largest priming effect, we conducted individual pair-wise comparisons. Not all pair-wise combinations were tested, as some effects would be redundant with the main effect of word set/relatedness. When the prime (first item) was a word and it was related to the second item, identification rates for that second item were better than when the prime was a non-word ($t(14) = -3.38, p = .004$), and better than when the prime was a non-word and the second item was from the unrelated word set (word set 2; $t(14) = -2.79, p = .015$). When the prime was a word and it was related to the second item, there was a trend for identification rates for that second item to be better than when the prime was a word but the second item was an unrelated word ($t(14) = -2.09, p = .056$). These results indicate that when both crowded items were words and they were related to each other, performance was better than when the prime was a non-word or the items were unrelated.

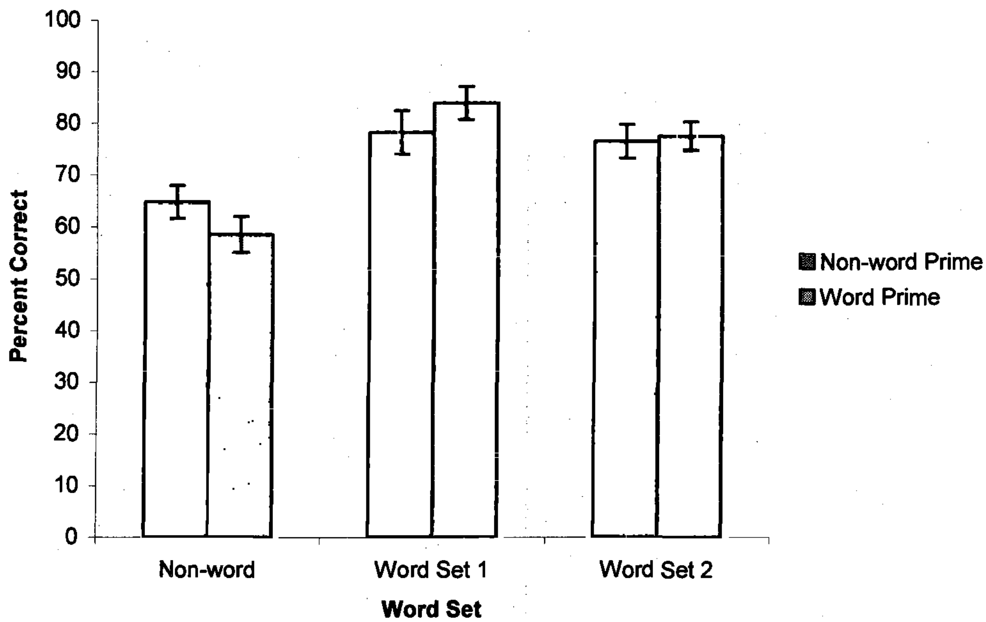


Figure 20. The effect of prime type and word set for Response 2. Word set 1 contained words that were related to the word prime, and word set 2 contained words that were unrelated to the word prime. Error bars represent the standard error of the mean.

Several studies have found that pronounceable non-words produce a smaller word superiority effect than non-pronounceable non-words, also called random letter strings (Baron & Thurston, 1973; McClelland & Rumelhart, 1981). Pronounceable non-words are more similar to real words in their bigram frequency than are non-pronounceable non-words. Additionally, non-pronounceable non-words can contain illegal bigram combinations, where as pronounceable non-words cannot. Therefore in comparing pronounceable non-words to real words we might be able to control for some of the letter sequence familiarity differences between words and non-words. Also, it can be argued that the majority of the difference between words and pronounceable non-words is that words contain semantic information. Therefore, a priming effect for words compared to pronounceable non-words would indicate that the semantic system is contributing to the word superiority effect above and beyond that of perceptual familiarity. In order to examine this effect of pronounceability, the non-words (along with their corresponding words) were grouped by whether the non-words were pronounceable (e.g. ank, sle) or non-pronounceable (e.g. gpm, lsp; as in Experiment 2; see Table 5) and subject to a 2 (Pronounceability: pronounceable non-word group, non-pronounceable non-word group) x 2 (Prime type: word, non-word) x 3 (Word set: non-word, word set 1 [containing words related to the word prime], word set 2 [containing words unrelated to the word prime]) x 2 (Visual field: left, right) within subjects ANOVA separately for response 1 and response 2.

Words	**Pronounceable Non-words**
ask	ank
its	ibs
old	oid
she	sle
Words	**Non-pronounceable Non-words**
gym	gpm
ink	iuk

lap	lsp
one	oue
sly	siy
yet	yct

Table 5. The grouping of pronounceable and non-pronounceable non-words, and their corresponding word.

For response 1, a word superiority effect was found, with greater accuracy in identifying the center letter when it was presented in the context of a word ($M = 71.28\%$) than in the context of a non-word ($M = 48.74\%$; $F(1, 14) = 39.23, p < .001$), and an effect of visual field was found, with greater identification accuracy for items presented to the right ($M = 63.18\%$) than the left visual field ($M = 56.85\%$; $F(1, 14) = 4.51, p = .05$). However, the only interaction with pronounceability was a pronounceability by prime type by word set/relatedness by visual field interaction ($F(2, 28) = 4.22, p = .025$).

For response 2, there was an effect of word set, such that identification rates were highest for word set 1 ($M = 83.43\%$), followed by word set 2 ($M = 76\%$), and lowest for the non-words ($M = 61.43\%$; $F(2, 28) = 22.38, p < .001$), and a prime type by word set/relatedness interaction ($F(2, 28) = 4.51, p = .02$), replicating the effects seen above (see Figure 20). Of interest, there was a pronounceability by word set/relatedness interaction ($F(2, 28) = 8.44, p = .001$), such that letters were identified better in word set 1 (the word prime-related items) when the item preceding it was a pronounceable word or non-word, than an item from the word and non-pronounceable non-word group, whereas, letters were identified better in word set 2 (the word prime-unrelated items) when the item preceding it was a word or non-pronounceable non-word, than when it was a pronounceable word or non-word (see Figure 21).

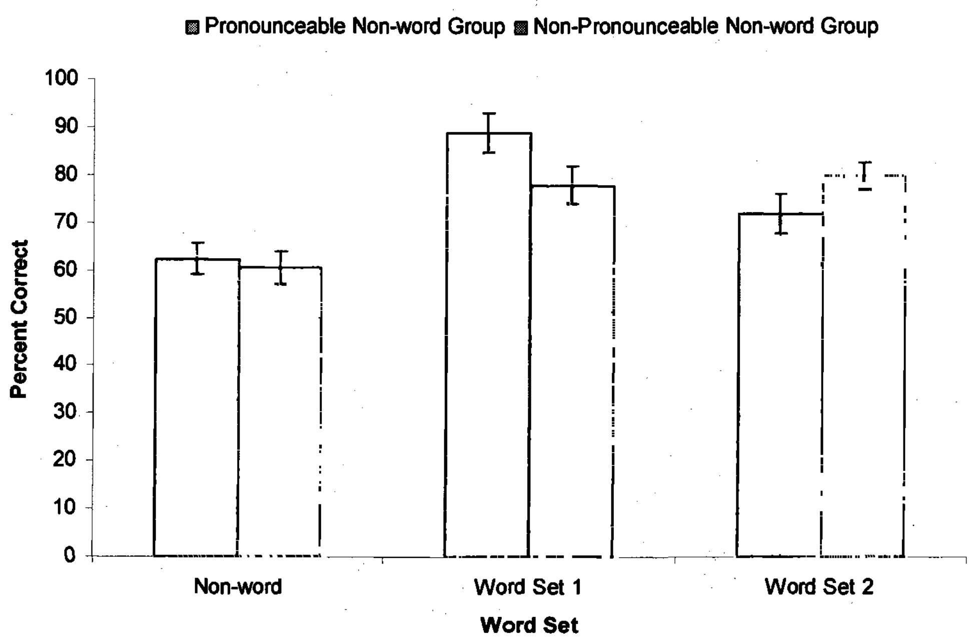
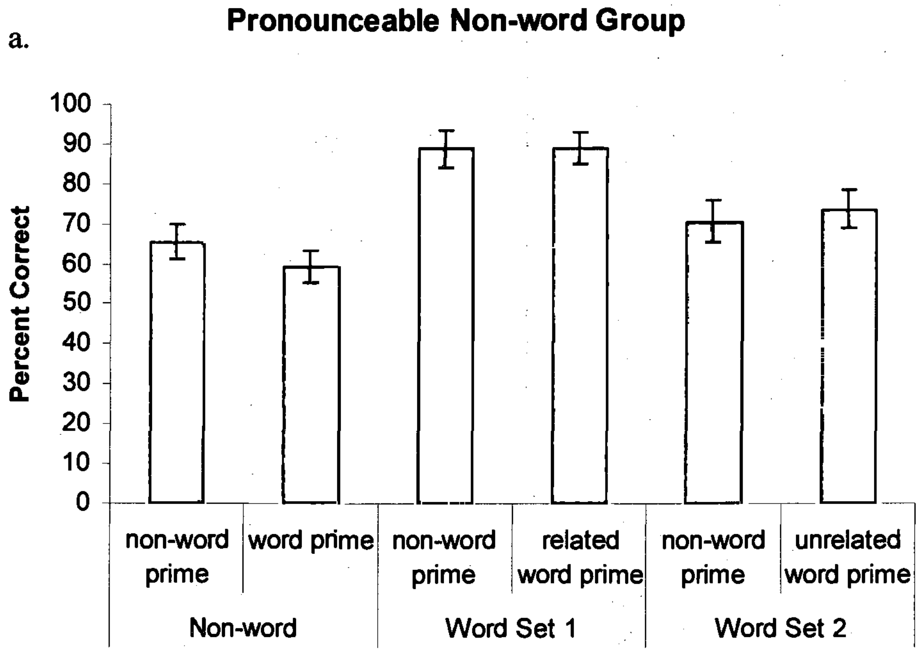


Figure 21. The pronounceability by word set effect for response 2. The pronounceable non-word group contained words and pronounceable non-words, and the non-pronounceable non-word group contained words and non-pronounceable non-words. Error bars represent the standard error of the mean.

In order to examine whether or not words would produce a priming effect above and beyond that of pronounceable non-words, two simple effects analyses were done to compare words and pronounceable non-words and then words and non-pronounceable non-words. As Figure 22 shows, center letter identification was better for items from word set 1 (word prime-related items) than word set 2 (word prime-unrelated items) for the pronounceable group ($F(1, 14) = 13.96, p = .002$), but pronounceable non-words produced just as much priming as their corresponding words, for word set 1 (and word set 2; $F(1, 14) = 0.25, p = .63$). For the word and non-pronounceable non-word group, there was no performance difference for word set 1 vs. word set 2 ($F(1, 14) = 0.33, p = .57$), but there was an effect of prime type ($F(1, 14) = 6.22, p = .03$), which was driven by the difference in word set 1. Non-pronounceable non-words produced significantly less priming than their corresponding words for word set 1 (containing word prime related items; $F(1, 14) = 14.41, p = .002$). There was no prime type effect in the unrelated condition ($F(1, 14) = 0.81, p = .38$).

a.



b

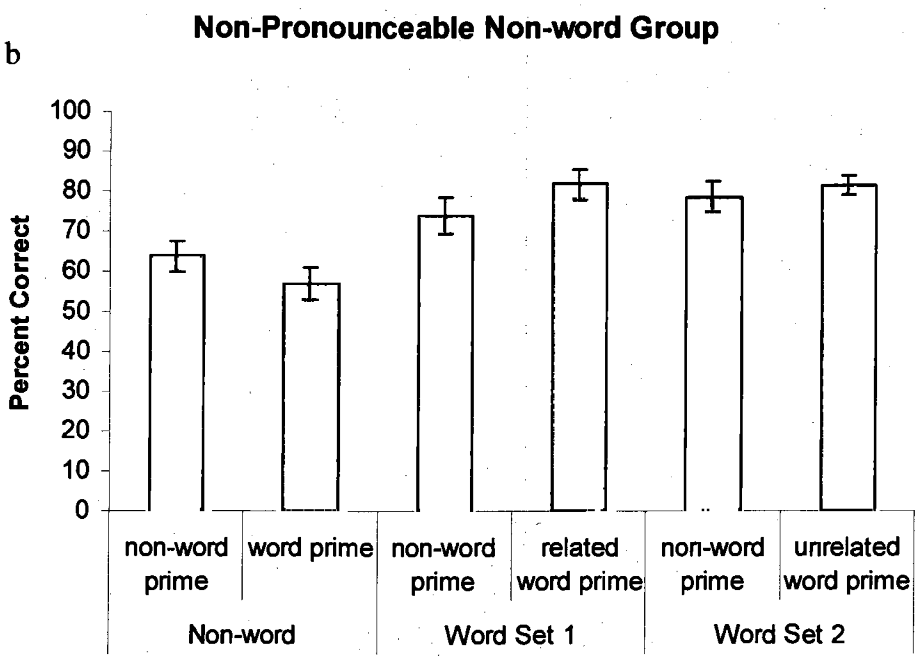


Figure 22. The effect of prime type on responses for each word set, split by whether the non-word prime was pronounceable (a.) or non-pronounceable (b.), for response 2. Error bars represent the standard error of the mean.

There was a word-superiority effect for response 1 ($F(1, 14) = 39.23, p < .001$), and response 2 ($F(1, 14) = 32.87, p < .001$), with higher letter identification rates when the letter was presented within a word ($M_{response1} =$ 71.28%, $M_{response2} =$ 79.72%) than within a non-word ($M_{response1} =$ 48.74%, $M_{response2} =$ 61.43%). Additionally, the word superiority effect did not differ for the word and pronounceable non-word vs. word and non-pronounceable non-word prime groups for response 1 ($F(1, 14) = 0.80, p = .05$) or response 2 ($F(1, 14) = 0.90, p = .05$; see Figure 23).

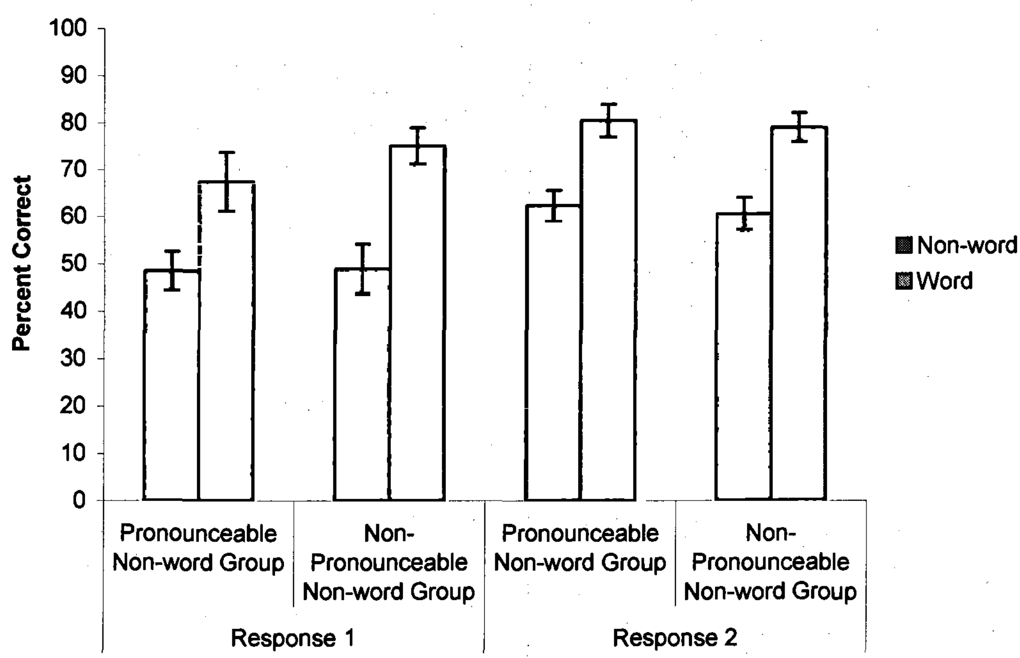


Figure 23. The word superiority effect for each pronounceable group and response. The pronounceable non-word group contained words and pronounceable non-words, and the non-pronounceable non-word group contained words and non-pronounceable non-words. Error bars represent the standard error of the mean.

