Attention, Perception, & Psychophysics (2019) 81:1366–1385
https://doi.org/10.3758/s13414-018-01656-6

Object-based biased competition during covert spatial orienting

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Published online: 25 January 2019

Abstract

Biased-competition models assert that spatial attention facilitates visual perception by biasing competitive interactions in favor of relevant input. In line with this view, past work has shown that the benefits of covert spatial attention are greatest when targets must compete with interfering stimuli. Here we propose a boundary condition for the resolution of interference via exogenous attention: Attention resolves visual interference between targets and distractors, but only when they can be individuated into distinct representations. Thus, we propose that biased competition may be object-based. We replicated previous observations of larger attention effects when targets were flanked by irrelevant distractors (interference-present displays) than when targets were presented alone (interference-absent displays). Critically, we then showed that this amplification of cueing effects in the presence of interference is eliminated when strong crowding hampers individuation of the targets and distractors. Likewise, when targets were embedded within a noise mask that did not evoke the percept of an individuated distractor, the attention effects were equivalent across noise and lone-target displays. Thus, we conclude that exogenous spatial attention resolves interference in an object-based fashion that depends on the perception of individuated targets and distractors.

Keywords Space-based attention · Object-based attention

A natural scene typically contains more information than the visual system can simultaneously process. Selective attention biases perceptual processing toward behaviorally relevant input—at the expense of irrelevant input—on the basis of spatial location, object identity, and/or feature values. Studies of space-based attention, the most investigated selective mechanism, have shown that items within an attended region are processed more effectively than those in unattended regions (Posner, 1980); in fact, one may even be unaware of salient unattended items (Neisser & Becklen, 1975; Simons & Levin, 1998). This facilitation is often explained via the biased-competition model of attention. According to this perspective, all items in a given scene compete for selection and further processing, but this competition is biased toward the attended items (Desimone & Duncan, 1995).

The biased-competition model has been supported in both neurobiological (e.g., Beck & Kastner, 2005; Bles, Schwarzbach, De Weerd, Goebel, & Jansma, 2006; Kastner, De Weerd, Desimone, & Ungerleider, 1998; Moran & Desimone, 1985) and behavioral (e.g., Awh, Matsukura, & Serences, 2003; Awh, Sgarlata, & Kliestik, 2005; Shiu & Pashler, 1994; reviewed in Beck & Kastner, 2009; Carrasco, 2011; Desimone & Duncan, 1995; Reynolds & Chelazzi, 2004; Vecera, 2000) studies of space-based attention. Moran and Desimone found that responses to unattended stimuli were attenuated within macaque V4 and inferior temporal cortex when both attended and unattended stimuli were simultaneously positioned in the same receptive field. This finding was extended in a human fMRI study (Kastner et al., 1998): In the absence of attention, simultaneously presented images competed in a mutually suppressive fashion in V4. When participants selectively attended to one of the images, the suppressive influences of the unattended items were attenuated.

The neural evidence in favor of biased competition indicates that space-based attention facilitates perceptual decision making in part by filtering out external interference so that relevant items can be selected for further processing. Mechanistically, this involves suppressing the response of

Electronic supplementary material The online version of this article (https://doi.org/10.3758/s13414-018-01656-6) contains supplementary material, which is available to authorized users.

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sensory neural populations that are "tuned to" the distractors, below what would be observed from passive sensory stimulation (e.g., Moran & Desimone, 1985). This model predicts that spatial-cueing effects should be relatively greater in the presence of interference than in displays containing a lone target (where no external interference is present to compete with target processing). Across several studies that have confirmed this prediction, "interference" has been broadly defined. For example, Awh et al. (2005) used nonpredictive peripheral cues to measure accuracy-based attention effects in the presence and absence of interference in the form of letter distractors. Critically, the benefits of spatial cueing were much larger when a target number was surrounded by irrelevant letters, indicating that target identification was facilitated by suppressing external distractors. Similarly, Shiu and Pashler (1994) observed greater attention effects in a number identification task in the presence of backward masks (number signs that onset immediately after target offset). Cheal and Gregory (1997) found larger cueing effects in a target identification task when targets were either surrounded by co-occurring distractors and/or followed by backward masks. Thus, a broad array of psychophysical data support the account that attention helps aid target selection by excluding external interference when it is present.

