Spatial attention, preview, and popout: Which factors influence critical spacing in crowded displays?

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Crowding refers to the phenomenon in which nearby distractors impede target processing. This effect is reduced as target–distractor distance increases, and it is eliminated entirely at a distance that is labeled the critical spacing point. Attention, distractor preview, and popout are each known to facilitate processing in crowded displays. Eight experiments examined whether this is accomplished via a reduction in critical spacing. Attention was manipulated via spatial cueing, whereby a peripheral cue elicited a stimulus-driven shift of attention. Distractor preview was examined by manipulating whether the crowding distractors were presented prior to or simultaneous with the target. Popout was examined by manipulating whether there was a salient color difference between the target and distractors. As demonstrated in previous studies, we found robust benefits of spatial cueing, preview, and popout in crowded displays. However, although spatial cueing led to robust improvements in target discrimination, there was no reduction in critical spacing for attended stimuli. By contrast, both preview and popout caused large reductions in critical spacing. These disparate results indicate that attention improves target discrimination in crowded displays in a qualitatively different manner than do the other factors.

Keywords: crowding, critical spacing, attention, spatial cues, distractor preview, popout

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Introduction

When multiple objects are presented in proximity to a peripheral target, the identification of that target can be strongly impaired, a phenomenon that is referred to as "crowding" or "lateral masking" (Bouma, 1970; Huckauf & Heller, 2004; Pelli, Palomares, & Majaj, 2004). Crowding can be demonstrated even in the absence of impaired target detection (Pelli et al., 2004) and may be caused by excessive integration of target and distractor representations (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Pelli et al., 2004). Crowding effects are reduced as the target–distractor distance increases, and they disappear entirely when the distractors exceed a specific distance from the target. This distance is labeled the "critical spacing" point. Thus, inside the critical spacing point, target identification improves monotonically as distractor spacing increases. For distractor distances beyond the critical spacing point, target identification is no longer affected by the distractors (Bouma, 1970; Pelli et al., 2004). Bouma (1970) determined that critical spacing is roughly 0.5 target eccentricity so that the further in periphery a target is presented, the greater is the critical spacing. Further studies have shown that critical spacing is independent of target and distractor size (Pelli et al., 2004; Strasburger, Harvey, & Rentschler, 1991), as well as the number of distractors (in cases of two or more) and distractor contrast (Pelli et al., 2004). Some have suggested that crowding is intimately related to the construct of attention, in that the spatial extent of the interactions between targets and distractors may be determined by the spatial resolution of attention (e.g., Intriligator & Cavanagh, 2001). By this view, closely grouped targets and distractors lead to impaired target discrimination because the resolution of attention is insufficient to disambiguate the relevant and irrelevant elements in the scene.

Spatial attention and critical spacing

It is well known that attention can facilitate the discrimination of visual information and that this effect is particularly pronounced when there is significant interference from

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irrelevant distractors (Awh, Matsukura, & Serences, 2003; Awh, Sgarlata, & Kliestik, 2005; Desimone & Duncan, 1995; Dosher & Lu, 2000, Kastner, De Weerd, Desimone, & Ungerleider, 1998; Shiu & Pashler, 1994). The increased amplitude of attention effects in the presence of distractor interference suggests that attention may facilitate target selection (at least in part) by distractor exclusion (Desimone & Duncan, 1995). If distractor representations are suppressed, it seems plausible that they could appear closer to the target before crowding effects are observed. That is, critical spacing might be reduced for attended targets.

This is not the only possibility, however. A subset of possible results is illustrated in Figure 1. Consider Figure 1A, where distractor distance is plotted against target accuracy for both attended and unattended conditions. As the distractor distance increases, accuracy increases. At a certain distance, however, distractors are no longer influencing identification and accuracy reaches asymptote. At this point, the distractors are effectively absent. The restriction of attention effects to spacings that are inside the critical spacing point would be consistent with selection via distractor exclusion, given that this process will have little effect when there is no significant interference from distractors. Notice, however, that both conditions reach asymptote at the same distractor distance, which means that the inflection point is the same for attended and unattended targets. This depicts one way in which at-

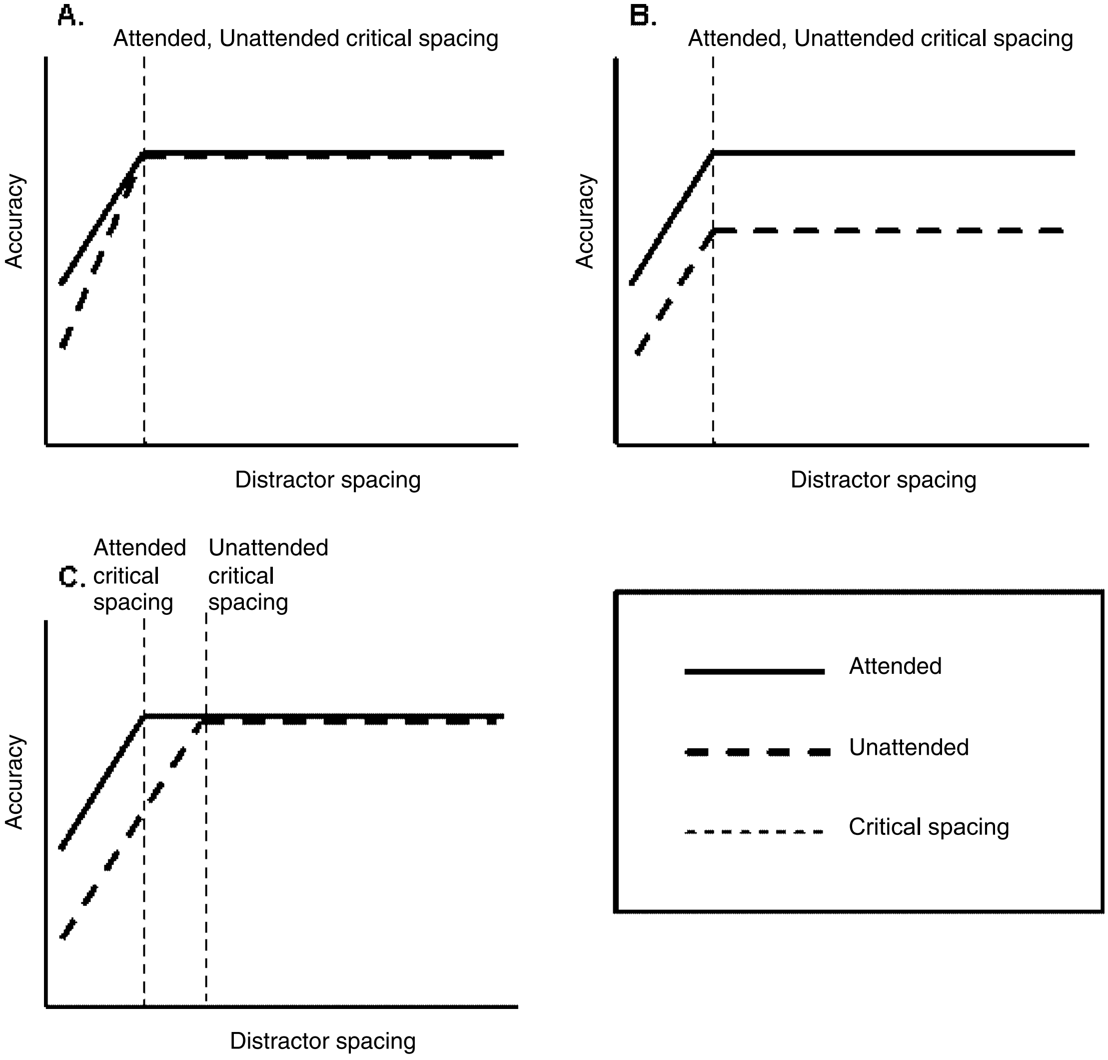

Figure 1. Each of these graphs represents hypothetical critical spacing results for the attended and unattended conditions. Accuracy is plotted on the *Y*-axis, and distractor spacing is plotted on the *X*-axis. Accuracy increases as distractor distance increases until asymptote is reached. (A) Both conditions have equivalent critical spacing estimates, indicating that attention does not influence critical spacing. Similarly, both conditions asymptote at an equivalent accuracy level, indicating that attention does not improve target identification outside of critical spacing. (B) Both conditions have equivalent critical spacing estimates, but the attended condition reaches asymptote at a higher accuracy than the unattended condition, indicating that attention influences target identification even in the absence of distractors. (C) The attended condition reaches critical spacing at a shorter distractor distance than the unattended condition, indicating that attention does reduce critical spacing. However, the two conditions reach asymptote at the same accuracy level.

tention could facilitate target identification when distractors are present, without a concurrent reduction in critical spacing. Figure 1B shows a similar situation where critical spacing again remains constant across the two conditions. The difference here is that the attended condition maintains greater accuracy even at asymptote. Given that there is no significant distractor interference beyond the critical spacing point, attention effects in the asymptotic range suggest selection via signal enhancement (e.g., Carrasco, Penpeci-Talgar, & Eckstein, 2000; Cheal & Gregory, 1997; Eriksen & Hoffman, 1974; Henderson, 1996; Luck, Hillyard, Mouloua, & Hawkins, 1996). Thus, although there have been clear demonstrations that attention facilitates processing in crowded displays, this does not necessitate a reduction in critical spacing for the attended items. Finally, Figure 1C depicts a case in which the critical spacing point is reduced for attended targets. Here, the inflection point is at a smaller target–distractor spacing. To summarize, while previous research has produced compelling evidence of both distractor exclusion and signal enhancement during spatial cueing tasks, it is not yet known whether attention changes the spatial extent of target–distractor interactions during crowding.

This issue has been addressed in previous studies, none of which have demonstrated a clear effect of attention on critical spacing (Nazir, 1992; Strasburger, 2005; Wilkinson, Wilson, & Ellemberg, 1997). However, these studies may not be conclusive. Nazir (1992) found that exogenous precues presented for 100 ms did not influence target identification of a Landolt ring in eccentric vision when the target was presented with distractors at a distance of 1 target width. Nazir suggested that the results may have been due to the low-acuity nature of attention; that is, attention did not provide the necessary spatial resolution to prevent interference from the distractors. In line with this, Wilkinson et al. (1997) also found that attention did not improve performance in peripherally presented crowded displays. These procedures may not have been ideal to investigate the effects of spatial cueing, however, because neither procedure was shown to be sensitive to spatial cueing effects. Given that spatial cueing can have robust effects on accuracy, especially in the presence of distractor interference (Awh et al., 2003; Dosher & Lu, 2000; Kastner et al., 1998; Shiu & Pashler, 1994), the most convincing test of whether attention influences critical spacing should demonstrate the known benefits of spatial cueing.

Strasburger (2005) conducted an experiment in which clear spatial cueing effects were observed. Unlike Nazir (1992) and Wilkinson et al. (1997), Strasburger included several distractor distances to assess critical spacing with different target eccentricities, where contrast threshold was the dependent measure. Like Nazir and Wilkinson et al., Strasburger concluded that attention does not reduce critical spacing. His results were conceptually similar to those illustrated in Figure 1A. However, his procedure is limited in its assessment of critical spacing. Specifically, estimating critical spacing requires a clear measurement of where accuracy reaches asymptote as distractor spacing is increased. Critical spacing, after all, is defined as the smallest distractor spacing that allows asymptotic performance. The range of distractor spacings that Strasburger used in the attended condition may not have extended far enough to allow a confident assessment of asymptote. He found that thresholds in the attended condition reached a distractor-absent baseline at smaller distractor spacings than in an unattended condition. However, because very few distractor spacings were tested beyond this point, it remains possible that asymptotic levels in the attended condition were actually better than in the distractor-absent condition. If so, then critical spacing could still be equivalent between the attended and unattended conditions (see Figure 1B).