The center letter accuracy data revealed that when both crowded items were words and they were related to each other, performance was better than when the prime was a non-word or the items were unrelated. This seems to indicate that the semantics of the word are contributing to performance. However, as with the lexical decision experiment, this conclusion is premature. When the primes are split by whether each words corresponding non-word is pronounceable or not, we see that for the pronounceable group, responses to word set 1 (the word prime-related items) were better than to word set 2 (the word prime-unrelated items), but performance was the same for the word and non-word primes. This indicates that pronounceable non-words produce the same benefit in performance as their corresponding words. This was not the case for non-pronounceable non-words, with related words producing a priming effect as compared to non-words. These findings indicate that perceptual familiarity can explain the performance benefit with related words, rather than semantic access.

Experiment 4: Cuing effects on Crowded Letter Identification

In Experiments 2 and 3, we investigated the role semantics play in the word superiority effect using a crowded display. In Experiments 4 and 5, we examined the role of attentional cuing in the crowding effect and how cuing might interact with the word superiority effect.

Method

Participants. Twenty-one subjects were recruited from the Rice University Psychology Department research pool (13 females and 8 males; Mean age = 20; one left handed subject). All subjects had normal or corrected to normal vision, were native English speakers, and participated only after providing informed consent. On subject's data was removed from the analysis because they showed a pattern opposite that of all the other subjects.

Stimuli and Apparatus and Procedure. Display and crowded letter characteristics were the same as in Experiment 1, with the exceptions noted below.

Each trial began with a fixation cross in the center of the screen, which stayed on throughout the trial. The subject initiated the trial by pressing the SPACE bar. A central arrow (endogenous condition), a peripheral flash (exogenous condition), or the respective neutral cue (see below) then appears. The arrow was presented for 83 ms and pointed either to the left or the right visual field. The peripheral flash was presented for 83 ms just above the location of the center letter in either the left or right visual field (see Figure 24). The respective neutral cue was also presented from 83 ms. There was a 17 ms ISI and then the three letter crowding sequence was flashed on the screen for 150 ms, followed by a 500 ms delay period and then a response probe. The response probe said "Select Center Letter," at which time the subject had 3 seconds to make a response on the keypad. They were instructed to make the most accurate judgment possible as to the identity of the center letter and if they were unsure, they were told to make their best guess. The 3 seconds response window was imposed to prevent subjects from deliberating over the identity of the letter. After the 3 seconds response window, the "Select Center Letter" was replaced by a fixation cross, at which time the subject could initiate a new trial.

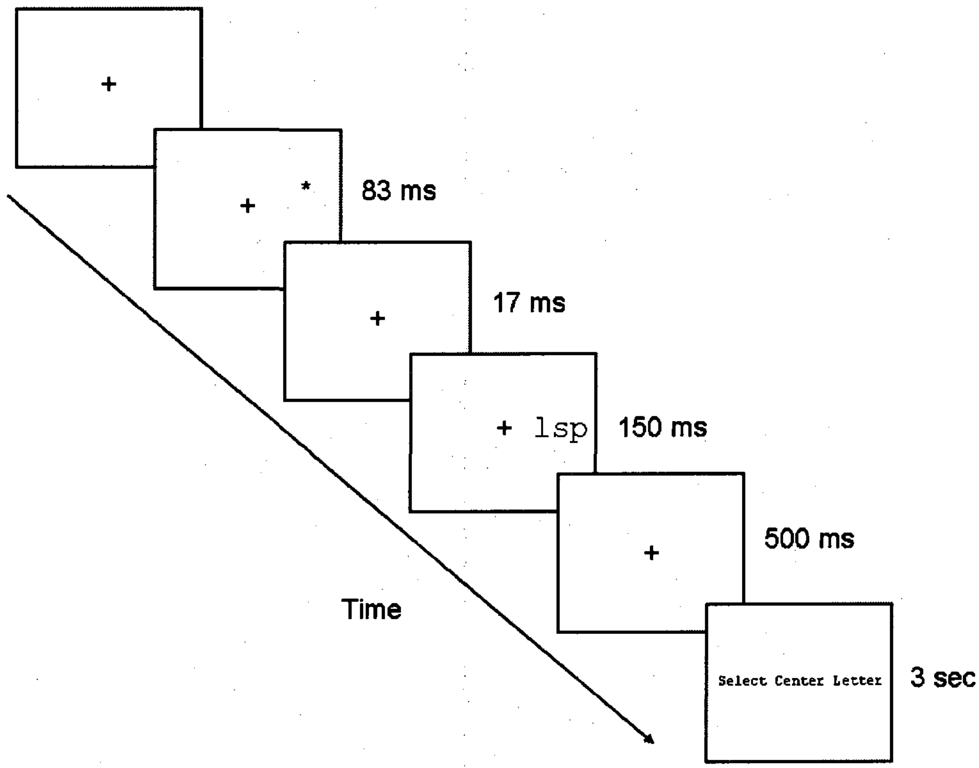


Figure 24. The sequence of events on any given trial in Experiment 4, examining attentional cuing effects on identification of crowded stimuli.

The type of cuing was blocked and the order of the blocks randomized across participants. Type of cue was chosen to be blocked because of the difference in the neutral conditions required for the different cue types. In the endogenous condition, the central arrow could either point in the direction of the following display (valid trial), point in the opposite direction of the following display (invalid trial), or there could have been two arrowheads pointing in both directions (neutral trial). Given that endogenous cues are characteristically predictive there were 70% valid trials, 20% invalid trials, and 10% neutral trials.

In the exogenous condition, there was a peripheral flash just above the location of the center letter (to prevent forward masking). The flash could either indicate the location of the following display (valid trial), indicate the opposite location of the following display (invalid trial), or there could have been two flashes indicating both locations (neutral trial). For comparison purposes, we kept the proportion of cue types the same as the endogenous condition. There were 70% valid trials, 20% invalid trials, and 10% neutral trials.

Each block began with 10 practice trials, which were not included in the analysis. There were two blocks: one with endogenous cues and one with exogenous cues. Each block consisted of 120 trials with stimuli presented to the left visual field and 120 trials to the right visual field. For each visual field, half of the trials (60 trials) were words and the other half were non-words. For each stimulus type (word, non-word) 70% of the trials had a valid cue, 20% had an invalid cue, and 10% had a neutral cue. There were a total of 250 (including practice) trials in each block for a total of 500 trials per session. Each session lasted about 45 minutes in duration. The subjects could take a break at any time during the experiment by not initiating a new trial. The dependent measure was the percentage of correct center letter identifications in each condition.

Design. The independent variables in this study were visual field (left, right), crowded stimulus type (word, non-word), cue type (endogenous, exogenous), and cuing condition (invalid, neutral, valid). The dependent variable was accuracy in identifying the center letter of the crowded stimulus.

Results and Discussion

The mean percent correct center letter identifications when the letter was presented within a word and when it was presented within a non-word were calculated for each condition and subject to a 2 (Visual field: left, right) by 2 (Stimulus type: word, non-word) by 2 (Cue type: endogenous, exogenous) by 3 (Cuing condition: invalid, neutral, valid) within subjects ANOVA. Any significant findings or a priori hypotheses were further investigated using simple effects analyses and/or t-tests.

Identification rates were higher for stimuli presented to the right visual field (M = 68.15) than the left visual field (M = 57.63; $F(1, 19) = 33.69$, $p < .001$). A word superiority effect was found ($F(1, 19) = 33.69$, $p < .001$), with higher center letter identification rates for letters presented within a word (M = 68.05%) than within a non-word (M = 57.73%). The word superiority effect was present in the endogenous cuing condition ($F(1, 19) = 32.15$, $p < .001$) and the exogenous cuing condition ($F(1, 19) = 12.44$, $p = .002$; see Figure 25). There was an effect of the type of cue used ($F(1, 19) = 9.42$, $p = .006$), with endogenous cues producing higher identification rates (M = 65.51%) than the exogenous cues (M = 60.27%). Cue type interacted with word type ($F(1, 19) = 5.30$, $p = .03$), such that there was a larger word superiority effect for the endogenous cue than for the exogenous cues. This effect was driven by the difference in the word condition, with endogenous cues producing higher levels of identification accuracy (M = 72.19%) than exogenous cues (M = 63.91%; $F(1, 19) = 10.80$, $p = .004$), while there was no such difference in the non-word condition ($F(1, 19) = 1.63$, $p = .22$). There was a significant cuing effect ($F(2, 38) = 3.99$, $p = .03$), with higher identification rates for the valid (M = 65.39%), than neutral (M = 62.81%), and lowest for the invalid condition (M

= 60.47%). This cuing effect was present for the exogenous cues (valid-invalid: $t(19)$ = 2.61, p = .017), and there was a trend for a cuing effect with endogenous cues (valid-invalid: $t(19)$ = 1.74, p = .09; see Figure 26).

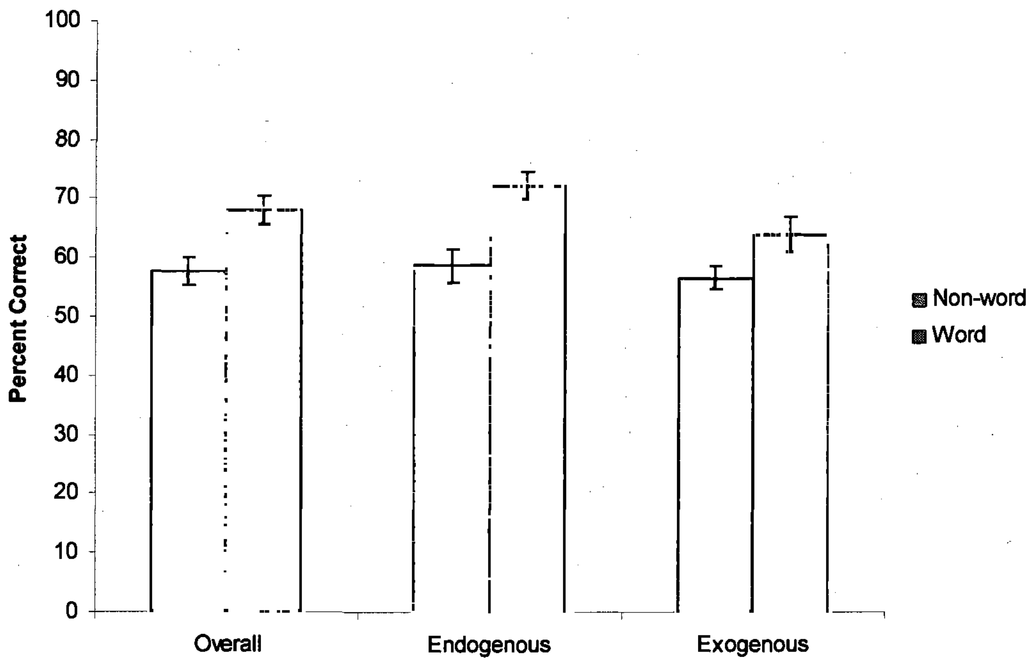


Figure 25. The word superiority effect overall, and for the endogenous and exogenous cuing conditions. Error bars represent the standard error of the mean.

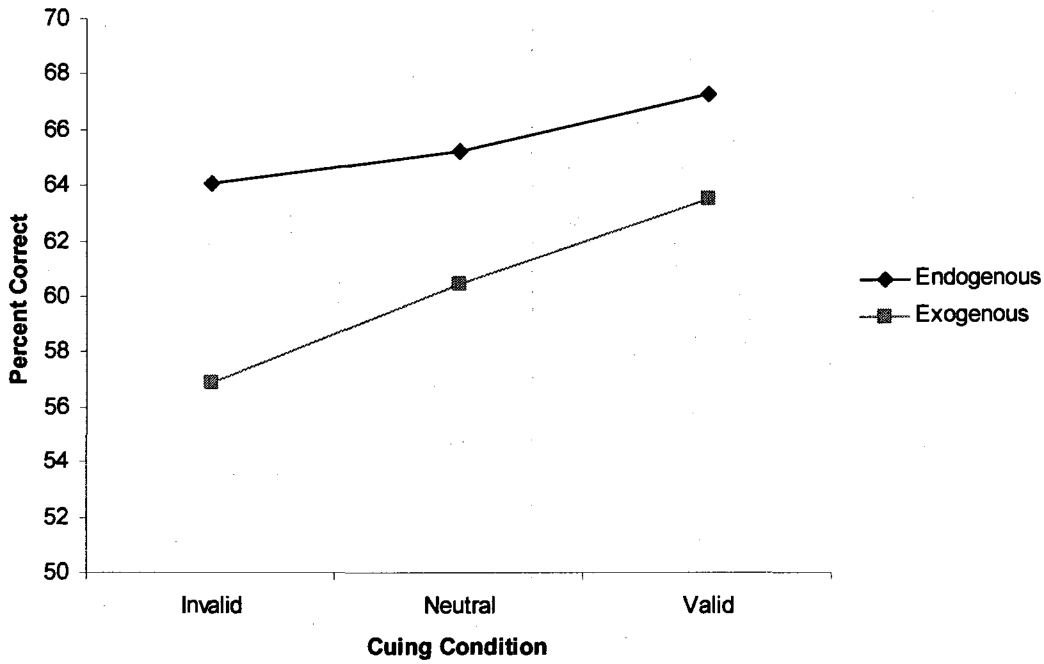


Figure 26. The cuing effect for the endogenous and exogenous cuing conditions.

Of special interest was the word type by cuing condition effects for the endogenous vs. exogenous cuing conditions. Figure 27 shows the predictions for attentional suppression, facilitation, and a combination of facilitation and suppression effects. Figure 28 shows the effects of an endogenous cue and Figure 29 shows the effects of an exogenous cue. The findings above show that an endogenous cue produces higher identification rates in the word condition compared to the exogenous cue, but the endogenous cue did not produce a differential effect of cuing condition. This seems to suggest that the endogenous cue was cuing the entire row of letters leading to a facilitation of the center letter in the word condition compared to the non-word condition, because the word's context letters were also receiving facilitation. However, the finding that the invalid condition does not differ from the valid condition for word stimuli suggests that the invalid condition was also cuing the entire row and facilitating performance. This seems unlikely and thus it should be concluded that the endogenous cue was having an overall alerting effect resulting in improved performance overall, but a valid cue is not producing any global hemifield or specific center letter facilitation, nor is it producing distracter suppression effects. The valid cue is performing similarly to the neutral, and (surprisingly) the invalid cue.