Not all results can be easily explained by interference resolution alone, however. For instance, reliable attention effects can be observed in displays that do not contain explicit distractors (henceforth, broadly termed "interference-absent" displays). These findings demonstrate that spatial attention also serves to enhance the signal from items presented in attended locations (Carrasco, 2011; Dosher & Lu, 2000; Lu & Dosher, 1998). This could be accomplished via increased fidelity of the neural representation and/or by a reduction of internally generated noise. Thus, we acknowledge that both signal enhancement and interference resolution contribute to spatial-attention effects. The central goal of the present work, however, was to refine our understanding of the boundary conditions for interference resolution via spatial attention. Thus, we focused in particular on the conditions under which we observed the signature of biased competition: larger benefits of spatial attention in the presence of significant interference.

The cases reviewed above demonstrated this signature of biased competition, but in other cases this empirical pattern has not been observed. Lu and Dosher (1998) manipulated target discriminability using superimposed interference patterns that obscured a target grating (henceforth termed "embedded noise"). They found that exogenous space-based attention effects *declined* as the intensity of the embedded noise increased, contrary to a biased-competition account, and thus they concluded that the results solely implicated signal enhancement (without concurrent external noise exclusion). Likewise, Scolari, Kohnen, Barton, and Awh (2007) measured spatial-cueing effects while manipulating the spacing between targets and flanking distractors. Notably, the targets and distractors had highly similar physical properties (rotated Ts and Is), which were likely to produce relatively strong interference effects (Baylis & Driver, 1992; Duncan & Humphreys, 1989). Nevertheless, the results showed no evidence that attention effects were larger when distractors closely flanked the target. These results seem to contradict the conclusion that spatial-cueing effects are larger in the context of any forms of external interference.

Boundary conditions of biased competition

Here we propose a refined hypothesis that may reconcile these apparently conflicting findings. Specifically, we argue that exogenous spatial attention may specifically resolve competition *between discrete object representations*, such that this effect is contingent on the successful *individuation* of targets and distractors. This account predicts that the behavioral signature of biased competition—augmented benefits of spatial cueing in the presence of distractor interference—may not be observed when target–distractor individuation is impeded. One such impediment is visual crowding. In cluttered peripheral displays, signals from physically discrete objects are often inappropriately pooled together to form the perception of an incoherently bundled object. Although there is debate regarding the nature of this pooling process (e.g., Ester, Klee, & Awh, 2014), a growing consensus has conceded that crowding impairs the observer's ability to individuate the feature values of tightly clustered items (Chen, Bao, & Tjan, 2018; Greenwood, Bex, & Dakin, 2009, 2010; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001). Barring eye movements, this jumbled percept is unlikely to be fully resolved by unlimited time or attention (Pelli et al., 2004; Scolari et al., 2007). Thus, we hypothesized that strong crowding would preclude effective individuation of targets and distractors, thereby eliminating the enhanced cueing effects that are often seen in the presence of strong distractor interference. We suspect that such perceptual integration may have occurred in Scolari et al. (2007), given the high interstimulus similarity and the close proximity of targets and distractors. Likewise, because Lu and Dosher (1998) employed embedded noise masks that were not perceived as individuated objects, interference resolution via spatial attention may have been precluded.

To test our hypothesis, we measured exogenously driven spatial-cueing effects while manipulating crowding strength by altering the intensity and nature of the interference in the display. We predicted that the cueing effects would be equivalent between interference-present and interference-absent displays when visual crowding was sufficiently strong. In addition, we examined the consequences of embedding targets within a noise mask (i.e., a speckled surface that obscured the target without eliciting the percept of a discrete distractor element). Here, we predicted that the spatial-cueing effects would be equivalent between a completely clean target display and a condition with individuated distractors that was nonetheless matched for perceptual difficulty.