Felisberti, Solomon, and Morgan (2005) also measured critical spacing while achieving reliable spatial cueing effects. They manipulated attention by cueing either the correct location (i.e., valid cueing) or all possible locations (i.e., neutral cueing) across several distractor spacings. The results showed that the valid cueing condition reached baseline (i.e., the threshold corresponding to a control distractor-absent condition) at a distance of 12 wavelengths, whereas the neutral cueing condition did not reach baseline at any of the tested spacings. However, neither condition reached asymptote based on the figures provided. Furthermore, the authors used a distractor-absent condition to measure baseline performance, which may have prevented an analysis of whether spatial cueing could have elevated performance beyond that in the baseline condition. If the valid cueing condition did elicit lower asymptotic thresholds than the control, then critical spacing in the valid cueing condition may not have been reduced. Therefore, because distances beyond those that allowed "baseline-level" performance were not employed, this experiment may not have provided a reliable estimate of critical spacing.

For the current study, we included a larger range of distractor distances in a procedure that allowed us to (a) achieve a strong spatial cueing effect and (b) more accurately estimate the asymptotes and inflection points for attended and unattended targets. To anticipate our results, we found robust spatial cueing effects both inside and outside the critical spacing point across four different studies, although the inflection point did not change between conditions. Thus, the results are like the hypothetical situation presented in Figure 1B. Spatial cueing did not reduce critical spacing.

Distractor preview and target popout

Finally, we examined two other factors that have been shown in previous research to influence the strength of crowding effects: distractor preview (Huckauf & Heller, 2004) and target popout (Felisberti et al., 2005; Kooi, Toet, Tripathy, & Levi, 1994; Pelli et al., 2004). Distractor preview refers to cases in which the crowding elements in the display are presented prior to target onset. Popout refers to cases in which a salient feature difference distinguishes the target from the distractors. Although previous research has made it clear that crowding is reduced by these factors, a rigorous test of whether critical spacing is reduced has not yet been provided.

When targets and distractors are presented together in visual search displays, reaction time increases as a function of the number of distractors in the display. This filtering cost can be reduced, however, when the distractors appear before the targets (Kahneman, Treisman, & Burkell, 1983). Watson and Humphreys (1997) suggested that this reduction is the result of deprioritization of the distractors, where old, irrelevant information is visually marked so it does not compete for selection with new information. In what may be a related phenomenon, distractor preview has been shown to benefit target identification in crowded target displays (Huckauf & Heller, 2004). Huckauf and Heller (2004) examined the effects of various negative and positive stimulus onset asynchronies (SOAs) on target identification accuracy at three different distractor distances. A negative SOA refers to distractor preview, where the distractors were presented prior to target onset, and a positive SOA refers to target preview. The study found clear crowding effects. When the target and distractors were presented simultaneously, accuracy increased with target–distractor distance. However, target–distractor distance had a much smaller effect with distractor preview. These results are consistent with the possibility that preview can reduce critical spacing. However, Huckauf and Heller were not interested in assessing critical spacing, and it cannot be determined from this particular study because the simultaneous condition did not reach asymptote within the range of distances tested.

The benefits of target popout have long been known. That is, when a salient feature differs between targets and distractors, targets can be quickly localized (Treisman, 1982). Other studies have also shown that the popout effect improves performance in crowded displays (Felisberti et al., 2005; Kooi et al., 1994; Pelli et al., 2004), suggesting that popout can facilitate discrimination as well as localization of targets. These data leave open the possibility that popout aids target discrimination by reducing critical spacing, but previous research has neglected to examine this issue. For example, although Felisberti et al. (2005) manipulated both distractor distance and target–distractor similarity, the two factors were not examined simultaneously, and thus, critical spacing for popout displays was not assessed.

Both popout and preview displays reflect situations in which target saliency is greater than that of the distractors. Previous research indicates that attention is influenced by target saliency; that is, when target saliency is high, attention may be captured at the target location (Treisman & Gelade, 1980). This may lead some to suggest that we are manipulating attention with the different displays (i.e., popout vs. nonpopout and preview vs. simultaneous distractor presentation). However, the benefits of target salience have, for the most part, been demonstrated within visual search procedures, where the limiting factor for performance is the process of localizing and directing attention toward the relevant element in the display (i.e., shifting spatial attention to the target). By contrast, observers were given valid precues on each trial, which allowed spatial attention to be directed to the correct location in advance for both distractor preview and simultaneous trials in Experiment 6 and for both popout and non-popout trials in Experiment 8. Because attention was already at the correct location prior to display onset, there is no reason to predict differences in the speed of spatial orienting to the target locations. For these reasons, we suggest that the effects of distractor preview and target popout are not well explained by differences in the allocation of spatial attention to the target locations.

The present experiments examined the influence of attention, distractor preview, and target popout on critical spacing. Although each of these factors has been shown to improve target discrimination in crowded displays, further evidence is needed to clarify whether they influence critical spacing. Experiments 1, 2, 3, and 4 employ spatial cueing manipulations to explore the possible impact of attention. Experiments 5 and 6 address the issue of distractor preview, and Experiments 7 and 8 address the issue of popout.

Spatial cueing studies

The following four experiments were designed to assess critical spacing for both attended and unattended targets, where attention was manipulated via spatial cues. Because Experiments 1, 2, 3, and 4 used very similar methods, we describe the method that was applied to the first study, and for each subsequent study, specifications of how they differed from this method. After the methods and results section of each experiment, we provide a combined discussion of the results and conclusions from these studies.

Experiment 1

The purpose of this experiment was to determine whether the effects of crowding are eliminated for attended targets at shorter distractor spacings than those that are unattended. This question was addressed by employing a cueing paradigm in which target locations were either validly or invalidly cued. Distractor spacings were also manipulated to determine critical spacing for both attended and unattended targets. Previous research has established that target identification should be better in the attended than in the unattended condition. The question of interest is how close distractors must be to begin impeding processing for attended and unattended targets and whether this distance is influenced by spatial cueing.

Method

Participants

Twelve students from the University of Oregon received partial course credit for their participation in a 1-hr session. Each participant had normal or corrected-to-normal vision.

Stimuli

All stimuli were presented in a gray color with a value of approximately 83.6 cd/m^2 on a white background (approximately 95.9 cd/m^2). These low-contrast stimuli yielded higher exposure durations during staircasing so that adjustments of target exposure duration constituted a smaller percentage of the overall duration. This enabled better control over asymptotic accuracy in this experiment.

Targets. The targets included four oriented uppercase Ts in a calculator letter font. The upright T subtended 0.8° of visual angle for both height and width. For each trial, there were two possible target locations, one on either side of the fixation point along the horizontal meridian at a distance of 10 target widths.

Distractors. The distractors were oriented thetas, also in calculator font. The thetas subtended 0.8° in height and width. In distractor-present trials, one distractor appeared above and one appeared below the target, each at the same distance from the target. Distractor onset coincided with target onset.

Masks. All stimuli (i.e., both targets and distractors) were masked with windowpanes (i.e., crosses inside squares), which subtended 0.8° in height and width. This object was selected because it effectively masked all possible targets.

Design and procedure

See Figure 2 for a schema of the sequence of events.

Each trial began with the onset of a fixation point in the center of the computer screen. One hundred three milliseconds following fixation onset, an exogenous cue appeared in one of the two possible target locations for 47 ms. This was followed by a 71-ms blank period. A target and two distractors then appeared in one of the two possible locations. In the valid condition, the target's location was the same as the cue; in the invalid condition, the target was in the opposite location as the cue. Each validity condition made up half of all trials and occurred at random. For distractor trials, the distractors appeared at a distance of 1–9 target widths. Each of these distractor spacings occurred for one tenth of the trials. For the remaining one tenth of the trials, no distractors were presented. All distractor-present and distractor-absent trials were intermixed. Target exposure duration was adjusted for each participant individually using a staircasing procedure (see timing procedure below), with a mean duration of 39 ms. Immediately after target offset, backward masks were presented over both the target and distractor locations for 325 ms. Then, a "?" probe appeared in the target location and remained on-screen until participants reported the orientation of the target with an unspeeded keypress. After each response, participants were given visual feedback

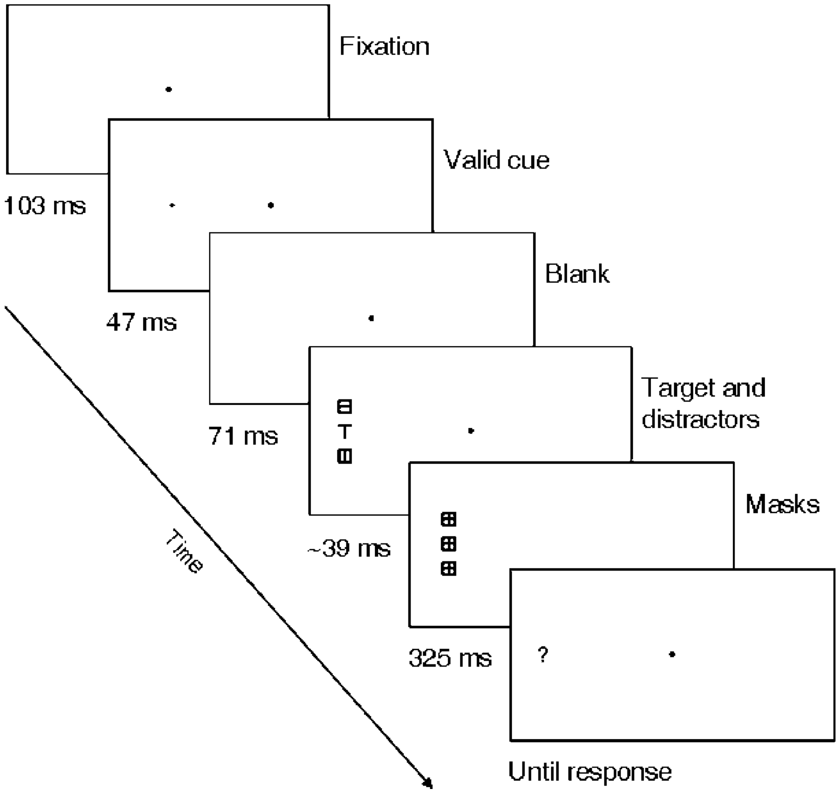

Figure 2. Sequence of events in a single trial of Experiment 1. A valid trial is displayed here, with distractors presented at a distance of 2 target widths. In the case of invalid trials, the target appeared on the opposite side of fixation as the cue.

regarding accuracy. Participants completed 400 trials of this task across two blocks.

Timing procedure. The time needed to discriminate these targets varied considerably between individuals. Therefore, exposure durations were adjusted for each participant in a staircased timing procedure prior to the experiment to equate task difficulty in one condition. This procedure included only valid distractor-absent trials. Exposure duration was adjusted on a trial-by-trial basis such that if a response was correct, the duration was reduced by 11.8 ms (1 monitor refresh rate cycle), and if the response was incorrect, duration was increased by 23.5 ms (2 refresh cycles). Participants completed two blocks of 40 trials each; additional blocks were included if needed to reach asymptote. All trials in the experiment were presented at the average duration of the last block of this procedure.

Results and discussion

One participant (out of 12) was removed from analyses because the data could not be modeled accurately (r = .26). A model was considered a poor fit if the correlation between the observed and predicted outcomes for either validity condition was greater than 1.5 *SD* below the mean Pearson's correlation coefficient value (r) and below an r value of .7. One other participant was removed because of low accuracy at each distractor spacing, including the valid distractor-absent condition for which duration was adjusted to equate performance (percentage correct was 50% in this condition).

To determine the critical spacing point, we modeled the observed values at each distractor spacing using an exponential function. This model was based on the following equation (see Figure 3 for a depiction of the model):

$$A \times (1 - 2.71828^{(-\mathrm{SF} \times (\mathrm{DS} - I))}), \tag{1}$$

where A is the asymptote, SF is the scaling factor, DS is the distractor spacing, and I is the x-intercept. The asymptotic value, scaling factor, and x-intercept were adjusted using the Microsoft Office Excel 2003 Solver function to determine the best fit for the data.

The inflection point of each prediction line was calculated as

$$I + \ln(1 - 0.90) / -\mathrm{SF} \tag{2}$$

so that inflection was defined as the distractor spacing at which accuracy achieved 90% of the asymptotic value. The value of this inflection point was our operational definition of critical spacing. Both the overall means and each individual's data were modeled using these equations.