Conversely, with a valid exogenous cue there appears to be a facilitation effect, with valid cues producing better performance than neutral ($t(19) = -2.09, p = .05$) and invalid cues ($t(19) = -2.17, p = .04$) for the word condition and valid cues producing better performance than the invalid cues ($t(19) = -2.18, p = .04$) for the non-word condition. Thus, for the non-word condition validly cuing attention does not improve performance relative to the neutral cue condition, but invalidly cuing attention impairs center letter identification. However, for the word condition validly cuing attention improves performance relative to the neutral condition, and invalidly cuing attention does not impair performance. In the non-word condition it is already difficult to identify the center letter because it is crowded and the other letters do not contribute any contextual cues, and the addition of attention does not help to improve performance, but directing attention to the incorrect hemifield does hurt performance. In the word condition there was an additional boost in performance above and beyond the surrounding letter's context effect with the addition of attention, however when attention is removed, as in the invalid condition, the effects of context already present are sufficient to preserve performance and keep response rates at the same level as the non-informative neutral condition. The fact that the invalid condition did not hurt performance speaks to the strength of the word superiority effect.

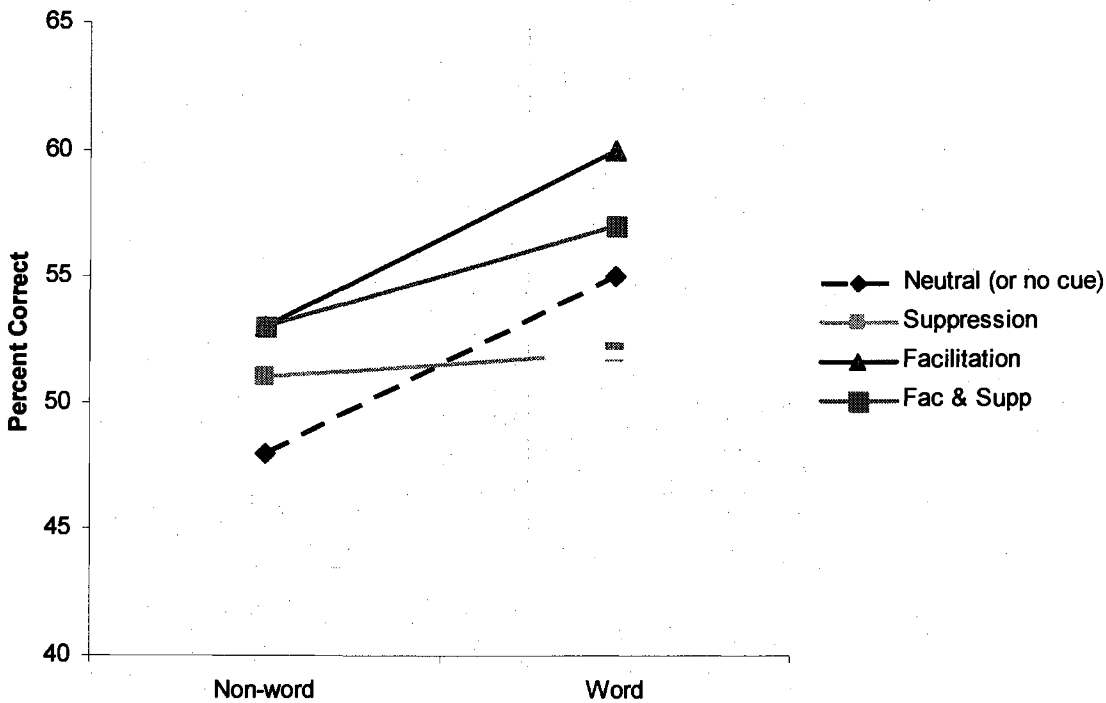


Figure 27. Predicted effects of attentional cuing on the word superiority effect.

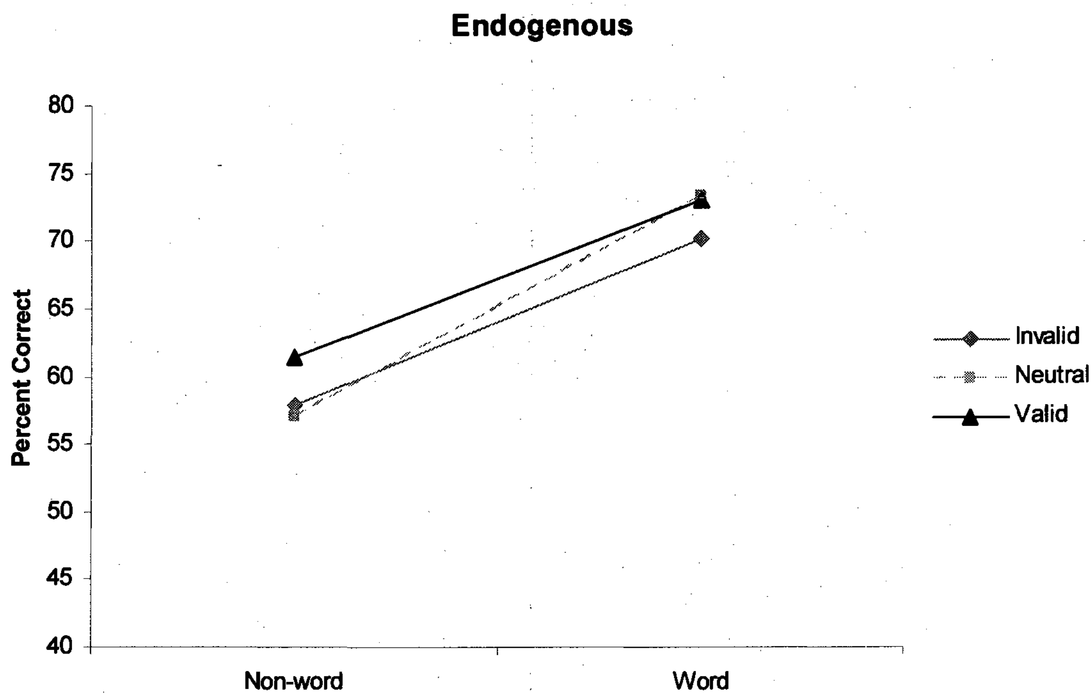


Figure 28. The effects of endogenous orienting on identification of letter within a word and within a non-word.

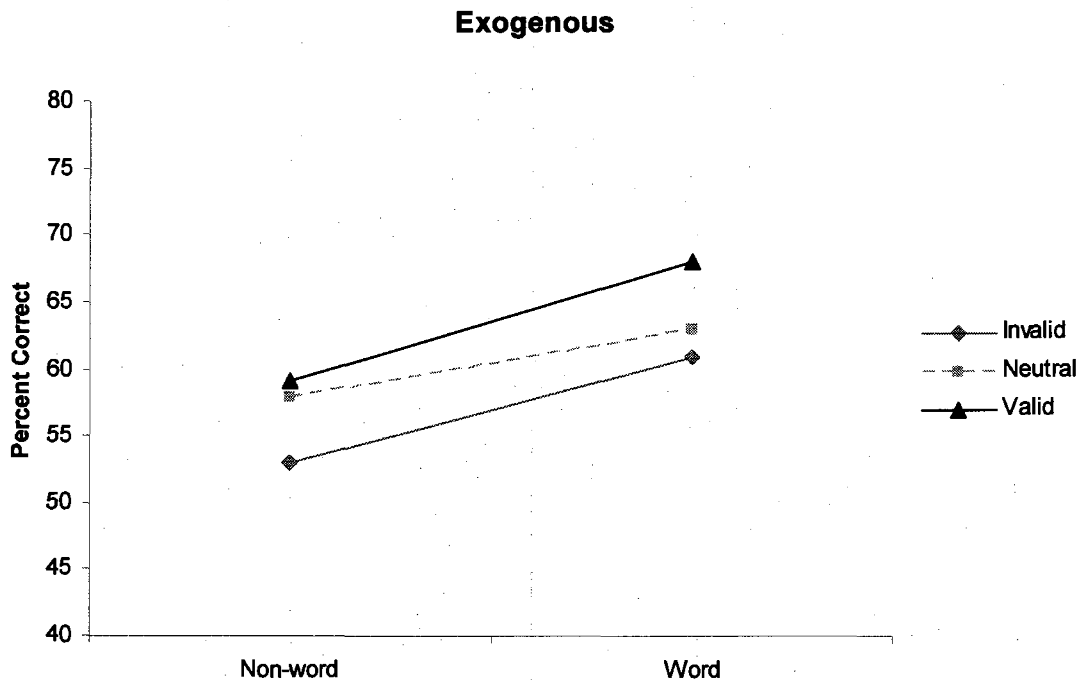


Figure 29. The effects of exogenous orienting on identification of letter within a word and within a non-word.

This study oriented attention toward the center letter of words and non-words using endogenous and exogenous cues. The results indicate that the endogenous cue was able to produce an overall alerting effect, as revealed by the higher identification rates overall, and produce a greater word superiority effect than the exogenous cue. The exogenous cue was able to orient attention properly, as seen in the advantage for valid cues over invalid cues, however this cuing effect reduced the performance difference between the word and non-word conditions relative to the endogenous cue. With an exogenous cue, validly cuing attention does not help to improve non-word performance, but directing attention to the incorrect hemifield does hurt performance. In the word condition, validly cuing attention provides an additional boost in performance above and beyond the letter's context effect, however when attention is removed, the effects of context already present are sufficient to preserve performance. The fact that the invalid condition did not hurt performance speaks to the strength of the word superiority effect.

Experiment 5: Cuing effects on Crowded Letter Discrimination

Method

Participants. Eighteen subjects were recruited from the Rice University Psychology Department research pool (13 females and 5 males; Mean age = 20; three left handed subjects). All subjects had normal or corrected to normal vision, were native English speakers, and participated only after providing informed consent

Stimuli and Apparatus and Procedure. Display and crowded letter characteristics were the same as in Experiment 1, with the exceptions noted below. For the response probe items, one third of the items were items not presented on that trial, one third were distracter items that were presented (half inner distracter and half outer distracter), and one third were center letters from that display.

Each trial began with a fixation cross in the center of the screen, which stayed on throughout the trial. The subject initiated the trial by pressing the SPACE bar. A central arrow (endogenous condition), a peripheral flash (exogenous condition), or the respective neutral cue (see below) then appeared. The arrow was presented for 83 ms and pointed either to the left or the right visual field. The peripheral flash was presented for 83 ms just above the location of the center letter in either the left or right visual field (see Figure 30). The respective neutral cue was also presented from 83 ms. There was a 17 ms ISI and then the three letter crowding sequence was flashed on the screen for 150 ms, followed by a 500 ms delay period and then a response probe. The response probe said "Was 'a' the center letter?"('a' was replaced with the appropriate probe type: a letter not presented, a distracter letter, or a center letter, for each trial; see Appendix D), at which time the subject had 3 seconds to make a response on the keypad. They were instructed to make the most accurate judgment possible as to the identity of the center letter and if unsure, they were to make their best guess. The 3 seconds response window was imposed to prevent subjects from deliberating over the identity of the letter. After the 3 seconds response window, a fixation cross reappeared, at which time the could subject initiate a new trial.

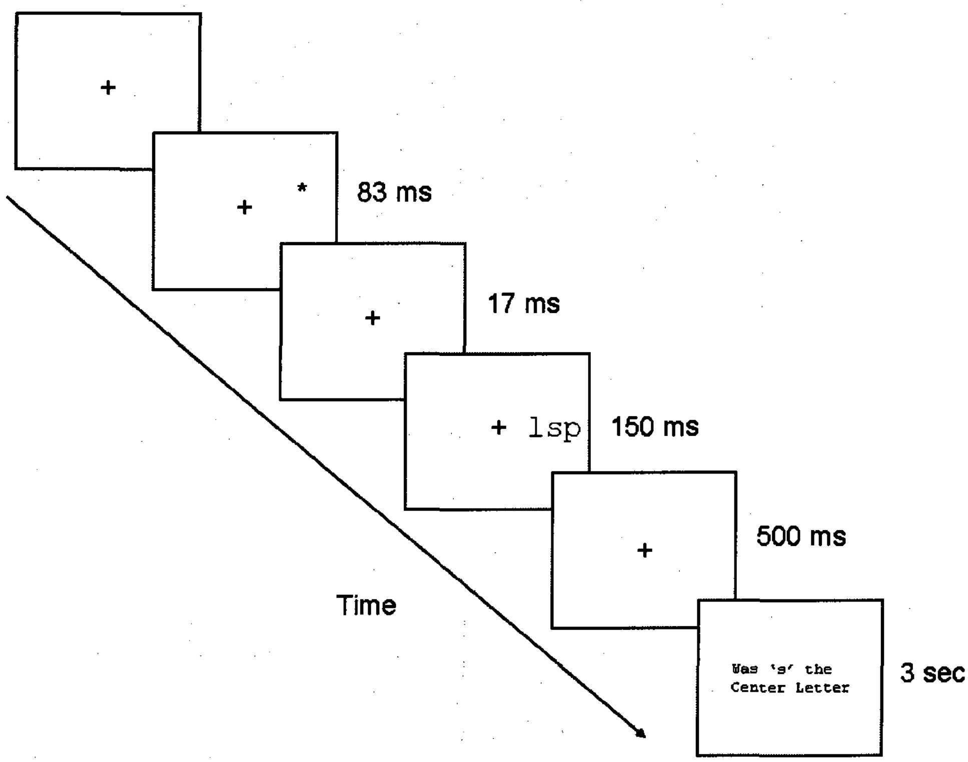


Figure 30. The sequence of events on any given trial in Experiment 5, examining attentional cuing effects on discrimination of crowded stimuli.

The type of cuing was blocked and the order of the blocks randomized across participants. This variable was chosen to be blocked because of the difference in the neutral conditions required for the different cue types. In the endogenous condition, the central arrow could either point in the direction of the following display (valid trial), point in the opposite direction of the following display (invalid trial), or there could be two arrowheads pointing in both directions (neutral trial). Given that endogenous cues are characteristically predictive there were 70% valid trials, 20% invalid trials, and 10% neutral trials.

In the exogenous condition, there was a peripheral flash just above the location of the center letter (to prevent forward masking). The flash could either indicate the location of the following display (valid trial), indicate the opposite location of the following display (invalid trial), or there could be two flashes indicating both locations (neutral trial). For comparison purposes, we kept the proportion of cue types the same as the endogenous condition. There were 70% valid trials, 20% invalid trials, and 10% neutral trials.

Each session began with 10 practice trials, which were not included in the analysis. There were two blocks: one with endogenous cues and one with exogenous cues. Each block consisted of 120 trials with stimuli presented to the left visual field and 120 trials to the right visual field. For each visual field, half of the trials (60 trials) were words and the other half were non-words. For each stimulus type (word, non-word) 70% of the trials had a valid cue, 20% had an invalid cue, and 10% had a neutral cue. For each condition the response probes: an item not presented, an inner distracter, an outer distracter, or the center letter from that display, occurred equally often. There were a total of 250 (including practice) trials in each block for a total of 500 trials per session. Each session lasted about 45 minutes in duration. The subjects could take a break at any time during the experiment by not initiating a new trial.

Design. The independent variables in this study were visual field (left, right), response probe type (outer distracter, inner distracter, center letter, item not present), crowded stimulus type (word, non-word), cue type (endogenous, exogenous), and cuing condition (invalid, neutral, valid). The dependent variable was accuracy in responding whether the probe was the center letter of the crowded stimulus or not.

Results and Discussion

The mean percent correct for each response probe type was calculated for each condition and subject to a 4 (Response probe: outer distracter, center letter, inner distracter, item not present) by 2 (Visual field: left, right) by 2 (Stimulus type: word, non-word) by 2 (Cue type: endogenous, exogenous) by 3 (Cuing condition: invalid, neutral, valid) within subjects ANOVA. Any significant findings or a priori hypotheses were further investigated using simple effects analyses and/or t-tests.