The mean accuracies for each of the distractor spacings are presented in Figure 4 for both the valid and invalid trials, as well as the best fitting exponential model for each trial type. The model for the overall results fits the data very well for both conditions (valid: r = .97; invalid: r = .99). The inflection points for the mean accuracies are 5.53 in the valid condition and 5.93 in the invalid condition; the average inflection points from each of the individual models are 6.12 in the valid condition and 6.55 in the invalid condition. A matched-sample t test of the individual inflections in-

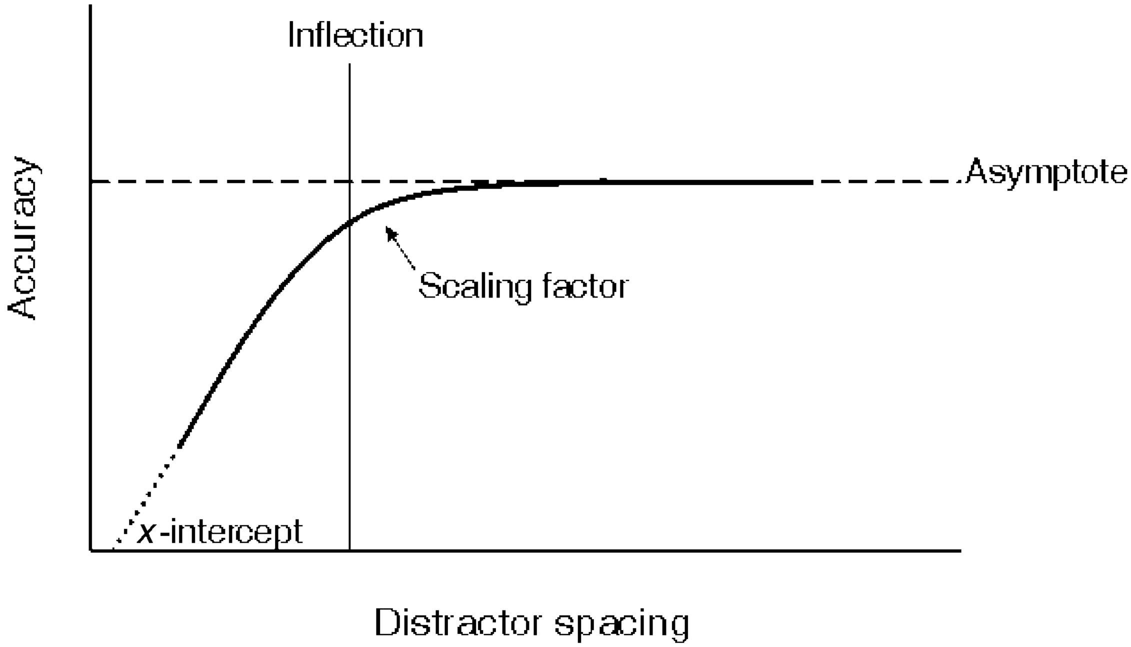

Figure 3. A schematic wherein each parameter of the exponential model is illustrated.

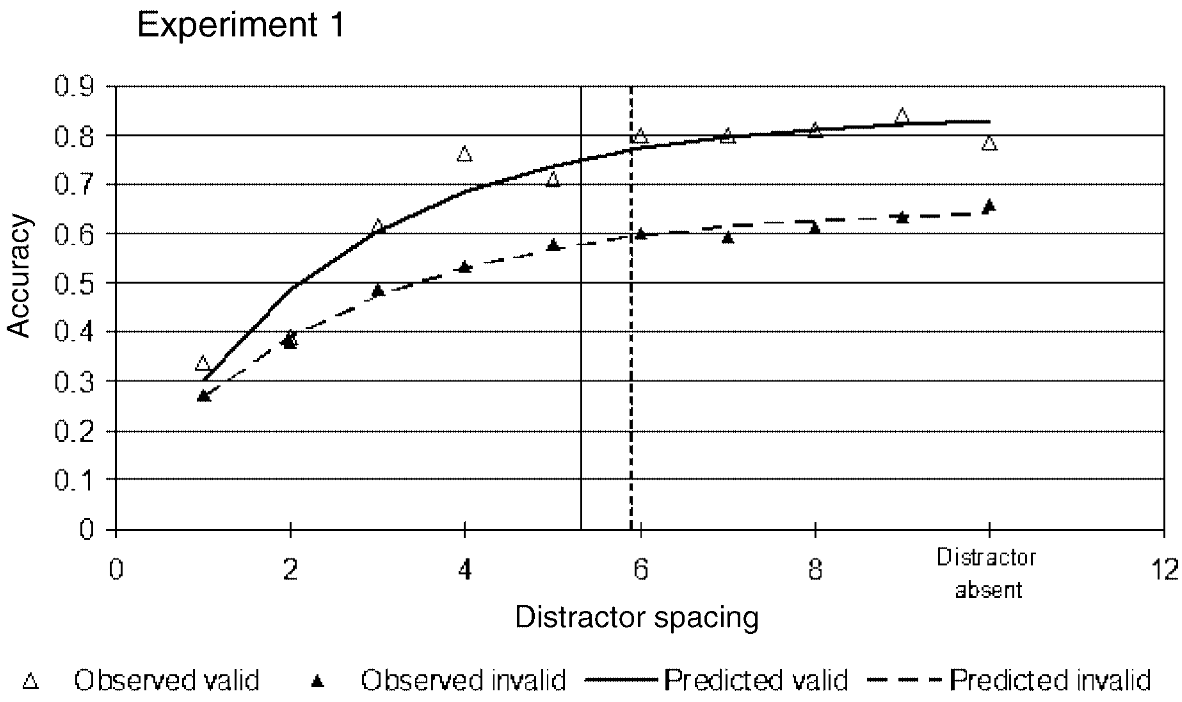

Figure 4. Observed and predicted mean accuracies based on the overall model at each distractor spacing for Experiment 1. The vertical lines indicate the critical spacing estimates for both the valid (solid line) and invalid (dashed line) conditions, as determined by the model of the means.

dicated no differences between the two validity conditions, $t(9) = 0.42$, $p = .68$. These results indicate that attention does not decrease critical spacing.

The overall predicted asymptotes for the valid and invalid conditions are 83% and 63%, respectively, which means that in the valid condition, accuracy reached 83% when distractors were effectively absent (i.e., no longer causing interference), whereas in the invalid condition, it reached only 63%. The average asymptotes of the individual models are 85% for valid trials and 65% for invalid trials. A matched-sample *t* test of the individual asymptotes resulted in significant differences between the two validity conditions, $t(9) = 4.56$, $p = .001$. These results suggest that attention influences target processing, even in the absence of distractors.

Experiment 2

The results of Experiment 1 indicate that attention does not reduce critical spacing. However, it is possible that the display did not produce strong-enough crowding effects to observe critical spacing differences. Pilot observations suggested that crowding effects could be enhanced by using oriented Is as distractors instead of orienting thetas. We reasoned that strengthening the crowding effect might provide greater sensitivity to modulations of this effect by attention.

Method

Participants

Eight students from the University of Oregon received partial course credit for their participation in a 1-hr session. Each participant had normal or corrected-to-normal vision.

Stimuli

The stimuli were the same as in Experiment 1, with the exception of the following changes.

The target luminance value was increased from approximately 83.6 to 91.4 cd/m^2, thus reducing its contrast against the white background.

Targets. Target eccentricity was reduced to 5 target widths, which resulted in shorter exposure durations. The mean duration was 27 ms.

Distractors. The distractors were letter Is, either upright or tilted 90°. These distractors are more similar to the target T and, thus, should increase crowding effects (see Figure 5).

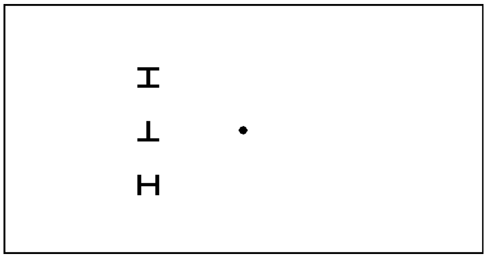

Figure 5. Target/distractor display for Experiment 2. Here, the distractors are presented at a distance of 2 target widths. See Figure 2 for an illustration of the sequence of events.

Design and procedure

The design and procedure were the same as those in Experiment 1, with the following changes.

For each distractor-present trial, distractors could appear at a distance of 1, 2, 3, 5, 7, or 9 spacings, each of which made up one seventh of the trials. The remaining trials were again distractor-absent. Participants completed this task in eight blocks of 56 trials each.

Timing procedure. The timing procedure was the same, except that all trials included distractors at a spacing of 9 target widths. This allowed participants an opportunity to get some experience with the distractors in displays with negligible interference. Participants completed two blocks of 40 trials each of this procedure.

Results and discussion

The mean accuracies for each of the distractor spacings are presented in Figure 6 for both the valid and invalid trials, as well as predicted accuracy outcomes for each of these trial types. The same modeling technique described in Experiment 1 was employed here, and predicted inflection and asymptote differences between validity conditions were tested.

Again, the overall model fits the data very well for both conditions (valid: r = .99; invalid: r = .95; see Figure 6). One participant (out of eight) was removed because the invalid condition could not be modeled (r = −.26). Although the individual models fit each participant's data from the valid condition (mean r = .91), the models did not provide a good fit for the invalid condition (mean r = .60; range = .18–.92). This improper fit is likely due to the difficulty of the task for invalid trials. Indeed, many participants' accuracies are consistently low across all spacings. Thus, it may be that the exponential function was not optimal in this study. However, as Figure 6 makes apparent, the deviations from the exponential model in the invalid condition of Experiment 2 do not indicate an increase in critical spacing. Thus, Experiment 2 still falls in line with the other studies in arguing against an influence of attention on critical spacing.

The inflection points for the overall graph are 5.12 in the valid condition and 2.88 in the invalid condition; the average inflection points from each of the individual models are 5.88

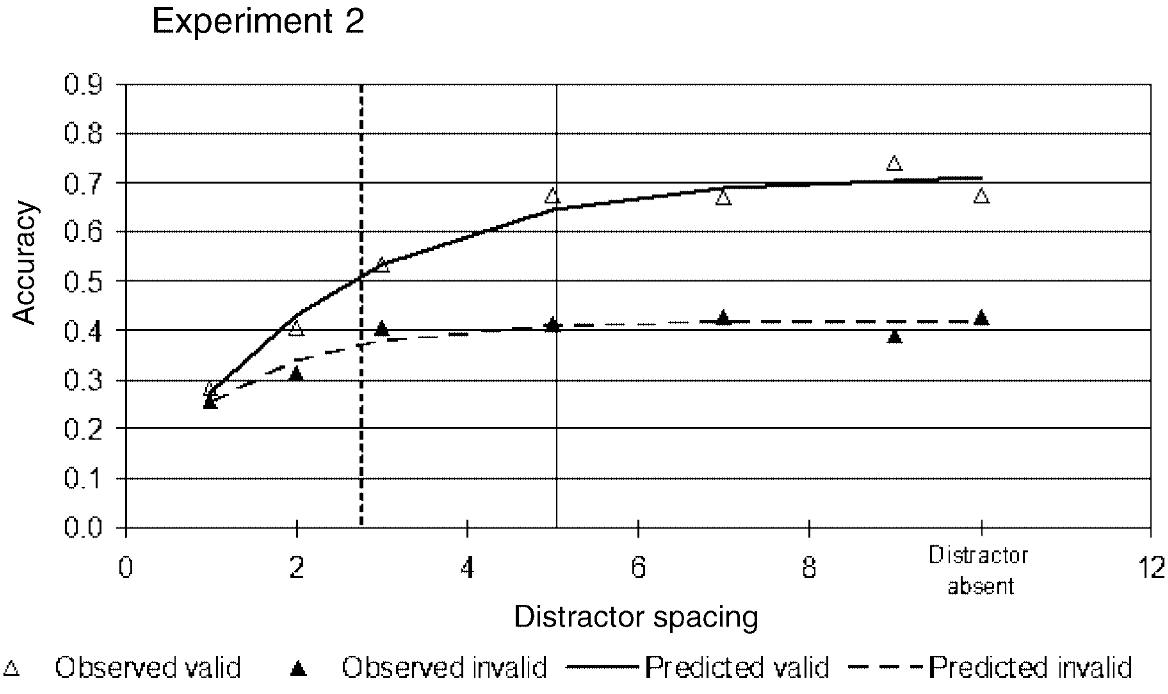

Figure 6. Observed and predicted mean accuracies based on the overall model at each distractor spacing for Experiment 2. The vertical lines indicate the critical spacing estimates for both the valid (solid line) and invalid (dashed line) conditions, as determined by the model of the means.

in the valid condition and 3.66 in the invalid condition. A matched-sample *t* test of the individual inflections indicated no differences between the two validity conditions, *t*(6) = 1.34, *p* = .23.

The overall predicted asymptotes for the valid and invalid conditions are 72% and 42%, respectively. The average asymptotes of the individual models are 73% for valid trials and 44% for invalid trials. A matched-sample *t* test of the individual asymptotes resulted in significant differences between the two validity conditions, *t*(6) = 4.76, *p* = .003. Therefore, attended targets were more accurately identified than those that were unattended, even when distractors were effectively absent.

Experiment 3

We were concerned that the previous experiment produced large attention effects that may have obscured our ability to measure critical spacing in the invalid condition. Our concern was that such large attention effects might prevent crowding from being the limiting factor for performance in the invalid condition. Thus, this experiment compared valid cueing to neutral cueing. In a neutral-cue trial, both possible target locations are cued, and thus, attention should be diffused across both locations instead of focusing on the incorrect location, as is the case with invalid cues.

Method

Participants

Fourteen students from the University of Oregon received partial course credit for their participation in a 1-hr session. Each participant had normal or corrected-to-normal vision.

Stimuli

The stimuli were the same as those in the previous experiment. We reduced the display contrast by setting the luminance to approximately 94.3 cd/m^2, decreasing target contrast, and, thus, increasing exposure durations (*M* = 36 ms).

Masks. We were concerned that the windowpane masks were causing more impairment than was intended and potentially eliminating any attentional benefits on critical spacing. Therefore, all stimuli were masked with open squares.

Design and procedure

The design and procedure were the same as those in Experiment 2, with the exception of cueing; in this exper-

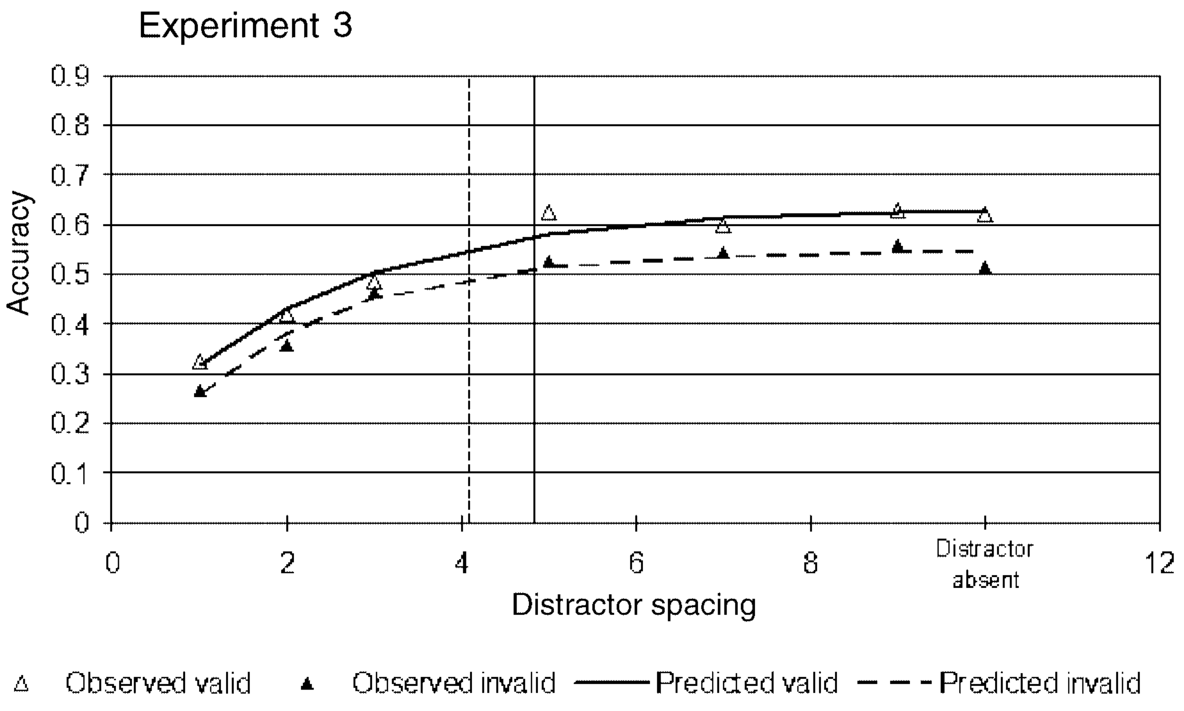

Figure 7. Observed and predicted mean accuracies based on the overall model at each distractor spacing for Experiment 3. The vertical lines indicate the critical spacing estimates for both the valid (solid line) and invalid (dashed line) conditions, as determined by the model of the means.

iment, we used valid and neutral cueing, where both possible target locations were precued.

Results and discussion

Two participants (out of 14) in Experiment 3 were removed from analysis for this reason (r = .5 and .4, respectively). The predicted model fits the mean data very well for both the valid (r = .99) and the neutral (r = .99) conditions (see Figure 7). This was true of the individual models as well (valid: mean r = .91; neutral: mean r = .82).

Inflection points for the overall model in the valid and neutral conditions are 4.85 and 4.09, respectively, and for the individual estimates, the average inflections are 6.0 and 4.95, respectively. These estimates are in the opposite pattern as the hypothesis; this indicates that critical spacing is smaller in the neutral condition than in the valid condition. However, the differences between these estimates were not significant, $t(11) = 0.83$, $p = .43$. The asymptotes for each condition differed in the overall model such that in the valid condition, predicted accuracy reached 64%, whereas accuracy in the neutral condition reached 55%. These differences were reflected in the individual models as well, with a mean accuracy of 67% and 58%, respectively, $t(11) = 3.05$, $p = .01$.

As in the previous experiment, the critical spacing effect is reversed; that is, the estimated distractor distance is shorter with neutral cueing than with valid cueing.

Experiment 4

The current experiment employed valid and invalid cues, as in the first two experiments. In this experiment, instead of equating difficulty via adjusting exposure duration, we adjusted display luminance in a staircased fading procedure. This would allow us to generalize our results to a broader set of situations.

Method

Participants

Twenty-seven members of the University of Oregon Community participated in a 1-hr to 1-hr 40-min session, for which they were either paid or received partial course credit. Each participant had normal or corrected-to-normal vision.

Stimuli

The stimuli were the same as those in the previous experiment with the exception of the following changes.

All stimuli were presented on a dark gray background. Due to the fading staircase procedure, the target luminance varied between participants ($M = 5.82$ cd/m^2).

Targets. Target eccentricity was 10 target widths, as it was in Experiment 1. The exposure duration was set to 82 ms.

Distractors. Distractors were oriented thetas, as in Experiment 1.

Masks. Only the targets were masked with windowpanes (as in Experiments 1 and 2).

Design and procedure

The design and procedure were the same as those in Experiment 3, with the following changes.

The cue was moved in toward fixation so that it did not appear in the same location as the target to prevent any possible forward masking. For the distractor-present trials, distractors could appear at a distance of 1, 2, 3, 5, 7, 9, 11, 13, or 15 spacings, each of which was equally likely to occur during the experiment. The remaining trials were free of distractors. Thirteen participants completed this task in 12 blocks of 40 trials each. The remaining 14 participants were given an additional 13 blocks to increase the number of observations per condition and, therefore, reduce any noise in the data.

Fading procedure. The luminance value of the target display was adjusted with accuracy in the staircased fading procedure. If a response was correct, the luminance value of the display would be reduced by 8%, thus making it more difficult to see against the gray background. If a response was incorrect, the display luminance was increased by 16%. During this procedure, only valid distractor-absent trials were presented.

Results and discussion

In this experiment, 4 participants (out of 27) were removed: 1 due to poor fit (r = .65), 1 for low accuracy in the valid distractor-absent condition (percentage correct = 46%), and 2 for not completing the experiment. The predicted model fits the mean data very well for both the valid (r = .99) and the invalid (r = .99) conditions (see Figure 8). This was true of the individual models as well (valid: mean r = .9; invalid: mean r = .91).

Inflection points for the overall model in the valid and invalid conditions were 6.03 and 6.65, respectively, and for the individual estimates, the average inflections were 4.85 and 5.23, respectively. A t test of the individual estimates revealed that the differences between the points of inflection were not significantly different, $t(22) = 0.69$, $p = .5$. Consistent with the previous three findings, attention did not reduce critical spacing.

The asymptotes for each validity condition differed in the overall model such that in the valid condition, predicted accuracy reached 78%, whereas accuracy in the invalid condition reached 74%. These differences were reflected in the individual models as well, with a mean accuracy of 79% and 75%, respectively, $t(22) = 3.36$, $p = .003$. This is the smallest attention effect of the four

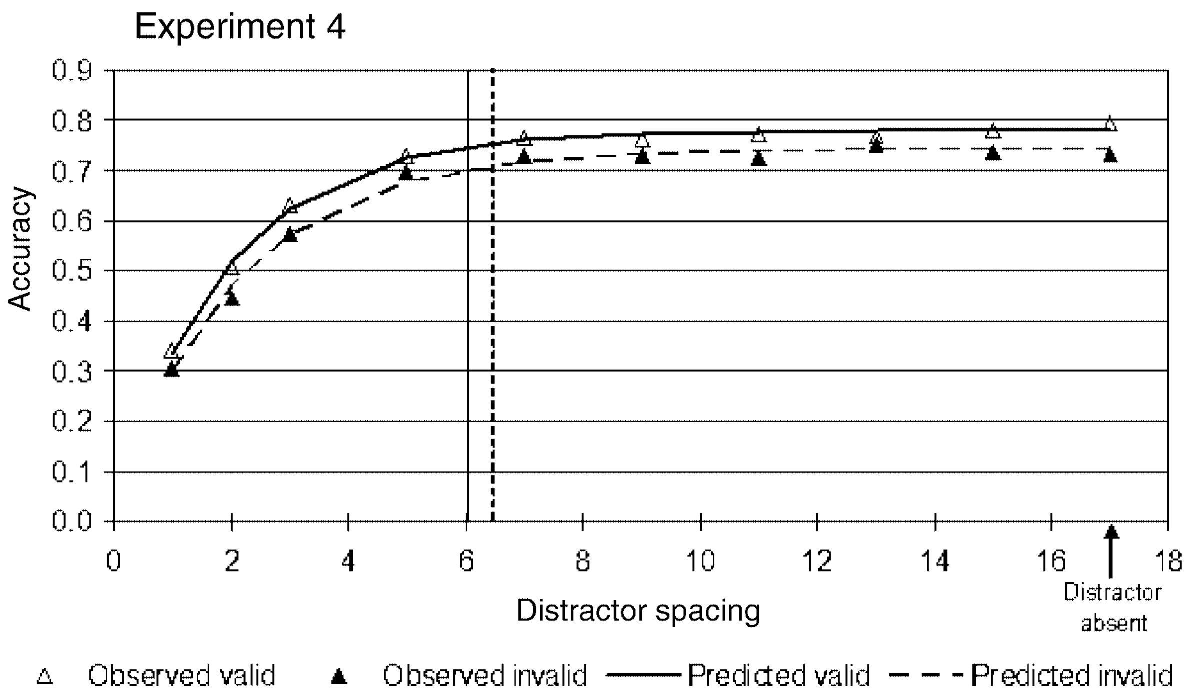

Figure 8. Observed and predicted mean accuracies based on the overall model at each distractor spacing for Experiment 4. The vertical lines indicate the critical spacing estimates for both the valid (solid line) and invalid (dashed line) conditions, as determined by the model of the means.

experiments described thus far, but the effect is still significant nonetheless. As in the previous experiments, attention is influencing target identification, even when the distractors are effectively absent.