There was a main effect of response probe ($F(3, 51) = 55.88, p < .001$), with the highest accuracy when probed with an outer distracter ($M = 93.85\%$), followed by when probed with an inner distracter ($M = 93.66\%$), an item not present ($M = 88.10\%$), and lowest when probed with a center letter ($M = 71.63\%$; see Figure 31). We conducted a simple effects analysis which showed that the responses for inner and outer distracters did not differ from each other ($F(1, 17) = 0.04, p = .85$), thus we will collapse across inner and outer distracter in future analyses. Responses to distracter probes ($M = 93.74\%$)

were more accurate than responses to item not present probes ($M = 88.10\%$; $F(1, 17) = 11.60$, $p = .003$).

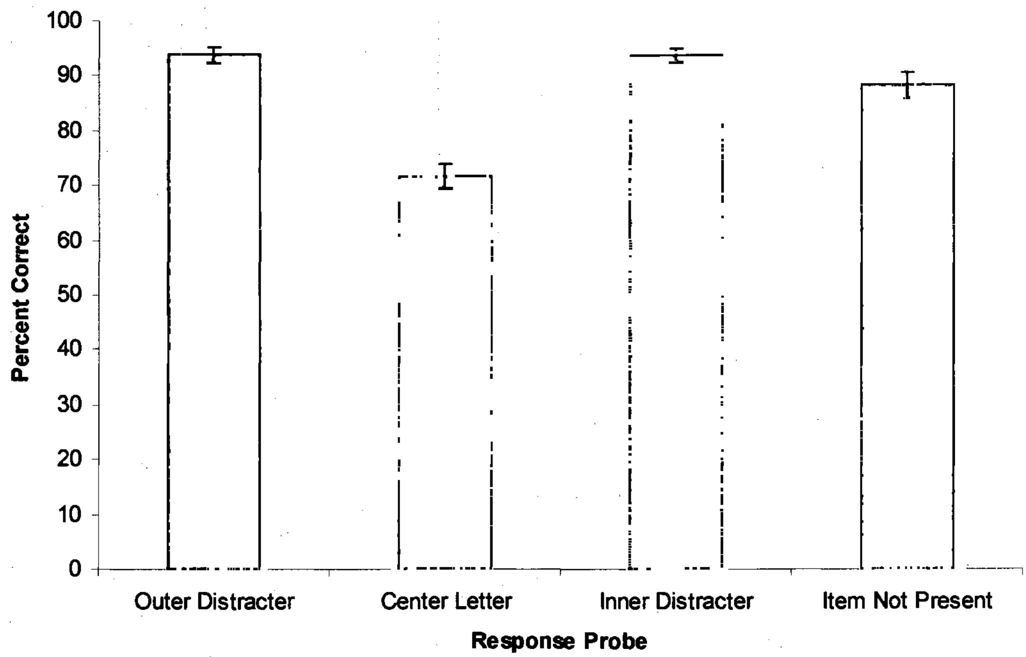


Figure 31. The percent correct for each probe type. Error bars represent the standard error of the mean.

There was an overall word superiority effect ($F(1, 17) = 8.59$, $p = .009$), with higher accuracy when the stimulus was a word ($M = 85.83\%$) than when it was a non-word ($M = 83.15\%$). More importantly, there was a response probe by word type interaction ($F(3, 51) = 11.75$, $p < .001$; see Figure 32), due to the fact that there was a word superiority effect for center letter probes ($F(1, 17) = 24.01$, $p < .001$), but not for item not present probes ($F(1, 17) = 0.74$, $p = .40$), nor for distracter probes ($F(1, 17) = 0.07$, $p = .79$).

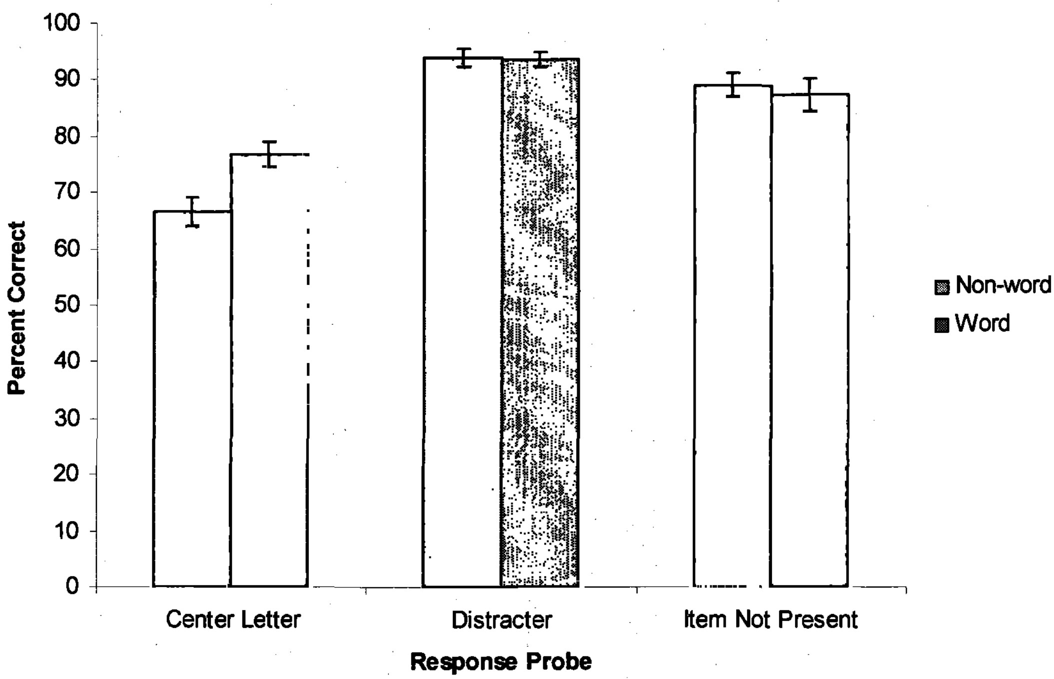


Figure 32. The word superiority effect for each response probe type. Error bars represent the standard error of the mean.

There was a main effect of visual field ($F(1, 17) = 8.01, p = .01$), such that response accuracy was higher when stimuli were presented in the right visual field (M = 86.33%) than in the left visual field (M = 82.65%). Visual field interacted with response probe type ($F(3, 51) = 15.85, p < .001$; see Figure 33), such that the visual field effect was only present for center letter probes and not present for the other probe types. There was a response type by visual field by cuing condition interaction ($F(4, 68) = 5.44, p = .001$, see Figure 34), such that the cuing effect interacted with visual field for the center letter response probe ($F(2, 34) = 6.97, p = .003$), but not for the distracter probe ($F(2, 34) = 0.04, p = .96$) or the item not present probe ($F(2, 34) = 1.56, p = .23$). There was also a larger 5-way visual field by response probe type by word type by cue type by condition interaction effect ($F(6, 102) = 2.97, p = .03$).

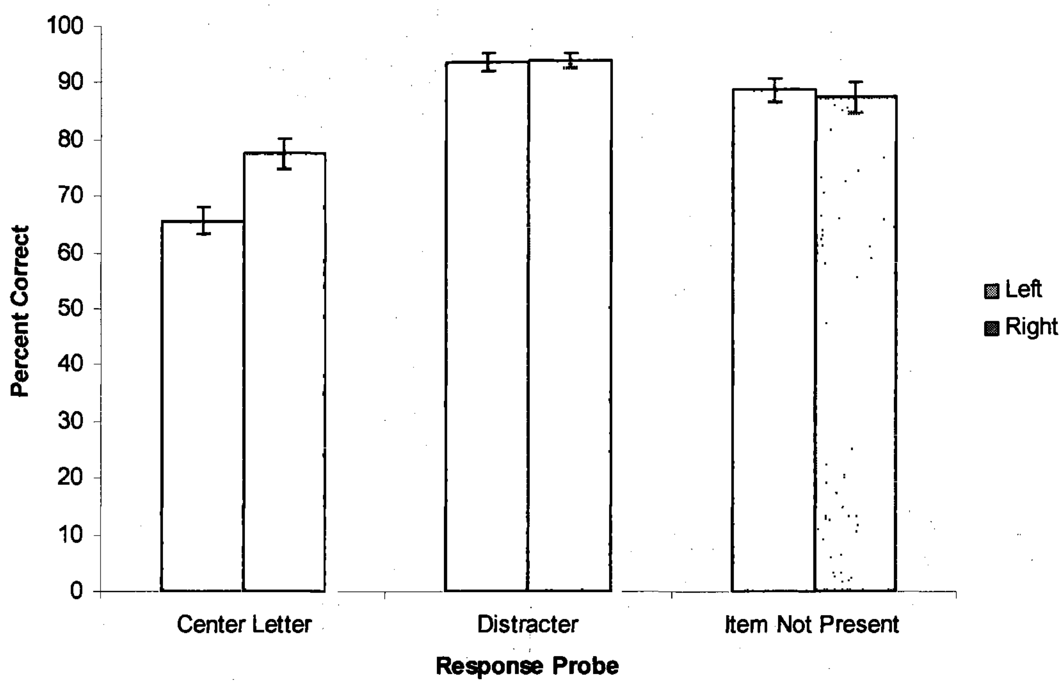


Figure 33. The effect of visual field for each response probe type. Error bars represent the standard error of the mean.

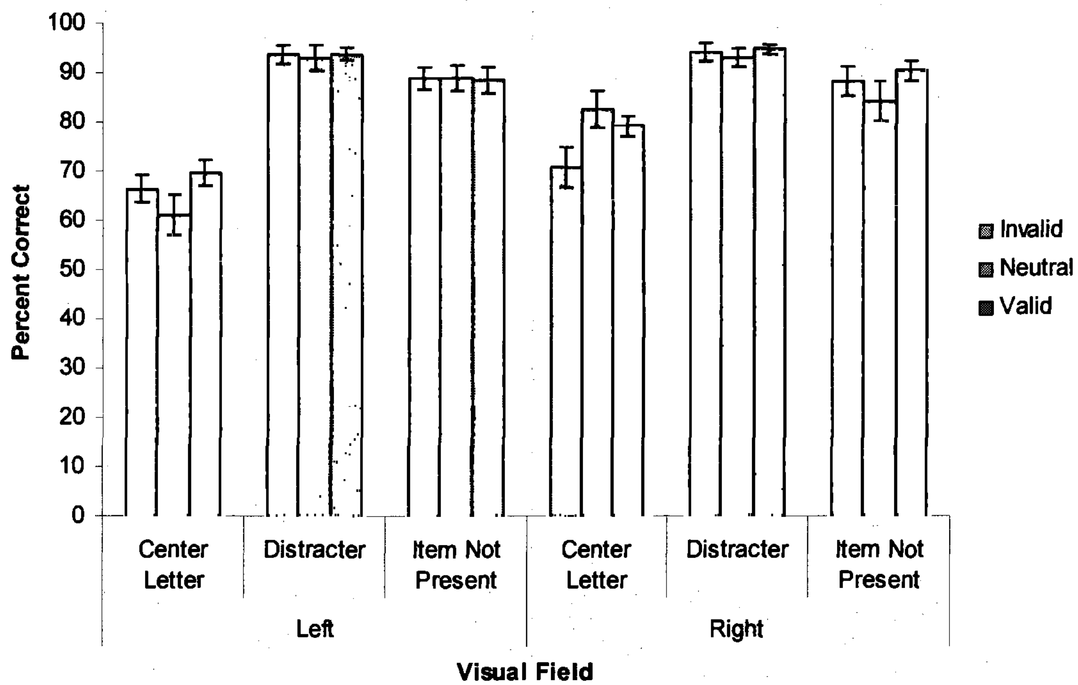


Figure 34. The cuing effect for each response probe type as a function of visual field. Error bars represent the standard error of the mean.

There were three findings that were of special interest in this experiment. The first was whether attentional suppression, possible in the valid cuing condition, would change the response to the distracters and to the items not present compared to when attention was not manipulated, as in the neutral condition. The second was whether identification of the distracters was worse when attention was manipulated than in the neutral condition. In this case "worse identification with attention" would manifest as lower accuracy rates in the valid condition than the neutral or invalid condition. The third was examining the cuing effects (facilitation or suppression effects) for the center letter probe items only, as a comparison to Experiment 4. To test the first two hypotheses, we performed a 2 (Response probe: distracter, item not present) by 2 (Word type: word, non-word) by 2 (Cuing condition: neutral, valid) within subjects ANOVA separately for each cue type. Figure 35 shows that for the endogenous cue with a distracter probe there was a trend for the valid condition to produce higher accuracy than the neutral condition, although this was not significant ($F(1, 17) = 3.90, p = .065$). No other effects were significant for the endogenous cue. For the exogenous cue, accuracy was higher when probed with a distracter item ($M = 95.33\%$) than an item not present ($M = 86.87\%$; $F(1, 17) = 9.85, p = .006$; see Figure 36). There was also a response probe by condition interaction ($F(1, 17) = 4.41, p = .05$; see Figure 37), such that validly cuing attention increased accuracy for the item not present probe, but decreased accuracy for the distracter probe. However, the cuing effect (valid vs. neutral) was not significant for either response probe type alone ($F_{\text{distracter}}(1, 17) = 1.99, p = .18$; $F_{\text{item not present}}(1, 17) = 3.77, p = .07$). No other effects were significant for the exogenous cue.

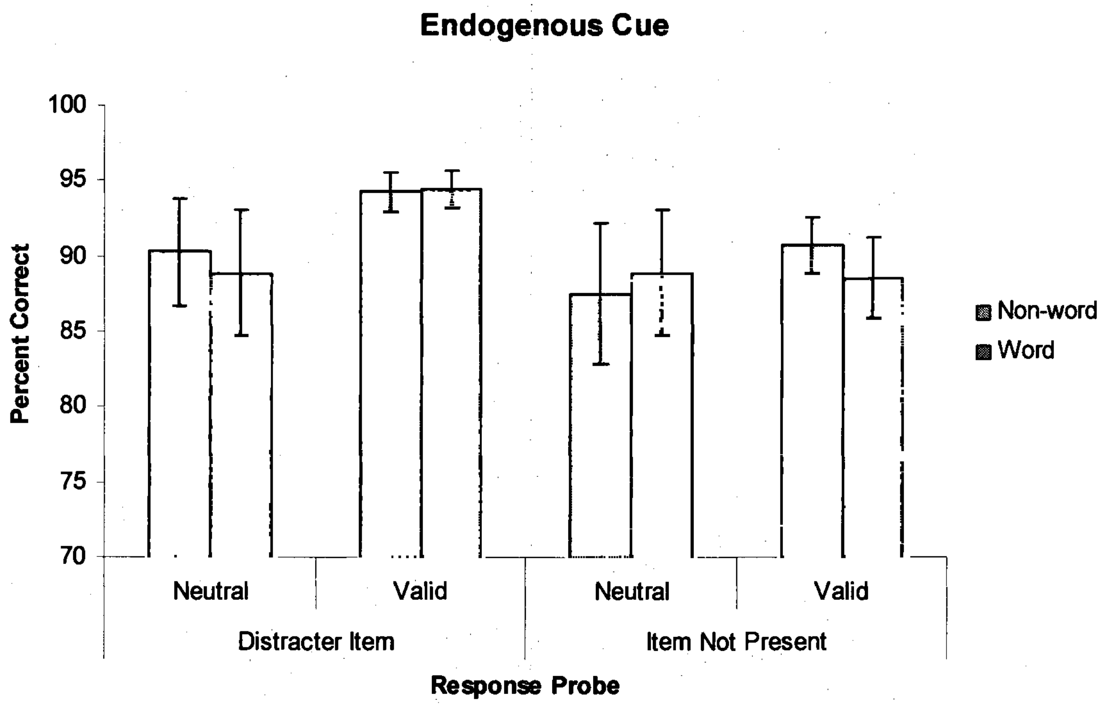


Figure 35. The effect of an endogenous cue on the accuracy of responses for distracters and items not present. Note that the scale starts at 70%.