Conclusions for Experiments 1–4

For each of the experiments, the model for the overall results fits the data very well for both conditions; the correlation between observed and predicted outcomes did not fall below an r value of .9 at any time; in fact, in all five studies, at least one validity condition reached a value of .99. The individual models generally resulted in strong correlations as well; however, in Experiment 2, the models did not provide a good fit for the invalid condition (mean r = .50; range = .18–.92). This improper fit is likely due to the difficulty of the task for invalid trials. This was made evident by the participants' consistently low accuracies across all spacings in the invalid condition. Thus, it may be that, in this study, the exponential model was not optimal. However, as Figure 6 makes apparent, the deviations from the exponential model in the invalid condition of Experiment 2 do not indicate an increase in critical spacing. Thus, Experiment 2 still falls in line with the other studies in arguing against an influence of attention on critical spacing.

We compared asymptotic values for the valid and invalid condition and found that the valid condition consistently reached a higher accuracy than did the other condition (see Table 1). This means that performance was better when the target location was cued even when distractors were effectively absent (i.e., no longer causing interference). The fact

	Valid	Invalid	*t* value	*df*	*p* value
Experiment 1	**83** (85)	**63** (65)	4.56	9	.001
Experiment 2	**72** (73)	**42** (44)	4.76	6	.003
Experiment 3	**64** (67)	**55** (58)	3.05	11	.01
Experiment 4	**78** (79)	**74** (75)	3.36	22	.003

Table 1. Asymptote estimates in percentage correct. Values in boldface were provided by the overall models. Values within the parentheses are the average of the individual estimates. Recall that Experiment 3 used neutral rather than invalid cues.

	Valid	Invalid	*t* value	*df*	*p* value
Experiment 1	**5.53** (6.12)	**5.93** (6.55)	0.42	9	.68
Experiment 2	**5.12** (5.88)	**2.88** (3.66)	1.34	6	.23
Experiment 3	**4.85** (6.0)	**4.09** (4.95)	0.83	11	.43
Experiment 4	**6.03** (4.85)	**6.65** (5.23)	0.69	22	.50

Table 2. Critical spacing in target widths. Values in boldface were provided by the overall models. Values within the parentheses are the average of the individual estimates. Recall that Experiment 3 used neutral rather than invalid cues.

that attention facilitated processing even in the absence of crowding suggests that at least part of the cueing effects here were due to signal enhancement (Carrasco et al., 2000; Cheal & Gregory, 1997; Eriksen & Hoffman, 1974; Luck et al., 1996) and not to distractor exclusion, given that the latter process will have no influence when there are no distractors to exclude.

The inflection points for each of the experiments are presented in Table 2. In every case, critical spacing estimates were not statistically different in the attended and unattended conditions. This suggests that stimulus-driven attention does not reduce critical spacing. It may be the case that while attention does facilitate processing in crowded displays, it does not do so by the direct suppression of distractor representations (see also Awh et al., 2005). Attention may instead impact the target representations, which would be consistent with signal enhancement theory as noted above.

The results of the four studies are consistent with one another, despite the several adjustments that were made to the paradigm from one experiment to the next. Experiment 1 resulted in a large attention effect at each distractor spacing, as well as a significant difference between asymptotic values for each validity condition. However, the critical spacing estimates did not differ. In Experiment 2, we reduced target contrast and increased target–distractor similarity to strengthen crowding effects, which, again, produced attention effects even at asymptote, but there was still no effect of attention on critical spacing. Experiment 3 compared valid and neutral cueing conditions to address the concern that crowding may not have been the limiting factor in the invalid condition of Experiment 2. Although this produced better fits of the individual models, the results concurred with those of the previous experiments. Finally, in Experiment 4, target discrimination was controlled by changes in luminance instead of exposure duration, which allowed us to generalize our results to a broader range of conditions. In all cases, attention did not influence critical spacing.

We arrived at the same conclusions regardless of the target eccentricity (i.e., 5 or 10 target widths), stimulus similarity, display contrast, and types of masks (i.e., windowpanes or open squares). With each of the aforementioned changes, we consistently found a significant attention effect (see asymptote results below), which ranged in size between 4% and 30%. Despite this large range of attention effects and display conditions, critical spacing remained unaffected by attention. We have therefore verified the null result across a broad range of conditions.

Summary of spatial cueing studies

Previous research has shown that attention facilitates target processing in crowded displays (Awh et al., 2003; Dosher & Lu, 2000, Kastner et al., 1998; Shiu & Pashler, 1994). However, no experiments prior to the current research had examined whether attention could reduce the necessary distance between targets and distractors in order for the distractors to impede processing. Other studies had examined the role of attention in peripherally presented crowded displays (Nazir, 1992; Strasburger, 2005; Wilkinson et al., 1997), but these studies were limited in their ability to assess critical spacing because they either (a) used a measure that failed to produce a spatial cueing effect at all (despite the strong empirical support of such an effect) or (b) did not include a wide enough set of distractor spacings to accurately determine critical spacing. The goal of the current set of experiments was to develop a paradigm that addressed these limitations and, therefore, could accurately assess any possible critical spacing differences between attended and unattended targets.

Each of the four experiments is consistent with previous studies of spatial cueing, in that attended targets were more easily identified than those that were unattended. Therefore, our paradigms have successfully overcome the first limitation, in that our measures were able to produce spatial cueing effects. The effect occurred at all distractor spacings, as shown in each of the plots. In addition, we included a large range of distractor spacings in each of the five experiments, which allowed a clear estimate of the inflection point that defines critical spacing. Thus, these studies also address the second limitation of the previous work. Nevertheless, critical spacing did not reliably differ between the attended and unattended conditions in any of the four experiments. Apparently, stimulus-driven attention does not reduce critical spacing.

Some have suggested that crowding is intimately related to the construct of attention, in that the spatial extent of the interactions between targets and distractors may be determined by the spatial resolution of attention (e.g., Intriligator & Cavanagh, 2001). By this view, closely grouped targets and distractors lead to impaired target discrimination because the resolution of attention is too coarse to disambiguate the relevant and irrelevant elements in the scene. This perspective operationalizes “attention” solely in terms of the degree to which target and distractor interactions can be observed. One important question, therefore, is whether this definition of attention refers to the same process that drives the spatial cueing effects in the present studies. We operationalized attention in terms of improved target discrimination at the attended locations relative to the unattended locations. Our results suggest that these attentional modulations of target discrimination had little influence on critical spacing. Thus, attentional resolution as defined by the spatial extent of crowding may refer to a kind of "attention" that is entirely different from the stimulus-driven shifts of "attention" that we observed in these studies.

Distractor preview studies

The following experiments were designed to explore whether presenting the crowding distractors prior to the onset of the target, referred to here as distractor preview, reduces critical spacing. Previous literature has shown that this manipulation facilitates processing in crowded displays (Huckauf & Heller, 2004), although the mechanism by which this occurs is unknown. Watson and Humphreys (1997) postulated that previewed distractors are inhibited via visual marking in cases of visual search, and this mechanism may be involved in crowding as well. It is also possible that in crowded displays, advanced distractor information prevents observers from completing unnecessary texture analysis, in which targets and distractors are integrated together (Parkes et al., 2001). In either case, it is plausible that when distractors are previewed, critical spacing will be reduced.

The following two studies were designed to test this issue. In Experiment 5, both distractor presentation and spatial cueing were manipulated. It was designed using a paradigm similar to the spatial cueing studies, in which displays were luminance limited and accuracy was the dependent measure. In Experiment 6, only distractor presentation was manipulated and we employed exposure duration as a new dependent measure because it elicited more stable patterns of performance as distractor spacing changed. The use of two different measures allows us to generalize our results to a broader set of situations.

Experiment 5

To test the possibility that preview reduces critical spacing, we used a paradigm similar to that of Experiment 4, but in this case, the distractors appeared prior to target onset (i.e., distractor preview). Because the main difference between this experiment and Experiment 4 was the distractor presentation manipulation (in Experiment 4, target and distractor onset occurred simultaneously), we made a between-groups comparison between these two studies.

Method

Participants

Fourteen participants completed a 1-hr session of this experiment, for which they were given partial course credit. All participants had normal or corrected-to-normal vision.

Stimuli

The stimuli were the same as those used in Experiment 4.

Design and procedure

The design was similar to that of Experiment 4, with the key difference being that, here, the distractors were previewed in the distractor-present trials. In these trials, the distractors appeared along with fixation at both possible target locations. This prevented the distractors from cueing participants to the eventual target location. Because critical spacing estimates in the previous experiment were approximately one third the distance of the largest distractor spacing, we chose to reduce the range here. Therefore, distractors were presented at 1 to 9 spacings or not at all, and these trials were intermixed. Participants completed 12 blocks of 40 trials each of this task.

Fading procedure. As in Experiment 4, the luminance of the display was adjusted on a trial-by-trial basis according to each participant's performance. Only distractor-absent trials were presented; hence, there was no distractor presentation manipulation.

Results and discussion

Three participants (out of 14) were removed from the analyses because at least one condition was poorly fit (r = .59, .25, and −.01). The overall model fits the means well (valid: r = .98; invalid: r = .99). This was true of the average of the individual models also (valid: r = .86; invalid: r = .87). The mean exposure duration for each distractor spacing is presented in Figure 9 for both distractor presentation conditions, as well as the associated exponential models.

The overall modeled data resulted in asymptotic values of 81% (with a mean of 82% for the individual models) in the valid condition and 74% (with a mean of 75% for the individual models) in the invalid condition, $t(10) = 2.80$, $p = .02$, thus replicating the attention effects of the previous studies. The inflection points based on the overall model were 1.82 (mean of individual models = 1.92) for valid and 1.90 (mean of individual models = 2.80) for invalid. As in the previous experiments, this difference was not significant, $t(10) = 1.27$, $p = .23$. This again replicates the spatial cueing findings; while attention does improve performance in crowded displays, it does not do so by reducing critical spacing (see Figure 9).

Interestingly, the inflections obtained from this study were much lower than those in Experiment 4, the main difference between the two studies being that, in the latter, stimuli were presented simultaneously. Recall that, in Experiment 4, the critical spacing points were 5.91 (mean of individual models = 4.74) in the valid condition and 6.56 (mean of individual models = 5.12) in the invalid condition, whereas, here, critical spacing is estimated to be around 2. We compared these differences across the experiments using a two-

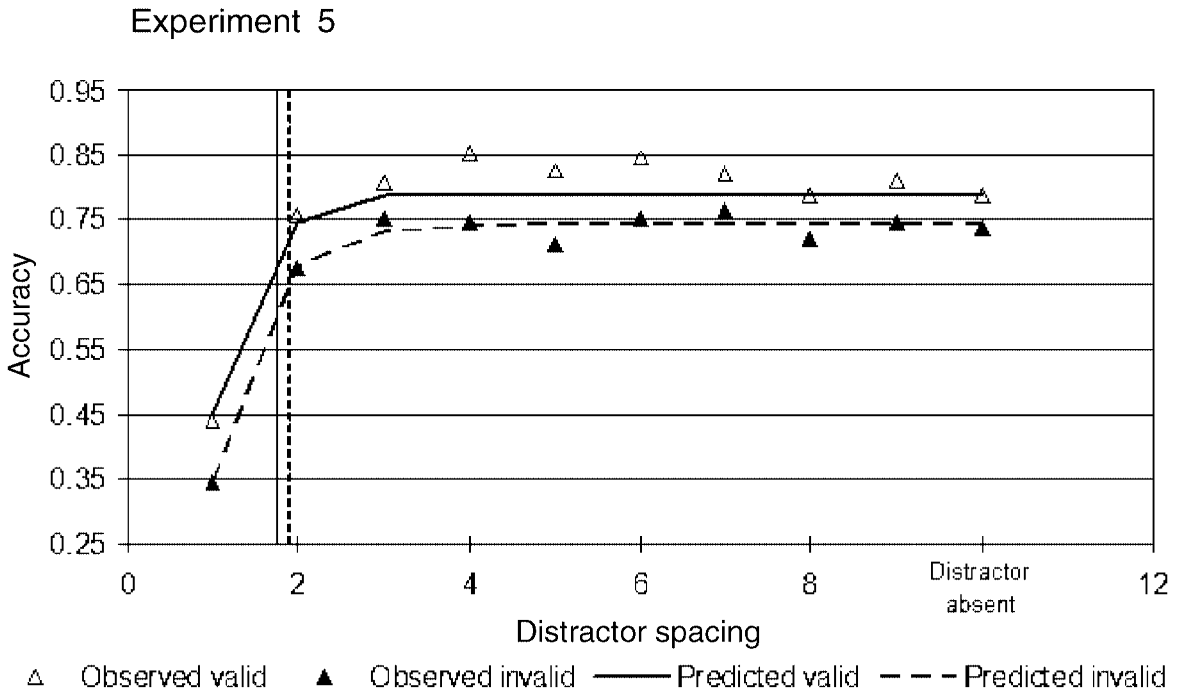

Figure 9. The observed and predicted mean accuracies at each distractor spacing in Experiment 5. The vertical lines indicate the critical spacing estimates for both the valid (solid line) and invalid (dashed line) conditions, as determined by the model of the means.

sample *t* test, assuming unequal variance and an α level of .008 based on the Bonferroni correction, which resulted in significant differences between the simultaneous-valid and preview-valid conditions, $t(30) = 5.10$, $p < .001$, and between both invalid conditions, $t(19) = 2.97$, $p = .004$. This suggests that when distractors are previewed, they must be closer to the target to cause interference. It is important to note that the distractors in Experiment 4 ranged across a greater distance than did those in this experiment, and this could have influenced the critical spacing differences. Furthermore, this study is a between-subjects comparison, and a within-subjects design would provide a more robust assessment.

Experiment 6

The results of Experiment 5 indicate that when distractors are previewed, critical spacing is reduced. This experiment was designed to replicate those results using a within-subjects design and with a somewhat different paradigm. In this case, we removed the spatial cueing manipulation and only manipulated distractor presentation. In addition, we moved to a new dependent measure in which we determined the exposure duration that observers required to achieve 70% accuracy at each distractor spacing. This measure provided more stable estimates of performance as distractor spacing changed, which enhanced our ability to model the data of individual participants.

Method

Participants

Twelve members of the University of Oregon community, including one of the authors, participated in a 60- to 90-min session, for which they received monetary compensation. All participants had normal or corrected-to-normal vision.

Stimuli

The stimuli were the same as those in Experiment 3. Because the presentation of the distractors in the preview condition may have reduced spatial uncertainty (i.e., the target always appeared directly in between the distractors), the eventual position of each distractor was indicated by four small dots in the simultaneous condition.

Design and procedure

See Figure 10 for a schema of the sequence of events. Each trial began with the onset of a fixation point in the center of the computer screen, which remained on-screen for the duration of each trial, except during the masks. In the preview condition, the distractors appeared with fixation on

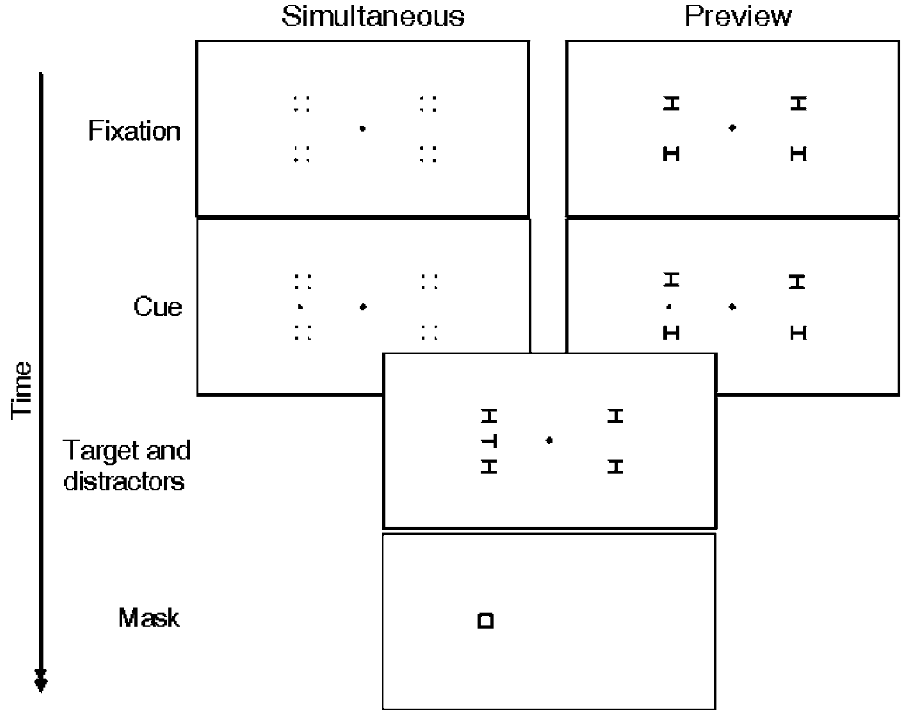

Figure 10. The sequence of events in the simultaneous and preview trials. A simultaneous trial is presented on the left. In this case, the eventual distractor locations were highlighted during fixation and cue, after which the distractors and target appeared together. A preview trial is presented on the right. In this case, the distractors appeared with fixation and remained on-screen until target offset. In both conditions, only the target location was masked.

both sides and remained on-screen until target offset. This prevented the distractors from cueing participants to the eventual target location. In the simultaneous condition, all four distractor locations were highlighted upon fixation onset and remained on-screen until target onset. One hundred fifty milliseconds following fixation onset, a brief valid cue flashed to indicate the location of the upcoming target (50 ms). The target appeared 67 ms following the cue, and in the simultaneous condition, the distractors appeared as well on both sides of fixation. Backward masks were then presented in the target location for 325 ms, followed by a "?" probe, which remained on-screen until participants reported the orientation of the target with an unspeeded keypress. After each response, participants were given visual feedback regarding accuracy.

The experiment consisted of two parts for each distractor presentation condition. Participants completed both parts for one condition before beginning the other, and the order of conditions was counterbalanced across participants. The first part included displays in which distractors only appeared at a spacing of 1 target width (i.e., adjacent to target). Exposure duration was adjusted on a trial-by-trial basis such that if a response was correct, the duration was reduced by 8.33 ms (1 monitor refresh rate cycle), and if the response was incorrect, duration was increased by 16.66 ms (2 refresh cycles). Participants completed two blocks of 40 trials each; additional blocks were included if needed to reach asymptote.

For the second part of the experiment, distractors appeared in a blocked design at a spacing of 2, 3, 5, 7, and 9 target widths, in that order. The initial target duration for each distractor spacing was set to the average value of the last block in Part 1. Duration was then adjusted on a trial-by-trial basis in the same manner as described above. Participants completed 48 trials for each distractor spacing, for a total of 240 trials across five blocks. The two parts were then repeated for the remaining distractor presentation condition.

Results and discussion

One participant (out of 12) was removed because she did not reach asymptote in the simultaneous condition. Therefore, the analyses were performed with data from 11 participants.

The mean exposure duration for each distractor spacing is presented in Figure 11 for both distractor presentation conditions, as well as the predicted outcomes. As in the previous experiments, we modeled the data using an exponential function and the Microsoft Office Excel 2003 Solver function to find the best fit. We used an approach similar to the previous studies; in this case, the data were modeled with a decreasing exponential function as exposure durations decreased with an increase in distractor distance.

The predicted model fits the observed data very well (preview: $r = .99$; simultaneous: $r = .99$). The mean correlation for the individual models is somewhat low for the preview

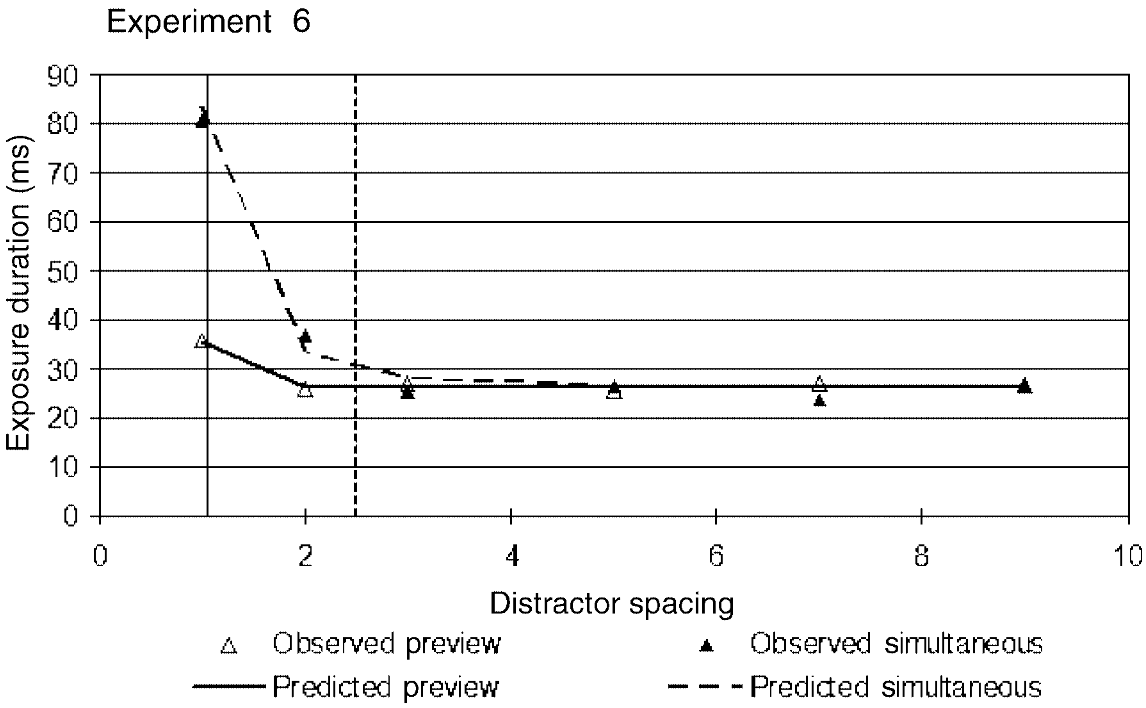

Figure 11. Observed and predicted mean durations at each distractor spacing for Experiment 6. The vertical lines indicate the critical spacing estimates for both the preview (solid line) and simultaneous (dashed line) conditions, as determined by the model of the means.

condition (r = .73) but remained high in the simultaneous condition (r = .98). Upon inspection of the individual exposure duration estimates in the preview condition, we see that for several participants, the durations were fairly consistent across all six distractor spacings. Because these lines are relatively flat, they are not easily modeled using an exponential function. Thus, the predicted outcomes are not as highly correlated with the observed data as they are in the simultaneous condition. Despite these lower correlations, however, we are confident in the inflection and asymptote values produced by the model (more on this below).

As evidenced in Figure 11, preview required shorter exposure durations than did simultaneous presentation for the spacings prior to asymptote (i.e., within critical spacing). The distractors are the only manipulated factor in this experiment; the displays are identical in all other aspects. Thus, once distractors are effectively absent (i.e., once asymptote is reached), the two displays are the same, and here, performance should be equivalent as well. Asymptotes were locked in both the overall model and in each of the individual parameter estimates to model this assumption. Durations for both conditions were matched at asymptote (overall model: duration = 26 ms; mean of individual models: duration = 25 ms). The question of interest is whether this distance is closer to the target in the distractor preview condition.

Based on the overall model, the inflection point for the preview condition was 1.08 spacings (mean of individual models = 1.81), and for the simultaneous condition, it was 2.67 spacings (mean of individual models = 3.0), $t(10) = 2.26$, $p = .02$. Due to the low correlations found in the individual parameter estimates in the preview condition, we decided to analyze critical spacing using a second approach. We examined the exposure duration differences between adjacent distractor distances, where the last significant difference would provide a critical spacing range. In the preview condition, there was a significant difference between the first and second spacings, $t(10) = 4.63$, $p < .001$ (the α levels were set to .01 based on the Bonferroni correction), but this difference disappeared between the second and third spacings, $t(10) = 0.89$, $p = .39$. Each subsequent paired comparison found nonsignificant differences as well. Based on these analyses, critical spacing in the preview condition should occur somewhere between Spacings 1 and 2. In the simultaneous condition, significant differences existed between Spacings 1 and 2, $t(10) = 6.29$, $p < .001$, and between Spacings 2 and 3, $t(10) = 4.84$, $p < .001$, but not between Spacings 3 and 5, $t(10) = 0.63$, $p = .54$. Again, each subsequent paired comparisons were also insignificant. This suggests that in the simultaneous condition, critical spacing occurs between Spacings 2 and 3. These results are consistent with the estimates produced by the model. Thus, we replicated our initial finding that critical spacing is reduced when the distractors are presented prior to target onset.