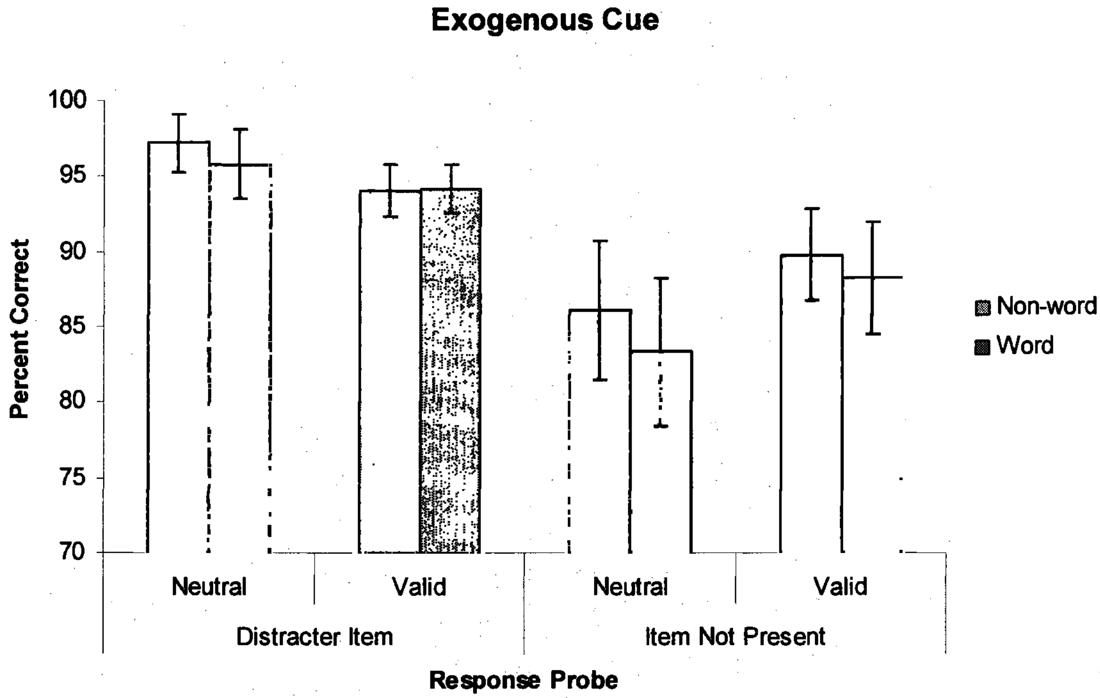


Figure 36. The effect of an exogenous cue on the accuracy of responses for distracters and items not present. Note that the scale starts at 70%.

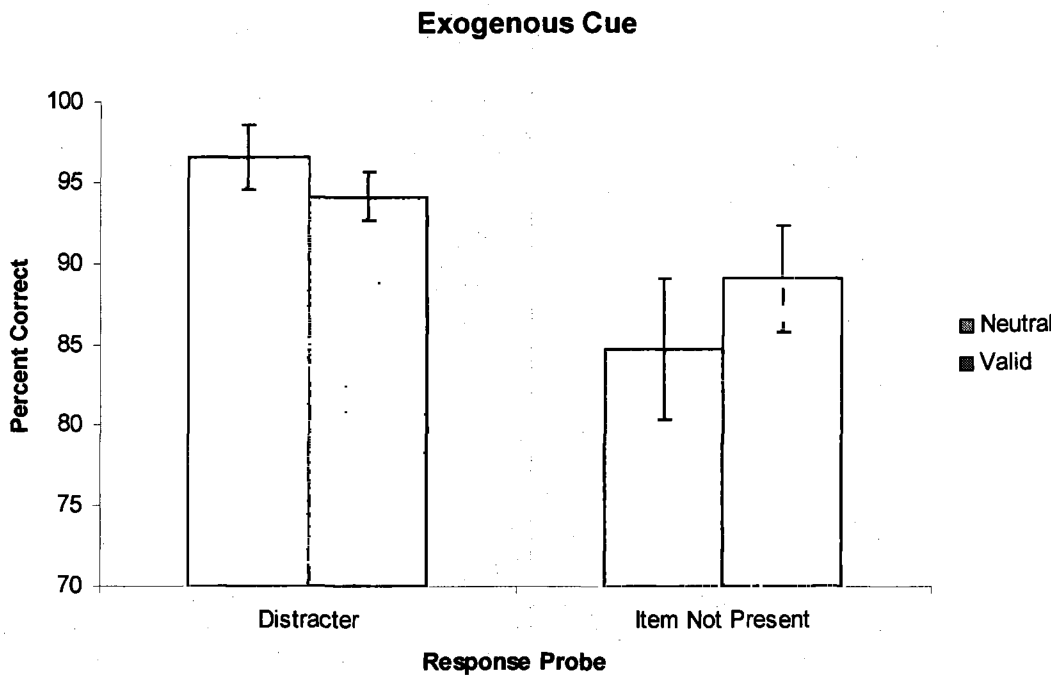
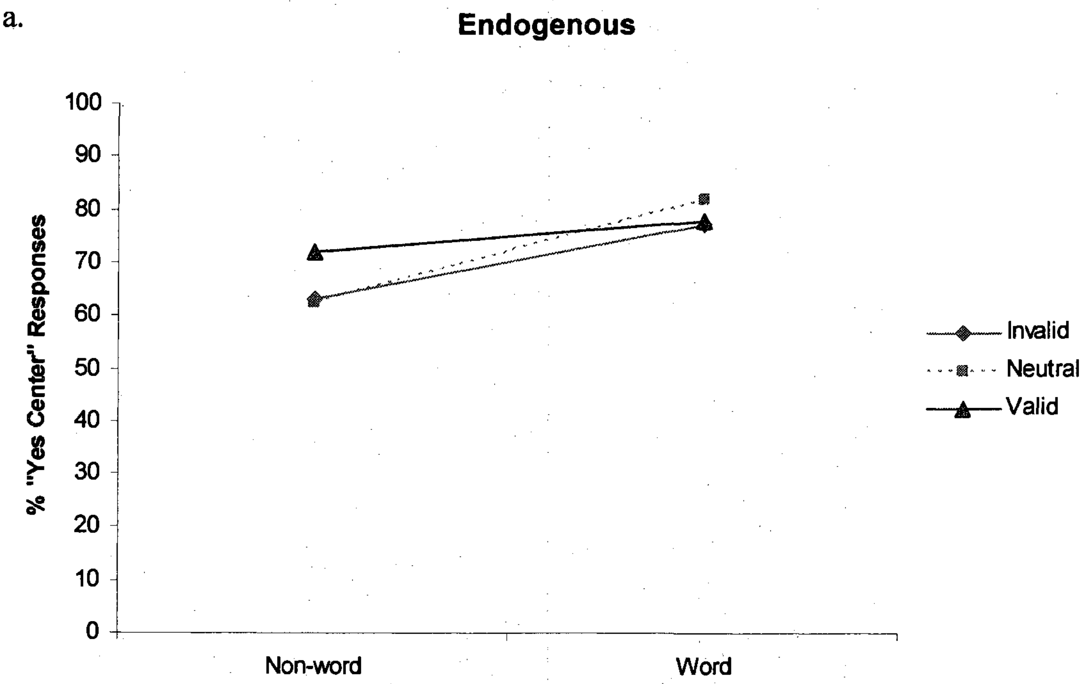


Figure 37. The exogenous cuing effect for distracters and items not present. Note that the scale starts at 70%.

To test the third hypothesis, we performed a 2 (Word type: word, non-word) by 2 (Cue type: endogenous, exogenous) by 2 (Cuing condition: neutral, valid) within subjects ANOVA on center letter probe responses only. Again there was a word superiority effect, with greater accuracy when the center letter appeared within a word than within a non-word (see Figure 32 above). Of particular interest was the word type by cue type by condition effect. As shown in Figure 38, there was a word superiority effect for the endogenous condition ($F(1, 17) = 16.09, p = .001$) and the exogenous condition ($F(1, 17) = 7.37, p = .015$), but there was no cuing effect for either cue type ($F_{\text{endogenous}}(2, 34) = 1.03, p = .37$; $F_{\text{exogenous}}(2, 34) = 1.24, p = .30$). Interestingly, the same cuing pattern emerged for both endogenous and exogenous cuing conditions.

a.



b.

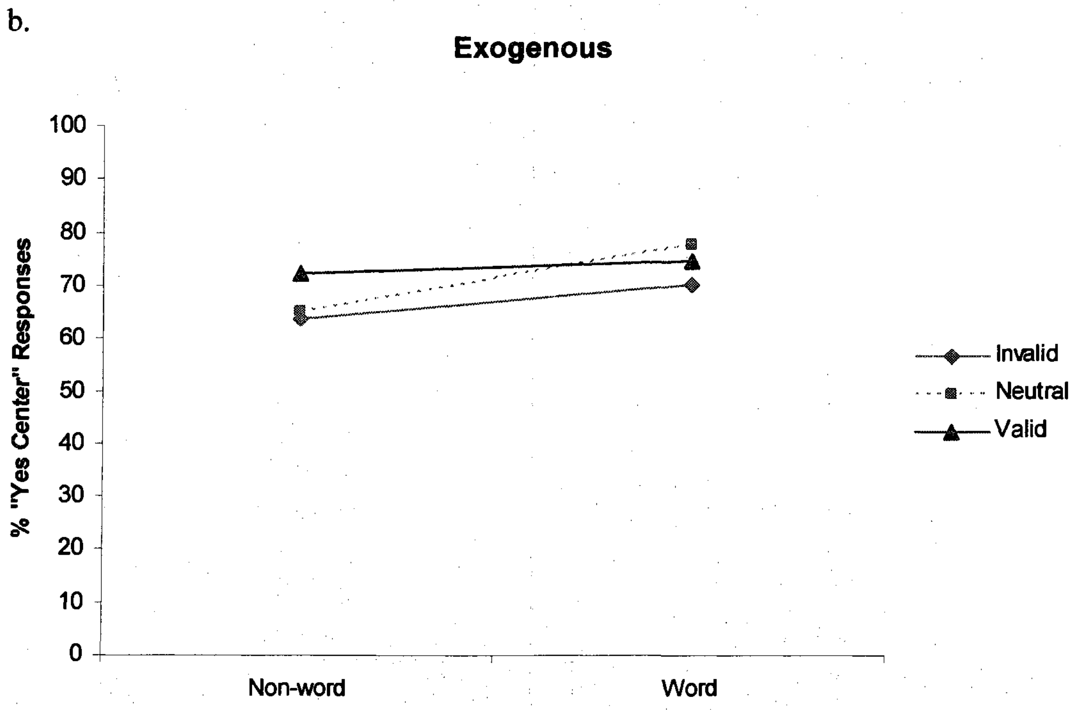


Figure 38. The cuing effect for word and non-word stimuli with an endogenous cue (a) and an exogenous cue (b).

This experiment was designed to assess whether attention suppresses processing of distracter items. This was done by probing subjects with distracters and items not present to assess the percentage of trials in which these probe types might be confused with the center letter. The results show that overall there was an advantage for distracter items over items not present in the display, in that subjects were more likely to say that an item not present was the center letter than a distracter item (i.e., they were less accurate in responding to items not present, than distracters). When broken down by cue type however, this pattern was only present for the exogenous cuing condition. This indicates that with an exogenous cue the distracter items were visible enough not to be confused with the center letter. For the endogenous cue, there was no difference in performance between the distracter probes and the item not present probes, but for the distracter probes there was a trend for attentional cuing to increase response accuracy (i.e., they reported "no" that was not the center letter more often) than when attention was not oriented. Because this effect did not reach significance, the finding should be interpreted with caution, however it suggests that endogenous attention might be producing a global cuing effect affecting the entire letter sequence, including the distracter items, making them less confusable with the center letter.

Comparison of the Word Superiority Effect Across Experiments

The word superiority effect was present in every experiment in this paper. This consistency across experiments speaks to the strength of the effect under the various conditions employed here. Figure 39 shows the size of the effect for each experiment. The effect was largest in the two-stimuli experiment (Experiment 3), and smallest in

Experiment 1 and the exogenous cuing condition of the identification and discrimination experiments (Experiment 4 and 5, respectively).

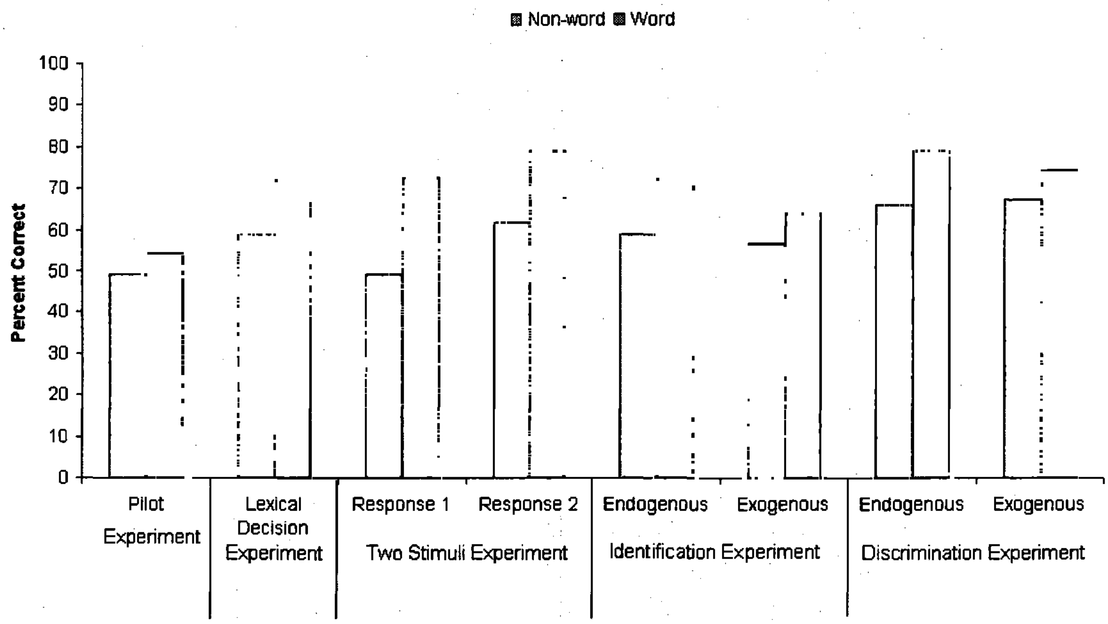


Figure 39. The word superiority effect for every experiment in this paper.

General Discussion

Crowding was used as a tool to examine the semantic contribution to the word superiority effect and investigate the role attentional cuing plays in both the crowding effect and the word superiority effect. Crowding was not manipulated, although a control test was performed (in Experiment 3) to ensure that our display parameters were sufficient to produce a crowding effect. Rather, we investigated how the word superiority effect and attentional cuing impact the crowding effect. In Experiment 1 we replicated the effects of Fine (2002, 2004) showing that there is an advantage in identifying the center letter in a crowded display if the letter was presented in the context of a word rather than in the context of a non-word; a word superiority effect with crowded stimuli. In

Experiments 2 and 3, we investigated the role semantics play in the word superiority effect using a crowded display, and then in Experiments 4 and 5, we investigated the role of attentional cuing in the crowding effect and how cuing might interact with the word superiority effect.

Assessing Semantics

In order to assess whether the semantics of a word contribute to the word superiority effect we presented a crowded word (i.e., a word with display conditions sufficient to produce a crowding effect, or a non-word control) that acted as a prime followed by a related target item. If subjects were reading the crowded items and deriving semantic information from them, then this semantic information could influence performance on another task (as in priming). In Experiment 2, we presented a crowded item followed by a lexical decision task at fixation. Likewise, in Experiment 3 we presented a crowded item followed by an additional crowded item and subjects randomly identified the center letter of either. The addition of a second stimulus, either the lexical decision item or the crowded item, allowed us to assess whether or not subjects were reading the initial crowded word and semantics were being derived to assist in performance, either identifying the word/non-word or identifying the center letter. For example, if the crowded item were a word such as "cat," the lexical decision word were "dog," and meaning was being derived from the crowded word, then performance on the lexical decision task should be better than the condition in which the crowded item is unrelated or is a non-word. A finding of no improvement on the second item when a semantically related word was the initial crowded item would indicate that semantics do not contribute to the facilitation of performance for the crowded letter within a word, but rather that a basic probability or familiarity effect likely causes the facilitation.

In Experiment 2, the lexical decision accuracy data show an advantage for words primed by a related crowded word compared to words primed by an unrelated crowded word, suggesting that the meaning of the crowded word is accessed and that there might be an influence of semantic information on lexical decision responses. The item analysis further supported this hypothesis by showing that certain related word pairs produce priming while others produce interference effects, with the net result dependent on how many of each type were present in the experiment. The lexical decision study revealed a net interference effect but if other word pairs were chosen there might have been a net priming effect (as in Experiment 3). However, the pronounceability analysis negated the hypothesis that semantic information influences responses. When we divided the primes into whether or not each words' corresponding non-word was pronounceable (contained legal bigrams) or non-pronounceable (did not contain legal bigrams), we found that when pronounceable non-words were used as primes they produced just as much of an interference effect in the related condition as their corresponding words. This was not true of non-pronounceable non-words. Non-pronounceable non-words showed a reduced effect compared to words. Since pronounceable non-words are similar to words in their letter co-occurrence, but differ in that they do not possess semantic information, any similar result might be attributed to the factor they have in common (perceptual familiarity or letter co-occurrence familiarity) and cannot be attributed to the factor they do not share (semantics). Thus, it would seem most plausible that a perceptual familiarity effect can explain the similar effects produced by words and pronounceable non-words in this task. This experiment indicates that semantics are not contributing to the word superiority effect, but rather perceptual familiarity is a more likely explanation, and that this could only be properly examined with the appropriate non-word comparison conditions.

The Interactive Activation model (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982) has been used to model this pronounceable effect because pronounceable non-words share two or three letters in common with a real four-letter word, while a non-word that is a random letter string does not. Therefore, the 2-3 letters activate words that are similar to the non-words, which leads to feed-back activation from the word level to the letter level, resulting in higher activation levels for related letters. The fact that this model can replicate the pronounceable non-word effect, and that the model does so based only on letter sequence probabilities, reiterates the point that the word superiority effect results from pattern familiarity.

The lexical decision response time data support the accuracy data in showing that there was no semantic effect when split by pronounceability. However, there were no real effects to speak of in the response time data. There were no differences in responding to words vs. non-words, and there was no differential effect of pronounceability.

The center letter accuracy data of the two-stimuli experiment (Experiment 3) revealed that when both crowded items were words and they were related to each other, performance was better than when the prime was a non-word or the items were unrelated. This again seems to indicate that the semantics of the word are contributing to performance. However, as with the lexical decision experiment, this conclusion is premature. When the primes were split by whether each words' corresponding non-word was pronounceable or not, we found that for the pronounceable prime group, responses to words were the same for related word primes and pronounceable non-word primes. This indicates that pronounceable non-words produce the same benefit in performance as their corresponding words. This was not the case for non-pronounceable non-words, with related words producing a priming effect as compared to non-pronounceable non-words. This finding validates the findings from the lexical decision experiment with a different paradigm and shows that perceptual familiarity can explain the apparent priming effect in the related condition, rather than semantic access.

In these experiments we were using priming performance to infer the level of processing that was occurring on the first crowded stimulus. The word superiority effect for the first item represents the depth of processing of the item, but the related priming effect for the second item manifests that depth. However, it is important to note that the two experiments differed in the word superiority effect for the first item once split by pronounceability, while demonstrating the same "priming" effect for the second item. For the first item, in the lexical decision experiment the words and pronounceable non-words produced comparable center letter identification rates, while in the two-stimuli experiment a word superiority effect was present. Based on the priming effects (seen in the second response) we now know that the word superiority effect results from pattern familiarity (letter sequence familiarity). Thus it makes sense that the word superiority effect for words vs. pronounceable non-words would be less than that of words vs. non-pronounceable non-words, which share less familiarity. The lack of such an effect in the two-stimuli experiment might simply reflect the small stimulus set used in this experiment. As we saw from the item analysis, the words that were chosen for an experiment differ in the effects that they produce, and so perhaps with a larger sample of words the word superiority effect in the two-stimuli experiment would be comparable to that seen in the lexical decision experiment.

It is interesting that in both experiments the pronounceable prime group produced overall higher performance on the second item for items in the related condition. In the lexical decision experiment, the pronounceable prime group produced higher accuracy for word set 1 (containing the word prime - related items) compared to the non-pronounceable prime group, whereas in the two-stimuli experiment, the pronounceable prime group produced higher center letter identification rates on the second item for word set 1 (the word prime - related condition) compared to word set 2 (the word prime - unrelated condition). There might be two explanations for this effect, 1) either there was an enhanced facilitatory effect of some kind from the words and pronounceable non-words or 2) there was an enhanced performance effect that was specific to the group of words in the related word set (i.e. center letter identification and word/non-word task was easier with the related word set). The latter hypothesis seems unlikely given that the same related word set appeared with the non-pronounceable prime group, and the advantage was not seen (in the lexical decision experiment). If there were an overall advantage in identifying items in the related word set, then the advantage would have also manifested for the non-pronounceable prime group. However, the response time data show that responses to the related word set were slower than to the other word sets for both the pronounceable and non-pronounceable groups, suggesting that there might have been a processing effect specific to this set of words.

It is difficult to explain why the pronounceable non-word primes would produce heightened response accuracy on the secondary task and why this accuracy would be comparable to that of related word primes. If pronounceable non-words produced a performance effect that is comparable to that of words due to their similarity in letter sequence probabilities, then this could aid in the judgment of the center letter and contribute to the word superiority effect for this item. However, the presence of familiar letter sequences does not lead to a logical explanation for why the pronounceable non-words produce "priming" effects in the lexical decision task comparable to the non-pronounceable group, or why center letter identification rates would improve from related pairs over unrelated pairs. We do not have a coherent explanation for this effect using the current data. Further investigation into this finding is required.

The finding that pronounceable non-words produce the same effects on performance as words in the "related" condition was present in the lexical decision experiment and in the two-stimuli experiment despite the methodological differences between the two experiments. Each experiment employed methodologies that had confounds which might have limited our interpretation or lead to misinterpretations of the data. However, the addition of the other experiment with a different methodology helped provide converging evidence on the topic, and in some cases to overcome some of the limitations of the other experiment and/or to control for them. We will now discuss several problems/issues with each experiment and possible explanations for each.

The lexical decision experiment involved presenting an additional task of identifying a word or non-word at fixation. This experiment required subjects to shift their attention from the crowded stimulus to the center of the screen in order to identify the lexical decision item, and it required two responses on each trial. This dual task paradigm placed heavy attentional and memory demands on the subject. Conversely, the two-stimuli experiment involved presenting two stimuli out in the periphery and having the subject remember the center letter of each in order to respond randomly to either the first or the second. In the two-stimuli experiment the subjects had to hold two center letters in memory in order to respond correctly. It may be hypothesized that this additional memory load would decrease center letter accuracy overall, as the task demands might have been too great. However, this is not what we found. The performance levels of the two-stimuli experiment were comparable to those seen in the other experiments of the paper (see Figure 39). It can also be argued that the lexical decision experiment was just as attentionally demanding as the two-stimuli experiment, as each required the subject to hold two responses in memory. However, neither experiment showed reduced performance compared to the other single task experiments in this paper.

In the lexical decision experiment the presence of the additional word/non-word task might have made subjects more likely to perceive the crowded stimuli as words and bias any center letter responses such that words might have been responded to more accurately than expected and non-word center letter responses would be biased to those that formed words (causing more errors), thus increasing the word superiority effect. However, the size of the word superiority effect was comparable to that seen in the other experiments of this paper and was slightly smaller than that seen in the two-stimuli experiment (see Figure 39). Therefore, the hypothesis that the presence of additional words in the lexical decision experiment would increase the word superiority effect seems unlikely.

Both the lexical decision and two-stimuli experiments had the opportunity to produce high memory confusion as subjects needed to hold two items in memory and remember their temporal distinction in order to respond appropriately. For the crowded letter identification task, the subject might have been able to identify the center letter of a word by holding the entire word in memory as a chunk. Upon response, the subject could recall the entire word and respond with its center letter. This might have helped prevent the center letter from becoming confused with the other item, and boosted performance in the word-word conditions compared to the word-non-word or non-word-non-word condition. For example, if the subjects were presented with the word "gym" followed by "fit," and the entire word were stored as a chunk it might have been easier to differentiate the center letters of the two words at recall than if the non-words "jyg" and "qil" were presented. In the first case the letters "y" and "i" have context to aid in their recall. Whereas in the second example, regardless of whether the subjects tried to remember the entire non-word sequence or just the center letters, there is no context (top-down information) that might aid in recall. It might even prove more difficult to remember the entire non-word if they are random letter strings and have no coherent flow. Thus, if subjects were employing this chunking strategy, center letter identification might have been more difficult in the non-word conditions, and especially the non-pronounceable non-word conditions, as there was no contextual or letter sequence information to aid memory. This might also suggest that in the lexical decision experiment the task of responding word/non-word would not have interfered as much with the task of identifying the center letter because subjects could distinguish the two chucks of information at recall.

Finally, the lexical decision experiment employed a much larger word set than the two-stimuli experiment which helped to overcome the disadvantage of that study's smaller group of words and non-words, thus allowing the findings to be generalized to a larger set of words and non-words. This benefit was seen overall, and when the stimuli were split by pronounceability. Thus the two experiments converge nicely to show that the word superiority effect results from letter sequence familiarity.

Attentional Cuing

We hypothesized that attentional cuing would produce results that differed depending on whether the crowded stimulus was a word or a non-word. We hypothesized that attentional cuing might act on non-words (or ordinary crowded items) such that it enhances the identification/discrimination of letters in a non-word. However, the role of attentional cuing in the word superiority effect is another matter. The word superiority effect is the difference in performance between the word and non-word conditions, so any differing effects of attentional cuing on words and non-words would either increase or decrease this difference. Attention is known to have two major mechanisms: target facilitation (enhancement) and distracter suppression (or external noise reduction). In this crowding paradigm where the presence of distracters decreases center letter identification, we hypothesized that attentional cuing might suppress the processing of the distracters such that they have less influence on the center letter resulting in decreased crowding and increased center letter discriminablity. However, with crowded word stimuli, if attention suppresses the distracter processing and stripped the target letter of its context we should have found that words and non-words produced similar results, manifest as a decrease in the word superiority effect when attention was manipulated. Alternatively, attentional cuing might have enhanced processing of the center letter leading to better discriminability of the center letter, while leaving the distracters unaffected. This would manifest as increased identification for the word and non-word conditions, but not affect the difference between the two. It was also possible that the word superiority effect was enhancing letter processing to the maximum allowed in a crowded display, and the addition of attention would not enhance letter processing.

The identification experiment (Experiment 4) oriented attention toward a crowded letter within a word or within a non-word using endogenous and exogenous cues. An endogenous cue produced higher identification rates in the word condition compared to the exogenous cue, but the endogenous cue did not produce a cuing effect. We predicted that the endogenous cue would facilitate the processing of the entire row of letters given its spatial imprecision, and that this would manifest as an advantage for words over non-words as the outside letters that crowd the center letter and provide context would be receiving facilitation in addition to the center letter. The fact that the endogenous cue produced higher identification rates in the word condition compared to the exogenous cue seems to suggest that the endogenous cue was cuing the entire row of letters leading to a facilitation of the center letter in the word condition compared to the non-word condition. However, the finding that the endogenous invalid cuing condition did not differ from the valid cuing condition for word stimuli suggests that the invalid condition was also cuing the entire row and facilitating performance. This seems unlikely given the short time interval between the onset of the cue and the onset of the crowded stimuli, and thus we should conclude that the presence of an endogenous cue was having an overall alerting effect resulting in improved performance overall. This alerting affected the word condition more than the non-word condition, but a valid cue did not producing any global hemifield or specific center letter facilitation, nor did it produce distracter suppression effects.

The exogenous cue apparently served to orient attention, as seen in the advantage for valid cues over invalid cues, and this cuing effect emerged despite the reduced performance difference between the word and non-word conditions relative to the endogenous cue. With an exogenous cue, validly cuing attention did not help to improve non-word performance, but directing attention to the incorrect hemifield did hurt performance. In the word condition, validly cuing attention provided an additional boost in performance above and beyond the letter's context effect (neutral condition), however when attention was removed as in the invalid condition, the effects of context already present was sufficient to preserve performance, and no performance decrement was seen. The fact that the invalid condition did not hurt performance speaks to the strength of the word superiority effect.

These exogenous cuing effects might be explained by the difference in difficulty in identifying the center letter in each word type condition. In the non-word condition, with no attentional manipulation, it is difficult to identify the center letter because there are no contextual cues to aid performance, and the letter is degraded due to crowding. With the addition of attentional cuing it is still difficult to identify the center letter because crowding is still present. When attention is directed to the incorrect hemifield performance drops because the stimuli are now 20 degrees in the periphery, and crowding is compounded. In the word condition, with no attentional manipulation, the effect of context allows the center letter to be identified easier than in the non-word condition, even though the center letter is degraded due to crowding in both conditions. However, with cued to the word the entire context has received facilitation and can aid in the identification of the center letter. The orienting of attention in the word condition appears to enhance the context effect, as performance is increased above that seen in the word condition without an attentional manipulation. When attention is directed to the incorrect hemifield, the baseline effect of context that is present due to the inter-letter interactions helps to keep performance comparable to that seen when attention is not manipulated. Additionally, even when attention is removed, as in the invalid condition, the word superiority effect is not eliminated. Therefore, based on these results, we can conclude that exogenously and endogenously orienting attention interact with the word superiority effect such that both enhance the effect of context for the words, but do so in different ways.