Distractors surrounded both possible target locations in both the preview and simultaneous conditions. This means that at target onset, in the preview condition, only the target flashed in the target location, but in the simultaneous condition, stimuli flashed at both locations, thus potentially causing different attentional manipulations between the two conditions. However, this is not likely because the target location was always precued. Thus, attention would have already been allocated to the target location prior to target onset.

Summary of distractor preview studies

We know from previous literature that, like spatial cueing, distractor preview facilitates processing in crowded displays (Huckauf & Heller, 2004), although a definitive test of whether critical spacing is influenced had not been carried out. The results were consistent across two different procedures, indicating that preview displays effectively reduced critical spacing. In fact, the results resemble the hypothetical situation presented in Figure 1C. These findings suggest that preview minimizes target–distractor interactions so that distractors can appear closer to previewed targets before the emergence of crowding effects.

The results from these two experiments are encouraging because we were able to find a factor that does reduce critical spacing using a paradigm similar to that used in the attention experiments. This gives us greater confidence in the null results found for spatial cueing. Furthermore, this provides clear evidence that critical spacing can change when advanced distractor information is provided. This suggests that there is a qualitative difference in the way that attention and distractor preview overcome crowding effects.

Popout studies

Previous research has shown that when distractors and targets differ on a salient feature, target identification is improved (Felisberti et al., 2005; Kooi et al., 1994; Pelli et al., 2004). Because the popout effect facilitates processing in crowded displays, we suspected that it may influence critical spacing as well. Therefore, the following experiments were designed to determine whether critical spacing is reduced when targets and distractors differ based on color. Experiment 8 was designed to be similar to the attention experiments, where we used accuracy as the dependent measure. As was the case in several of the previous experiments, each participant completed a fading procedure, thereby producing luminance-limited displays in the experiment. Experiment 8 was designed similar to Experiment 7, where exposure duration was the dependent measure, and therefore, duration was adjusted via a timing procedure.

Experiment 7

To test the possibility that popout displays reduce critical spacing, we measured critical spacing when targets and distractors were presented either in the same color or in different colors from one another.

Method

Participants

Ten members of the University of Oregon community participated in a 1-hr session of this experiment, for which they received monetary compensation. All participants had normal or corrected-to-normal vision.

Stimuli

The display was very close to that of Experiment 4. The target color (either red or green for each participant, counterbalanced across participants) was adjusted via luminance for each participant during a fading procedure (mean luminance for red = 0.21 cd/m^2; mean luminance for green = 0.11 cd/m^2). Distractors were randomly colored red or green during the experimental procedure. When distractors appeared in the same color as the target (i.e., non-popout trial), they were presented in the same luminance as the target. For popout trials, the distractor color was measured using a photometer to determine a luminance value that would maintain a similar contrast for both target and distractors against the gray background.

Targets. As in the previous experiments, the targets were rotated Ts. One target appeared for each trial.

Distractors. The distractors were rotated Is in the same font as the targets. Two distractors appeared with the target, one below and one above.

Masks. Windowpanes were used as backward masks, which masked the full display. They were presented in the same color and luminance as the target.

Design and procedure

The sequence of events for each trial was similar to that of Experiments 4 and 5 (but see Figure 12); however, there was no validity manipulation here. For all trials, both possible target locations were cued. For half of the participants,

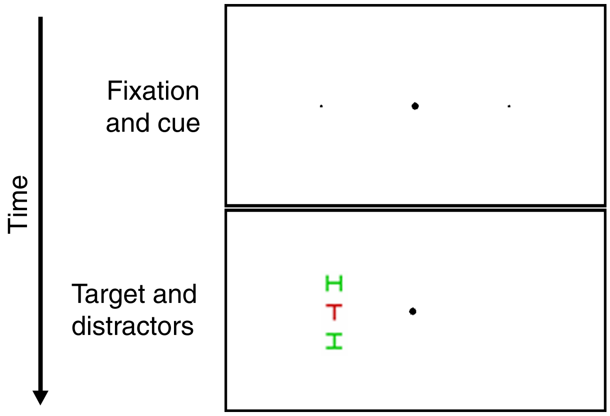

Figure 12. Sequence of events in a single trial of Experiment 7. A popout trial is depicted here, with distractors at a spacing of 2 target widths. For non-popout trials, the distractors and target were colored the same. Both possible target locations were cued, and the target appeared in one of the cued locations.

targets were only colored green, and for the other half, targets were only colored red. The possible distractor distances were the same as those used in Experiments 4, 5, and 6.

Fading procedure. The fading procedure was similar to that of Experiments 4 and 5. Only validly cued distractor-absent trials were presented. As in the experiment, participants only saw targets in one of the two colors in all trials. The color used in this procedure was subsequently used in the rest of the experiment.

Results and discussion

One participant (out of 10) was removed because of experimenter error. Therefore, 9 participants are included in the analyses. The mean exposure duration for each distractor spacing is presented in Figure 13 for both distractor presentation conditions, as well as the predicted outcomes. As evidenced by the graph, we are getting a strong popout effect at distractor distances of 2, 3, and 5, where accuracy is between 10% and 20% higher in the popout condition. The predicted model fits the overall observed data quite well for both the popout (r = .97) and non-popout (r = .99) conditions (see Figure 13). The individual's parameter estimates also fit each participant's observed data well (popout: mean r = .84; non-popout: mean r = .91).

As was the case with distractor preview, the distractors are the only manipulated factor in this experiment; the displays are identical in all other aspects, and thus, performance should be equal once distractors are effectively absent. Thus, asymptotes were locked in both the overall model and in each of the individual parameter estimates as they were in Experiment 6. The overall model reached asymptote at 81% in both conditions. The average asymptotic value for the individual models was 82%.

The key question is whether the two display types differed in critical spacing. Inflection points for the overall model in the popout and non-popout conditions were 4.38 and 7.80, respectively, and for the individual estimates, the average inflections are 5.82 and 9.65, respectively. These differences were significant, $t(8) = 2.65$, $p = .03$. Therefore, the popout displays did reduce critical spacing.

It is the case that when target saliency is high, attention may be captured to its location. Thus, popout displays may allow for a faster allocation of attention than non-popout displays, which means that attentional manipulations may be responsible for these critical spacing differences. Because we used a neutral cue, we cannot rule out this possibility. Therefore, in Experiment 8, we presented targets in both possible locations on every trial to ensure that attention was dispersed across the display.

Experiment 8

The results of Experiment 7 show that when the distractors were colored differently than the target, critical spacing was reduced. The current experiment was designed to replicate these results using a different display that two of the authors had designed for an unrelated study. In previous research, this display had produced larger popout effects than that used in Experiment 7. Furthermore, this display prevents possible unintended attentional manipulations. As in Experiment 6, we used exposure duration as the dependent measure instead of accuracy because it has been more stable in other studies.

Method

Participants

Nine members of the University of Oregon community participated in a 1- to 1.5-h session of this experiment, for

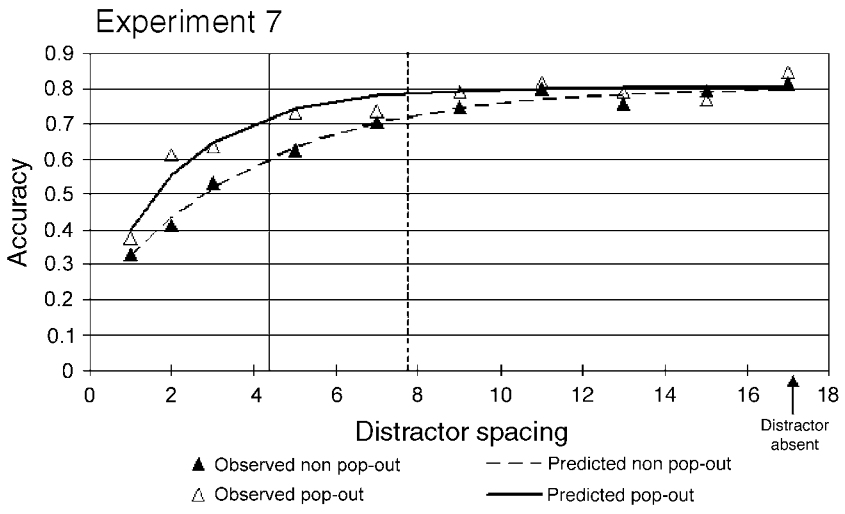

Figure 13. Observed and predicted mean accuracies at each distractor spacing in Experiment 7. The vertical lines indicate the critical spacing estimates for both the popout (solid line) and non-popout (dashed line) conditions, as determined by the model of the means.

which they were paid. All participants had either normal or corrected-to-normal vision.

Stimuli

All stimuli were colored either orange (approximately 67.7 cd/m^2) or green (approximately 49.0 cd/m^2). We used the average luminance value to choose an appropriate gray background to equate contrast for both colors (approximately 58.4 cd/m^2). Pilot studies verified that accuracy was approximately matched across the two target colors.

Targets. The targets have the same height and width as those used in the previous experiments. There were four possible letter targets presented in Arial font, including B, C, F, and P. On each trial, two targets appeared on either side of the fixation point across the horizontal meridian, each at an eccentricity of 3 target widths. This display prevents possible attentional manipulations and makes it more advantageous for participants to keep their eyes on the fixation point. Targets always appeared in these same locations.

Distractors. Three distractors surrounded each target; one appeared above the target, one below, and one on the side furthest from fixation. The distractors were false font characters created to mimic the shapes and spatial frequencies of the targets. They appeared in every trial, all at the same distance from the target.

Masks. All stimuli were masked with white pound symbols.

Design and procedure

See Figure 14 for a schema of the sequence of events. Each trial began with three white dots on the computer screen; the center dot was the fixation point, and the other two dots cued participants to both target locations. These

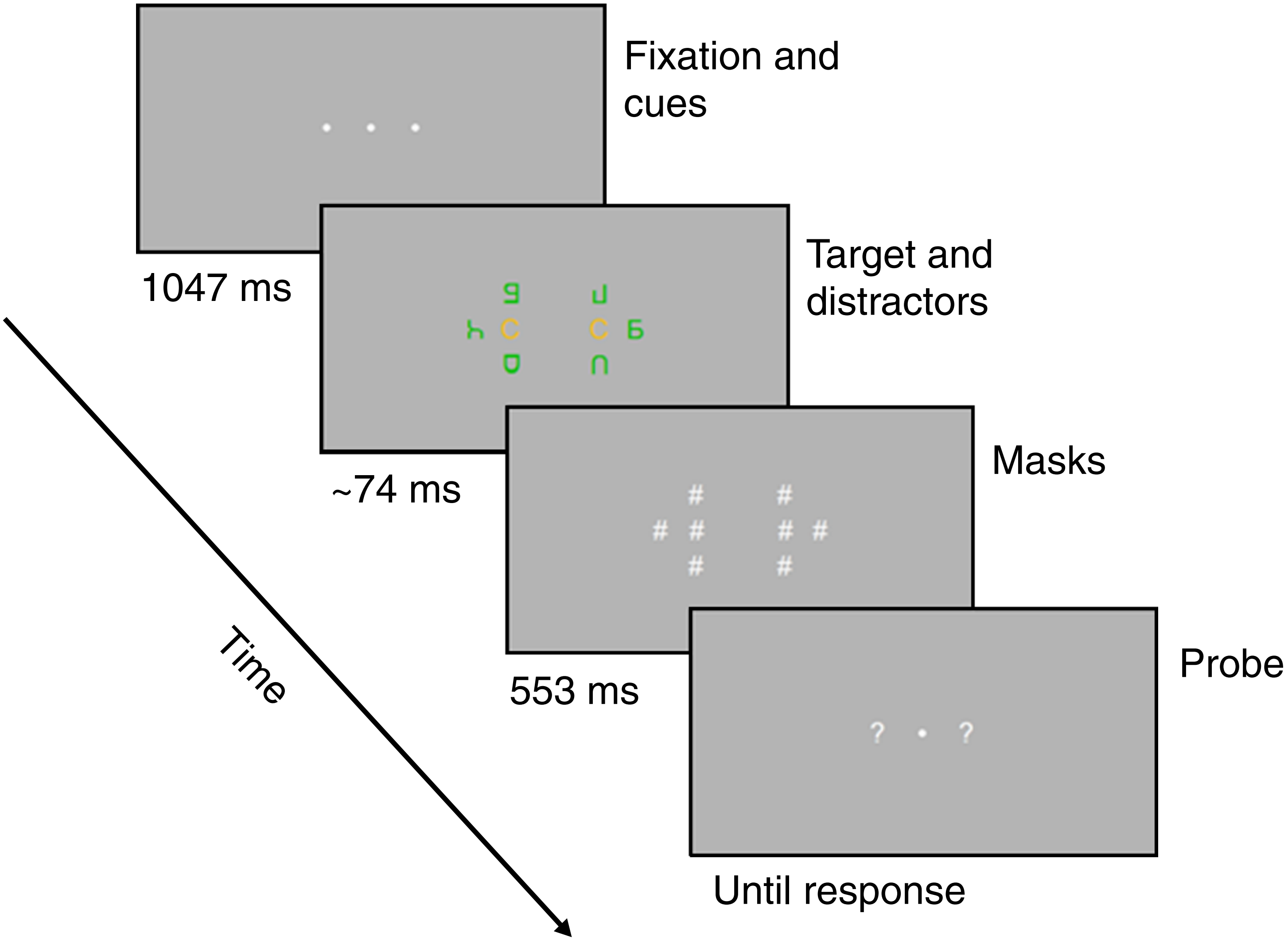

Figure 14. The sequence of events for a popout trial in Experiment 8. Here, the distractors are at a spacing of 2 target widths. The exposure duration listed for the target display is the average duration for a popout trial at this distractor spacing. In the case of non-popout trials, the distractors and targets were presented in the same color. Both target locations were cued for every trial, and a target appeared in each location. All stimuli were masked.

remained on-screen for 1,047 ms and were followed by the onset of targets and distractors. Target and distractor colors (either orange or green) were randomly selected for each trial, with the constraint that all targets had the same color and all distractors were of a uniform color. In the popout condition, distractors were colored differently than the targets (e.g., the targets may be colored orange while the distractors are colored green, or vice versa). In the non-popout condition, all stimuli in the display were presented in the same color (e.g., targets and distractors may both be colored orange). Similar to Experiment 6, participants completed one condition first, followed by the second condition, and the order of completion was counterbalanced across participants. The display was followed by 553 ms of full-field masks, after which "?" probes appeared in the two target locations. These remained on-screen until the participants responded using an unspeeded keypress, in which they first reported the left target followed by the right one. Feedback was provided after each response.

The procedure of this experiment was identical to that of Experiment 6.

Results and discussion

The mean exposure duration for each distractor spacing is presented in Figure 15 for both distractor presentation conditions, as well as the predicted outcomes. Each participant's exposure duration at each distractor distance was determined by averaging all the trials along asymptote (i.e., from the point at which durations stabilized). As evidenced by the graph, we are getting large popout effects for the first three distractor distances, all of which were within critical spacing for the non-popout condition (see inflection results below). At a spacing of 1 target width, target processing time (i.e., the duration needed to perform at approximately a 70% accuracy level) was 46 ms faster in the popout condition; at Spacings 2 and 3, the difference was 21 and 18 ms, respectively.

The overall model fits the data quite well (popout: $r = .97$; non-popout: $r = .99$); this was true of the individual models as well (popout: mean $r = .92$; non-popout: mean $r = .96$). One participant (out of nine) was removed from the analyses because his data could not be modeled ($r = -.25$).

As was the case with distractor preview, the distractors themselves are the only manipulated factor; hence, when they are effectively absent, the two displays are equivalent. Therefore, the predicted asymptotes were locked, and both reached it at 63 ms (mean of individual models = 63 ms).

The key question of this experiment was whether the two conditions differed in critical spacing estimates. The overall model produced inflection points of 2.62 spacings in the popout condition and 5.43 in the non-popout condition. The mean of the individual models resulted in a similar pattern, where popout reached inflection at 2.5 spacings, whereas non-popout reached inflection at 5.78 spacings. These inflection differences were significant, $t(7) = 4.49$, $p = .003$. Therefore, color popout displays did reduce critical spacing. Furthermore, we can conclude that these results are not due to attentional manipulations because both target locations were cued prior to target onset. Attention would have already been captured at both target locations before the stimuli appeared, and thus, there would not have been capture differences between popout and non-popout trials. This

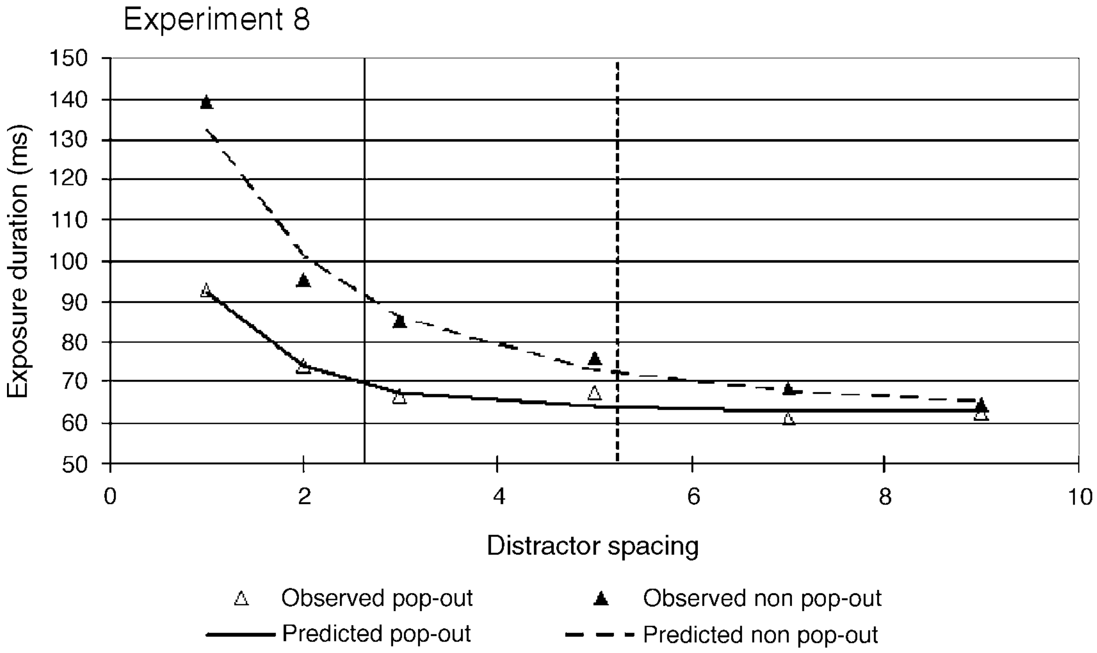

Figure 15. Observed and predicted mean durations at each distractor spacing for Experiment 8. The vertical lines indicate the critical spacing estimates for both the popout (solid line) and non-popout (dashed line) conditions, as determined by the model of the means.

suggests that the results of Experiment 7 were due to the target-saliency differences themselves and not to the possible attentional differences associated with saliency.

Summary of popout studies

Previous research has shown that when a salient feature differs among targets and distractors in crowded displays, target processing is facilitated (Felisberti et al., 2005; Kooi et al., 1994); this is termed popout. However, prior to this research, the possible influences of popout on critical spacing had not been explored. Therefore, these two experiments were designed to determine if critical spacing differed for popout and non-popout displays. In both experiments, we varied target and distractor color such that a non-popout trial consisted of both types of stimuli presented in the same color, whereas in a popout trial, the distractors were colored differently than the target. The first experiment used accuracy as the dependent measure, whereas the second experiment used exposure duration, much like the distractor preview studies presented earlier.

In both experiments, our measures appropriately elicited a popout effect. We found fairly large differences between conditions at the distractor spacings within critical spacing (see Figures 13 and 15), and in both cases, performance in the popout condition was better. What is more interesting is that we found a significant inflection difference between the two conditions in both experiments such that popout displays required the distractors to be closer to cause interference than did the non-popout displays. These results are consistent with those discussed earlier for distractor preview. Again, the fact that we found a critical spacing for both distractor preview and popout using a paradigm similar to our spatial cueing experiments strengthens our confidence in the null results from those studies. Given the null results of the spatial cueing effect and the positive results in these studies, this suggests that these two factors may facilitate target processing in crowded displays in a qualitatively different manner than does attention.

General conclusions

Attention facilitates target processing in crowded displays (Awh et al., 2003; Dosher & Lu, 2000, Kastner et al., 1998; Shiu & Pashler, 1994), but the method by which this is accomplished remains unclear. We conducted four experiments to determine if attention improves target identification via a reduction of critical spacing. We designed a paradigm that elicited robust spatial cueing effects, providing an opportunity to measure the critical spacing point for both attended and unattended targets. None of the four experiments revealed an attention effect on critical spacing, suggesting that when attention is captured via stimulus-driven cueing, critical spacing remains unchanged.

These results can be contrasted with the effects of two other variables that are also known to ameliorate crowding effects. Both distractor preview and popout caused a robust reduction in critical spacing in each of the experiments. For example, in Experiment 6, critical spacing in the preview condition was only 39% of that in the simultaneous condition. In Experiment 8, critical spacing in the popout condition was only 43% of that in the non-popout condition. These reductions were replicated using different procedures in which either accuracy or exposure duration was measured. These data show that our general paradigm is sensitive to changes in critical spacing when such changes exist. Therefore, we are confident in the conclusion that stimulus-driven spatial selection does not reduce critical spacing.

The disparate results between attention and the other two variables suggest that attention facilitates processing in crowded displays differently than do preview and popout. One possibility is that distractor preview and target popout help to minimize the confusing integration of target and distractor signals, whereas the stimulus-driven shifts of attention (at least in this procedure) influenced target processing through signal enhancement (as evidenced by higher levels of accuracy at asymptote in the attended conditions). Signal enhancement may operate in one of two ways. First, it may effectively increase target contrast while maintaining distractor contrast, thus increasing target saliency. However, if this were the case, then we would expect stimulus-driven spatial attention to affect critical spacing in a manner similar to the popout displays. Alternatively, it may operate by focusing on the target, thereby allowing for a more veridical visual representation of the target compared to items outside of attention (i.e., a reduction in internal noise). This explanation of signal enhancement does not require similar results between spatial cueing and popout displays and is, therefore, consistent with our results. If this is the mechanism by which stimulus-driven attention operates in crowded displays, then it might not be affecting the strength of distractor representations at all. Future studies should examine endogenous cues to determine if internally generated shifts of attention have a different effect in crowded displays than does stimulus-driven attention.

At least in the case of stimulus-driven shifts in attention, our results call into question whether the spatial extent of crowding is synonymous with the spatial resolution of attention. Instead, these data are more in line with the view offered by Pelli et al. (2004) that crowding results from the harmful pooling of signals within an “integration field” whose radius is defined by critical spacing. Pelli et al. argued that this integration field operated in a largely preattentive fashion.

Although signal enhancement may provide the best explanation of the cueing effects observed in these studies, this model cannot explain the significant differences found for preview and popout. These two variables must be influencing some aspect of the spatial interactions between targets and distractors. Recall that Parkes et al. (2001) found that items in peripherally presented crowded displays were often integrated such that observers reported the average signal of relevant and irrelevant stimuli. It may be the case that distractor preview and popout facilitate the perceptual segregation of targets and distractors, thus preventing unnecessary texture analysis. This could be accomplished via Gestalt cues (Koffka, 1935). In distractor preview, distractors may be grouped separately from targets based on temporal presentation. In popout, distractors may be perceived in a different group based on color. This speculation is consistent with the reduction in critical spacing found for both factors. This hypothesis may also explain why spatial attention did not influence critical spacing, given that the bottom–up grouping cues between targets and distractors remained constant across the valid and invalid spatial cues. In this case, stimulus-driven shifts of attention may have enhanced target processing without directly influencing the tendency to group targets and distractors.

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