The fact that the endogenous cue produced higher identification rates overall and a stronger word superiority effect compared to the exogenous cue, might lead some to suggest that perhaps the exogenous cues were not processed as extensively as the endogenous cues. Evidence for this hypothesis comes from the fact that the exogenous cues were presented in the periphery where there are fewer cortical resources devoted to processing the stimuli. However, this hypothesis seems unlikely given that the exogenous cue was able to produce a valid cuing advantage for both words and non-words, indicating that the cue was processed to the level at which it facilitated either the center letter only, or the entire word.

The endogenous cuing condition did not produce a differential effect of cuing condition, that is validly or invalidly cuing attention did not differentially affect performance. This might have been due to the cue-target timing that was used in these studies. The duration of the cue (83 ms) and the cue onset to stimulus offset interval (250) was chosen in order to preclude an eye movement to the crowded stimulus. However, while this timing was appropriate for producing an exogenous cuing effect, it was shorter than what has been deemed optimal for producing an endogenous cuing effect. Endogenous cuing utilizes voluntary orienting which responds usually 250 ms post-cue, whereas exogenous cuing utilizes reflexive orienting, and responds optimally approximately 150 ms post-cue (Posner & Cohen, 1984; Jonides, 1981; Muller & Rabbit, 1989). Thus, if it took 250 ms for the endogenous cue to properly orient attention, then under the current display conditions the crowded stimulus would no longer be present on the screen. Therefore, an endogenous cue might have been able to facilitate target identification or suppress distracter processing had the optimal timing been used in the current studies. Future studies will be needed to address this issue.

The discrimination experiment (Experiment 5) was specifically designed to assess whether attentional cuing suppresses the processing of distracter items. We examined this by probing subjects with center letters, distracter items, and items not present in the display to assess the percentage of trials in which these distracters might be confused with the center letter. We found that overall there was an advantage for distracters over items not present in the display, in that subjects falsely reported an item not present as the center letter more often than a distracter item. When broken down by cue type however, this pattern was only present for the exogenous cuing condition. This indicates that in crowding, the distracter items were visible enough not to be confused with the center letter, and the addition of an exogenous cue exerted no additional effect on the distracters, as the valid and neutral condition produced the same effect. For the endogenous cue, there was no difference in performance between the distracter probes and the item not present probes, but for the distracter probes there was a trend for attentional cuing to increase response accuracy (i.e., they reported "no" that was not the center letter more often) than when attention was not oriented. Because this effect did not reach significance, the finding should be interpreted with caution, however it suggests that endogenous attention could affect the entire letter sequence, including the distracter items, making them less confusable with the center letter.

The low rate at which subjects confused the distracter with the center letter (6.25% of trials) suggests that when subjects do not know what the center letter is, they are not very likely to report a distracter. Upon visual inspection of all the crowding data from these experiments, we found that when subjects were incorrect in their identification they were more likely to report a letter that is shaped similar to the center letter than a distracter. Nazir (1992) has found that crowded identification performance is best for small, dissimilar distracters, and worst for equivalent size, similar distracters. This indicates that similar distracters produce a larger crowding effect than dissimilar distracters. In crowding, the mechanism which integrates features belonging to one object and separates them from other objects (the feature integration mechanism, or comparator mechanism; Tyler & Likova, 2007, Pelli, et al., 2004) fails to work properly, such that the individual elements of a letter can become jumbled with other letters in the display. Thus, if the subject could parse some of the features of the center letter, but could not distinguish them all because of crowding (e.g., could tell the letter had an ascender but could not tell if it was a "l" or "t"), then they might be more likely to report a letter that shares that feature with the center letter then a distracter letter which is visible. Huckauf & Heller (2002) have found that there are commonly two types of errors subjects make when they incorrectly report the center letter. The first are "location errors," or errors in which the subject reports a distracter item (most often an adjacent distracter) which is said to result from a deficit in parsing the features of a letter from the features of the other letters in the display. A deficit in identification can be seen in "item errors," or errors occurring when a subject reports an item not present in the display (Huckauf & Heller, 2002). Our results indicate that when subjects commit an item error they are most likely to report a letter that is similar in shape to the center letter. In the discrimination experiment the items not present in the display were chosen based on their similarity to the other letters in the display (see Appendix D). For instance, if the other letters contained ascenders, then the item not present probe was a letter with an ascender, or if an "o" center letter was present it might have been probed with an "e" as the item not present. This similarity might provide another reason why the subjects incorrectly identified the item not present probe as the center letter more often than the distracter item.

Attentional facilitation or suppression?

One of the main goals of these experiments was to examine whether attentional cuing would produce distracter suppression effects or facilitation effects. We did not find any evidence for distracter suppression effects in any experiment. Rather, the cuing discrimination experiment found that distracters were less likely to be confused with the center letter indicating that they were visible on the display and could be distinguished from the center letter. We did find evidence for attentional facilitation effects. In the cuing identification experiment the exogenous cue produced a cuing advantage for words relative to the neutral condition, indicating that a facilitory effect was present. This facilitation appears to be a whole item effect rather than just a center letter facilitation, given that there was a cuing advantage for words and not for non-words. If the exogenous cue were producing facilitation of just the center letter then the same facilitation effect should have emerged for the word and non-word stimuli. This did not happen. Only the word stimuli received facilitation suggesting that exogenously orienting attention added an extra boost to the context effect produced for words, while it was not possible for this effect to emerge for the non-words.

It is interesting that the lack of a distracter suppression effect was equivalent for the word and non-word conditions. Based on the hypothesis that the word superiority effect results from inter-letter interactions that facilitate letter identifications for the word, this suggests that the outer letters of the word receive some type of feedback information or information from lateral connections which might facilitate their processing in addition to that of the center letter, whereas this would not be true for non-words because there is no context and thus no facilitation. This would predict that when probed with a distracter item, there might have been more confusion in the non-word condition because there was no top-down inter-letter information. However, this is not what we found. In the neutral condition for both the endogenous or exogenous cuing blocks, there was no advantage for words over non-words. That is, subjects falsely reported that a distracter was the center letter equally often in the word and non-word conditions. The only condition in which we saw an advantage for words over non-words was when subjects were probed with the center letter. Additionally, in contrast to other studies (Chastain, 1983; Petrov & Popple, 2007) that have found differential effects for inner and outer distracters, which might be expected based on the differences in eccentricity, we did not find a difference in falsely reporting an inner or outer distracter, suggesting that they were equally visible to the subjects. These results taken together suggest that crowding effects were only occurring on the center letter of the display both for words and non-words, and that the inter-letter interactions of the word only facilitate identification of the center letter in a crowded display.

Several studies have found that attentional manipulations can impact crowding (Van der Lubbe & Keuss, 2001; Montaser-Kouhsari & Rajimehr, 2005; Strasburger, 2005; Freeman & Pelli, 2007; Scolari, Kohnen, Barton, & Awh, 2007). However, the current work extends the work of Strasburger (2005), who has been the only one to examine the effects of attentional cuing on crowding identification performance. The other studies examined attentional effects on critical spacing, which we argue below might be differentially affected by attentional cuing. Strasburger used a 100% valid ring cue around the center (to be crowded) letter's location, and different target eccentricities of 1, 2, and 4 degrees of visual angle and found that there was a cuing effect (increase in target identification) at 1 and 2 degrees that disappeared at 4 degrees. The current studies extend this advantage seen with an exogenous cue to an eccentricity of 10 degrees, using only a 70% valid cue.

Strasburger (2005) also found that the probability of incorrectly reporting a distracter item as the center item was equal in the cued and no cue conditions. He interpreted these results as indicating that while there was an enhancement of the center letter (as seen with better identification in the cued condition), there was no attentional suppression of the distracter items. One of the problems with this study was that Strasburger analyzed these error rates post hoc and did not employ manipulations to test for such a suppression effect. Although our discrimination experiment was designed to test for distracter suppression effects, we did not find any suppression with an exogenous cue either; there was a trend for such an effect, however, with an endogenous cue. Therefore, the conclusions of the two studies are harmonious, both showing that an exogenous cue can facilitate identification of the central item in a crowded display and that exogenous cues do not suppress the influence of distracters to alleviate crowding.

Scolari, Kohnen, Barton, and Awh (2007) asked whether attentional orienting to a crowded target could reduce the critical spacing effect. They predicted that if cuing attention could reduce the critical spacing then in a valid precue condition the target should be identified (at a certain accuracy level) at a smaller distracter spacing distance than in an invalid or neutral condition. They found that exogenous attentional cuing increased response accuracy at each distracter spacing used, but it did not affect the critical spacing (the valid, invalid, and neutral conditions reached 90% asymptote at the same spacing). Interestingly, while a precue alone did not reduce critical spacing, they found that presenting the context on the screen before the cue and using a display that elicits pop-out of the target (or makes it highly salient) did reduce the critical spacing. Taken together, these results indicate that different attentional manipulations (in conjunction with display features) have different effects on critical spacing

If exogenously precuing attention acts in a facilitatory (enhancing) manner on the target then you would expect this facilitation to lead to a benefit in performance, which Scolari, et al. (2007) argue it did not in their study. They argue that orienting attention might not operate to enhance the signal in a crowded display. Although the work of Van der Lubbe and Keuss (2001) and Freeman and Pelli (2007) found that attention improves identification of crowded items, these studies could not distinguish signal enhancement from distracter suppression effects. The current studies investigated the signal enhancement vs. distracter suppression effects and found that exogenously precuing does lead to a facilitation in performance, as seen in the higher accuracy rates in the validly cued condition of Experiment 4. Scolari, et al. (2007) also found that attentional cuing increased response accuracy at each distracter spacing used. The measure in which they were interested, however, was critical spacing, and because attentional cuing did not affect the critical spacing (the valid, invalid, and neutral conditions reached 90% asymptote at the same spacing), they concluded that precuing does not diminish crowding. However, these are two different ways of assessing the impact of attentional cuing on crowding: one involves how well an item can be identified and the other involves how close the distracters can be to the item to preserve that identification. Both Scolari, et al. (2007) and the current studies have shown that attentional cuing can facilitate identification, and the current experiments have shown that attentional cuing does not suppress the influence of the distracters. Given that the crowding effect increases as distracter spacing decreases, it follows that the influence of the distracters on the identification of the central item increases with decreasing distracter spacing. If attentional cuing does not suppress the influence of the distracters, it also follows that as the distracter influence on crowding increases, the addition of attention will have no effect. Therefore, attentional cuing can increase target identification because it has a facilitatory effect, but it cannot reduce the critical spacing effect because it does not reduce the influence of distracters on identification performance.

In the introduction we argued that different cue types and different task demands produced differing demands on attention, such that when the stimuli are near threshold attention must boost the signal to enhance discriminability, whereas when stimuli need to be discriminated from noise, attention must diminish the influence of that external noise (suppress distracters). This was based on the work of Carrasco, Ling, and Read (2004) who found signal enhancement using exogenous cues and near-threshold stimuli that needed to be discriminated from the background, while Dosher and Lu (2000a; Lu & Dosher, 2000) found signal enhancement and external noise reduction (distracter suppression) effects with exogenous cues, and external noise reduction effects with endogenous cues using suprathreshold stimuli that needed to be discriminated from the noise.

Lu's and Dosher's Perceptual Template Model (Lu & Dosher, 2000b; Lu & Dosher, 1998) proposes that signal enhancement occurs because the system turns up the gain on the stimulus (i.e., sensory perceptual facilitation), which occurs under low external noise conditions, and external noise reduction involves changing the perceptual filter or task template (fine tuning) which occurs under conditions of high external noise, when there is external noise to diminish. Given that the current studies found no evidence for external noise reduction or distracter suppression, it might be argued that the current studies did not employ conditions with sufficiently high levels of external noise. The Lu and Dosher studies (Dosher & Lu, 2000a; Lu & Dosher, 2000) that have found external noise reduction under high levels of noise used superimposed noise that degraded the visual input to the system. In the crowding effect, the distracter items prevent the features of the crowded item from being correctly parsed and joined to that item, but they do not physically degrade the signal. The signal is still present, but it cannot be properly resolved. Crowding results from a disruption in identification of the stimuli while feature processing in primary visual cortex is preserved (Pelli, et al., 2004). Crowding is thought to occur at a level higher than V1. One strong line of evidence that the crowding effect does not result from processing in V1 comes from findings that adaptation is immune to crowding (He, Cavanagh, & Intriligator, 1996; He, Cavanagh, & Intriligator, 1997; Montaser-Kouhsari & Rajimehr, 2005). Adaptation has been shown to occur in early visual areas (V1 neurons), and thus if such orientation adaptation is immune to crowding then crowding must occur at some higher level. Therefore, it can be argued that because the diminished processing that results from crowding is not due to physical noise, but rather to noise in the processing stream, this noise was not sufficient to employ attentions' external noise reduction properties. The signal enhancement properties of attention have been shown to operate on the raw signal and as early in the stimulus processing stream as the lateral geniculate nucleus of the thalamus (O'Conner, Fukui, Pinsk, & Kastner, 2002), and so it is possible to see signal enhancement properties under crowded conditions. However, the lack of physical degradation in the signal with crowded stimuli might have prevented attention from employing the noise reduction mechanism. Future research should investigate whether or not different types of stimulus noise affect these attentional mechanisms in different ways.

Practical implications

The current work adds to the growing body of evidence that context aids in the processing of information. Using the word superiority effect we found that familiarity with letter sequencing (e.g. words and pronounceable non-words) improves letter identification in the periphery. However, in real word displays it is more common for words to be presented in the context of other words in a sentence, thus it could prove useful to try to extend this work to incorporate sentence processing in the periphery.

This work demonstrated the importance of context in the processing of information. An important extension of this finding would be to examine whether or not visually searching for a word (or other item that contains context) would be better than searching for a non-word. There are two obvious reasons for why search performance for a word might be better than search performance for a non-word. The first is that the processing of the word is more efficient, as evidenced from the word superiority effect and the findings of Reber et al. (2004) that words are processed more quickly, appeared in higher contrast and of larger size than non-words. This efficiency in processing would make response times to words faster than to non-words even if they were detected at the same time. Second, words might attract attention to themselves, as the work of Sieroff et al. (1988) has shown that words might act as a type of cue to draw attention to themselves. We also found that orienting attention to words improves performance above and beyond that with no attentional orienting, while attention did not improve performance when there was no (word) context. These two lines of evidence suggest that visual search for words might be better than that of non-words, and thus should be investigated further. Improved visual search for words would have practical implications for displays containing words and acronyms, as acronyms tend to contain lower bigram frequencies than words. If labels need to appear in the periphery or to be located, than they should be words rather than acronyms, as the words will be processed more efficiently.

This work also has practical implications for patients who have had damage to parts of their retina and must read text presented parafovealy. When text must be read parafovealy it is important to make the words high frequency as we have shown that familiarity with letter sequencing or letter co-occurrence can improve identification and recognition.

Conclusions

The current studies attempted to assess whether semantics contribute to the word superiority effect and whether attentional cuing produces target enhancement or distracter suppression effects using crowded displays. In Experiment 1 we replicated the effects of Fine (2002, 2004) showing that there is an advantage in identifying the center letter in a crowded display if the letter is presented in the context of a word than in the context of a non-word; a word superiority effect with crowded stimuli. The first goal of these experiments was to assess the semantic contribution to the word superiority effect. The results of Experiments 2 and 3, assessing semantics, converge nicely to show that the word superiority effect results from a perceptual familiarity effect, with center letter responses favoring the familiar letter sequencing of words over non-words. When letter sequence probabilities are held constant, the remaining additional semantic information that is associated with the word does not contribute any additional facilitory inputs to the word superiority effect.

The second goal of these experiments was to examine whether attentional cuing would produce distracter suppression effects or target facilitation effects. In Experiments 4 and 5, using both endogenous and exogenous cues we did not find any evidence for distracter suppression effects, possibly because of the fact that the crowded display did not induce sufficient noise levels to cause attention to employ the distracter suppression mechanism, or because crowding induces a different kind of noise (feature integration noise) that does not elicit the distracter suppression mechanism. We did find evidence for attentional facilitation effects. In Experiment 4 we found that the presence of an endogenous cue was having an overall alerting effect resulting in improved performance for the word condition, but not the non-word condition. The exogenous cue produced a cuing advantage only for words, suggesting that exogenously orienting attention added an extra boost to the context effect produced for words. We found that exogenously and endogenously orienting attention interact with the word superiority effect such that they enhance the effect of context for the words, but do so in different ways.

References

Baron, J. & Thurston, I. (1973). An analysis of the word superiority effect. *Cognitive Psychology, 4*, 207-228.

Breitmeyer, B. G. (1984). *Visual masking. An integrative approach.* New York: Oxford University Press.

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature, 226*, 177-178.

Boyer, J., & Ro, T. (2007). Attention attenuates metacontrast masking. *Cognition, 104*, 135-149.

Carrasco, M., Ling, S., & Read, S. (2004). Attention alters appearance. *Nature Neuroscience, 7*(3), 308-313.

Chastain, G. (1983). Task and contrast effects on performance with parafoveal stimulus pairs. *Psychological Research, 45*, 147-156.

Dosher, B. A., & Lu, Z. (2000a). Noise exclusion in spatial attention. *Psychological Science, 11*(2), 139-146.

Dosher, B. A., & Lu, Z. (2000b). Mechanisms of perceptual attention in precuing of location. *Vision Research, 40*, 1269-1292.

Eriksen, B. A. & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 16*(1), 143-149.

He, S., Cavanagh, P., & Intriligator, J. (1996). Attentional resolution and the locus of visual awareness. *Nature, 383*, 334-337.

He, S., Cavanagh, P., & Intriligator, J. (1997). Attentional resolution. *Trends in Cognitive Sciences, 1*(3), 115-121.

Huckauf, A., & Heller, D. (2002). What various kinds of errors tell us about lateral masking effects. *Visual Cognition, 9*(7), 889-910.

Huckauf, A., & Heller, D. (2004). On the relations between crowding and visual masking. *Perception & Psychophysics, 66*(4), 584-595.

Fine, E. M. (2001). Does meaning matter? The impact of word knowledge on lateral masking. *Optometry and Vision Science, 78*(11), 831-838.

Fine, E. M. (2004). The relative benefit of word context is a constant proportion of letter identification time. *Perception and Psychophysics, 66*(6), 897-907.

Freeman, E., Sagi, D., & Driver, J. (2001). Lateral interactions between targets and flankers in low-level vision depend on attention to the flankers. *Nature Neuroscience, 4*(10), 1032-1036.

Freeman, J. & Pelli, D. G. (2007). An escape from crowding. *Journal of Vision, 7*(2), 1-14.

Johnston, J. C., & McClelland, J. L. (1973). Visual factors in word perception. *Perception and Psychophysics, 14*(2), 365-370.

Johnston, J. C., & McClelland, J. L. (1974). Perception of letters in words: Seek not and ye shall find. *Science, 184*(4142), 1192-1194.

Jonides, J. (1981). Voluntary vs automatic control over the minds eye. In J. Long & A. Baddeley, (Eds.) *Attention and Performance IX* (pp. 187-203) Hillsdale, NJ.; Earlbaum.

Kapadia, M. K., Ito, M., Gilbert, C. D., & Westheimer, G. (1995). Improvements in visual sensitivity by changes in local context: Parallel studies in human observes and in V1 of alert monkeys. *Neuron, 15*, 843-856.

Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review, 1*(4), 476-490.

Lu, Z., & Dosher, B. A. (2000). Spatial attention: Different mechanisms for central and peripheral temporal precues? *Journal of Experimental Psychology: Human Perception and Performance, 26*(5), 1534-1548.

Lu, Z., Lesmes, L. A., & Dosher, B. A. (2002). Spatial attention excludes external nose at the target location. *Journal of Vision, 2*, 312-323.

Marcel, A. J. (1983). Conscious and unconscious perception: Experiments on visual masking and word recognition. *Cognitive Psychology, 15*(2), 197-237.

Maunsell, J. H. R., & Newsome, W. T. (1987). Visual processing in monkey extrastriate cortex. *Annual Review of Neuroscience, 10*, 363-401.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part 1. An account of basic findings. *Psychological Review, 88*(5), 375-407.

Meyer, D. E., & Schaneveldt, R. W. (1971). Facilitation in recognizing pairs of words: Evidence of a dependence between retrieval operations. *Journal of Experimental Psychology, 90*(2), 227-234.

Montaser-Kouhsari, L., & Rajimehr, R. (2005). Subliminal attentional modulation in crowding condition. *Vision Research, 45*, 839-844.

Muller, H. J. & Rabbit, P. M. A. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance, 15*(2), 315-330.

Nazir, T. A. (1992). Effects of lateral masking and spatial precuing on gap-resolution in central and peripheral vision. *Vision Research, 32*(4), 771-777.

Neely, J. H. (1991). *Semantic priming effects in visual word recognition: A selective review of current findings and theories.* In Basic processes in reading: Visual word recognition.

O'Conner, D. H., Fukui, M. M., Pinsk, M. A., & Kastner, S. (2002). Attention modulates responses in the human lateral geniculate nucleus. *Nature Neuroscience, 5*(11), 1203-1209.

Poder, E. (2006). Crowding, feature integration, and two kinds of "attention". *Journal of Vision, 6*, 163-169.

Posner, M. I. & Cohen, Y. (1984). *Components of visual orienting. In Attention and Performance Vol. X* (Bouma, H. and Bouwhuis, D., eds), pp. 531-556, Erlbaum.

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

Rastle, K., Harrington, J., & Coltheart, M. (2002). 358,534 nonwords: The ARC nonword database. *Quarterly Journal of Experimental Psychology, 55*(A), 1339-1362.

Reber, R., Zimmermann, T. D., & Wurtz, P. (2004). Judgments of duration, figure-ground contrast, and size for words and nonwords. *Perception & Psychophysics, 66*(7), 1105-1114.

Reicher, G. M. (1969). Perceptual recognition as a function of meaningfulness of stimulus material. *Journal of Experimental Psychology, 81*, 275-280.

Rousselet, G. A., Husk, J. S., Bennett, P. J., & Sekuler, A. B. (2005). Spatial scaling factors explain eccentricity effects on face ERPs. *Journal of Vision, 5*, 755-763.

Rumelhart, D. E., & McClelland, J. L. (1982). An interactive activation model of context effects in letter perception: Part 2. The contextual enhancement effect and some tests and extensions of the model. *Psychological Review, 89*(1), 60-94.

Scolari, M., Kohnen, A., Barton, B. & Awh, E. (2007). Spatial attention, preview, and popout: Which factors influence critical spacing in crowded displays? *Journal of Vision, 7*(2), 1-23.

Shiu, L., & Pashler, H. (1994). Negligible effect of spatial precuing on identification of single digits. *Journal of Experimental Psychology: Human Perception and Performance, 20*(5), 1037-1054.

Sieroff, E. & Posner, M. I. (1988). Cuing spatial attention during processing of words and letter strings in normals. *Cognitive Neuropsychology, 5*(4), 451-472.

Sieroff, E., Pollatsek, A., & Posner, M. I. (1988). Recognition of visual letter strings following injury to the posterior visual spatial attention system. *Cognitive Neuropsychology, 5*(4), 427-449.

Strasburger, H. (2005). Unfocused spatial attention underlies the crowding effect in indirect form vision. *Journal of Vision, 5*, 1024-1037.

Tyler, C. W., & Likova, L. T. (2007). Crowding: A neuroanalytic approach. *Journal of Vision, 7*(2), 1-9.

Van der Lubbe, R. H. J., & Keuss, P. J. G. (2001). Focused attention reduces the effect of lateral interference in multi-element arrays. *Psychological Research, 65*, 107-118.

Zipser, K., Lamme, V. A. F., & Shiller, P. H. (1996). Contextual modulation in primary visual cortex. *The Journal of Neuroscience, 16*(22), 7376-7389.

Notes

1. A Gabor is a spatially sinusoidal luminance pattern (a grating) "windowed" by a Gaussian (bell-shaped) weighting function. The end result is a grating pattern with fuzzy rather than sharp edges (see Figure 40).

Figure 40. A Gabor patch.

Appendix A

Word and non-word stimuli used by Fine (2001; 2004) and in the current studies.

Words		Non-words	
lap	one	lsp	oue
wag	ink	wsg	iuk
lay	any	lsy	auy
ace	hoe	aoe	hme
act	cog	aot	cmg
ice	wok	ioe	wmk
ado	ape	afo	aje
ode	spy	ofe	sjy
ads	apt	afs	ajt
yew	ark	ycw	avk
yet	ore	yct	ove
net	wry	nct	wvy
aft	ask	aht	ank
ifs	ash	ihs	anh
oft	use	oht	une
age	ate	aqe	abe
ago	sty	aqo	sby
ego	its	eqo	jbs
thy	out	tly	oet
who	jug	wlo	jeg
she	sum	sle	sem
rib	owe	rtb	oze
pin	owl	ptn	ozl
sip	two	stp	tzo
sly	bye	siy	bpe
elf	rye	eif	rpe
old	gym	oid	gpm
amp		awp	
emu		ewu	
ump		uwp	

Appendix B

Fifty-three of the word and non-word stimuli used by Fine (2001; 2004) and their related, unrelated, and non-word matches.

Fine Words	Fine Non-words	Related Words	Unrelated Words	Non-words
ace	aoe	card	told	priv
act	aot	play	side	soav
ado	afo	much	mind	nuid
aft	aht	fore	room	jeuk
age	aqe	youth	clear	cruns
ago	aqo	long	name	voar
amp	awp	speaker	country	sprirbs
any	auy	more	full	zals
ape	aje	monkey	school	theuse
apt	ajt	fitting	history	prowntz
ark	avk	noah	wife	solk
ash	anh	tray	rate	wuzz
ask	ank	why	car	unz
ate	abe	food	city	krug
bye	bpe	good	form	goph
ego	eqo	self	half	cusc
elf	eif	fairy	group	danth
emu	ewu	bird	said	twol
gym	gpm	fit	far	sni
hoe	hme	rake	case	gucs
ice	ioe	cold	tell	dirg
ink	iuk	pen	act	olp
its	jbs	his	saw	nyn
jug	jeg	water	think	nirts
lap	lsp	dog	air	bav
lay	lsy	down	face	jafs
net	nct	fish	four	lilv
ode	ofe	poem	turn	tieb
oft	oht	often	world	lurmb
old	oid	new	top	ses
one	oue	day	art	kal
ore	ove	iron	look	lusc
out	oet	exit	kind	gink
owe	oze	money	light	grocs

owl	ozl	night	force	faish
pin	ptn	needle	course	murved
rib	rtb	bone	down	senc
rye	rpe	grain	music	clent
she	sle	her	cab	paz
sip	stp	drink	money	rirls
sly	siy	fox	few	oag
spy	sjy	agent	first	shusk
sty	sby	pigpen	second	jooled
sum	sem	add	job	tyb
thy	tly	your	town	wace
two	tzo	three	board	flawn
ump	uwp	umpire	office	threip
use	une	consume	million	cheeths
wag	wsg	tail	type	voed
wok	wmk	bowl	west	rurk
wry	wvy	turn	girl	bolk
yet	yct	now	can	mec
yew	ycw	tree	once	toab

Appendix C

Eleven of the word and non-word stimuli used by Fine (2001; 2004) that had three letter related words. The unrelated and non-words were matched to the words in number of letters.

Fine Words	Fine Non-words	Related Words	Unrelated Words	Non-words
ask	ank	why	car	unz
gym	gpm	fit	far	sni
ink	iuk	pen	act	olp
its	ibs	his	saw	nyn
lap	lsp	dog	air	bav
old	oid	new	top	ses
one	oue	day	art	kal
she	sle	her	cab	paz
sly	siy	fox	few	oag
sum	sem	add	job	tyb
yet	yct	now	can	mec

Appendix D

The response probes used for each word and non-word in the discrimination experiment (Experiment 5).

Words	Distracter	Center letter	Distracter	Not Present
ace	a	c	e	n
act	a	c	t	h
ado	a	d	o	k
ads	a	d	s	h
aft	a	f	t	l
age	a	g	e	p
ago	a	g	o	u
amp	a	m	p	n
any	a	n	y	r
ape	a	p	e	g
apt	a	p	t	b
ark	a	r	k	e
ash	a	s	h	u
ask	a	s	k	o
ate	a	t	e	h
bye	b	y	e	g
cog	c	o	g	e
ego	e	g	o	y
elf	e	l	f	h
emu	e	m	u	a
gym	g	y	m	p
hoe	h	o	e	a
ice	i	c	e	a
ink	i	n	k	e
its	i	t	s	f
jug	j	u	g	n
lap	l	a	p	r
lay	l	a	y	o
net	n	e	t	c
ode	o	d	e	t
oft	o	f	t	l
old	o	l	d	b
one	o	n	e	s
ore	o	r	e	c
out	o	u	t	r
owe	o	w	e	v
owl	o	w	l	v

pin	p	i	n	j
rib	r	i	b	f
rye	r	y	e	j
she	s	h	e	d
sly	s	l	y	h
spy	s	p	y	g
sty	s	t	y	q
sum	s	u	m	n
thy	t	h	y	k
two	t	w	o	x
ump	u	m	p	n
use	u	s	e	c
wag	w	a	g	u
who	w	h	o	m
wok	w	o	k	b
wry	w	r	y	v
yet	y	e	t	f
yew	y	e	w	s
Non-words	**Distracter**	**Center letter**	**Distracter**	**Not Present**
aoe	a	o	e	n
aot	a	o	t	u
afo	a	f	o	t
afs	a	f	s	h
aht	a	h	t	k
aqe	a	q	e	j
aqo	a	q	o	u
awp	a	w	p	r
auy	a	u	y	r
aje	a	j	e	y
ajt	a	j	t	y
avk	a	v	k	l
anh	a	n	h	r
ank	a	n	k	o
abe	a	b	e	h
bpe	b	p	e	q
cmg	c	m	g	n
eqo	e	q	o	b
eif	e	i	f	k
ewu	e	w	u	v
gpm	g	p	m	q
hme	h	m	e	n
ioe	i	o	e	u
iuk	i	u	k	d
ibs	i	b	s	k
jeg	j	e	g	o
lsp	l	s	p	y
lsy	l	s	y	j

nct	n	c	t	d
ofe	o	f	e	d
oht	o	h	t	f
oid	o	i	d	u
oue	o	u	e	a
ove	o	v	e	a
oet	o	e	t	b
oze	o	z	e	x
ozl	o	z	l	v
ptn	p	t	n	h
rtb	r	t	b	f
rpe	r	p	e	g
sle	s	l	e	t
siy	s	i	y	v
sjy	s	j	y	q
sby	s	b	y	j
sem	s	e	m	a
tly	t	l	y	f
tzo	t	z	o	e
uwp	u	w	p	c
une	u	n	e	r
wsg	w	s	g	j
wlo	w	l	o	r
wmk	w	m	k	v
wvy	w	v	y	c
yct	y	c	t	v
ycw	y	c	w	n