Experiment 1

Awh et al. (2005) demonstrated relatively larger attention effects when irrelevant distractors were present than in lone-target displays. The interaction between display type (with and without interference) and the size of the attention effect was the critical empirical pattern, in that it provides evidence for biased competition. Our first goal was to replicate this empirical pattern using a similar procedure. In Experiment 1, subjects reported the identity of a target digit that was presented in parafoveal space either alone (distractor-absent condition) or flanked by letter distractors (distractor-present condition), and we compared the sizes of the attention effects between these two conditions, as measured by performance accuracy. Any attention effects in the distractor-absent condition would indicate signal enhancement, wherein target identification was facilitated by suppressing internally generated noise and/or increasing the fidelity of the internal representation (Dosher & Lu, 2000; Lu & Dosher, 1998). Comparatively larger effects observed in the distractor-present condition would indicate that target identification was further improved via external noise reduction, such that the signals generated from distracting elements were suppressed.

Method

Subjects

A total of 24 subjects participated in Experiment 1, matching the largest sample size reported in Awh et al. (2005; across five experiments, their sample sizes ranged from 8 to 24 subjects, with a mean of 16.4). All subjects were students from the University of Oregon with normal or corrected-to-normal vision and gave written informed consent before participating. All experimental sessions were 90 min in length, and each student received partial course credit for participation.

Stimuli

The stimuli were generated using Microsoft Visual Basic 6.0 and presented on an 18-in. CRT monitor with a refresh rate of 120 Hz. Each stimulus display consisted of one target and six distractors. The target was a single digit selected randomly from the set of integers 1–9. The distractors were randomly drawn without replacement from a set of 24 English alphabet characters (excluding I and O). All stimuli were presented in a dark gray calculator font on a white background and measured 0.70° width × 0.80° height of visual angle. On each trial, the target was presented along the horizontal meridian to either the left or the right of a fixation point at a distance of approximately 3.5°. Six distractors were presented simultaneously, three centered above the target and three centered below (the center distractor of each trigram was approximately 1.4° away from the target and was spaced 0.6° from the neighboring distractors). Each stimulus in the target display was masked by a "number sign" stimulus (i.e., a hash or pound sign; see Fig. 1).

Experimental procedure

See Fig. 1 for an illustration of the sequence of events. Subjects were seated comfortably at a desk in a completely dark room at a distance of approximately 60 cm from the computer monitor. Each trial began with a fixation point at the center of the screen, measuring 0.35° of visual angle. Following 103 ms of fixation, a peripheral cue (a black dot measuring 0.27° in diameter) appeared in one of the two possible target locations for 33 ms, followed by a 50-ms blank period. The target display then appeared for a duration that had been predetermined using a previous staircased timing procedure (see the Timing Procedure section below). The target was equally likely to appear in the cued (valid condition) or the uncued (invalid condition) location, rendering the peripheral cue wholly uninformative. On half of all trials the target appeared alone (distractor-absent condition), and on the other half it appeared surrounded by six distractors (distractor-present condition). All four conditions (valid–distractor absent, valid–distractor present, invalid–distractor absent, and invalid–distractor present) were intermixed. The target display was followed by the number sign masks for 325 ms, after which a "?" probe appeared at the correct target location and remained onscreen until a response was made. Subjects reported the identity of the number target that had appeared in the probed location with an unspeeded button press using the number pad on a standard QWERTY keyboard, and the target stimulus associated with the button press was displayed in place of the probe. To avoid incorrect responses due to errant presses, subjects could change their responses by selecting a different key and pressed "Enter" once they were ready to submit their answer. After each response, subjects were given written feedback on their single-trial performance. Subjects completed eight blocks of this procedure, for a total of 320 trials.

Timing procedure

The amount of time needed to sufficiently encode a stimulus can vary widely between individuals. To account for these individual differences and ensure that task difficulty could not explain any of the observed results, each subject

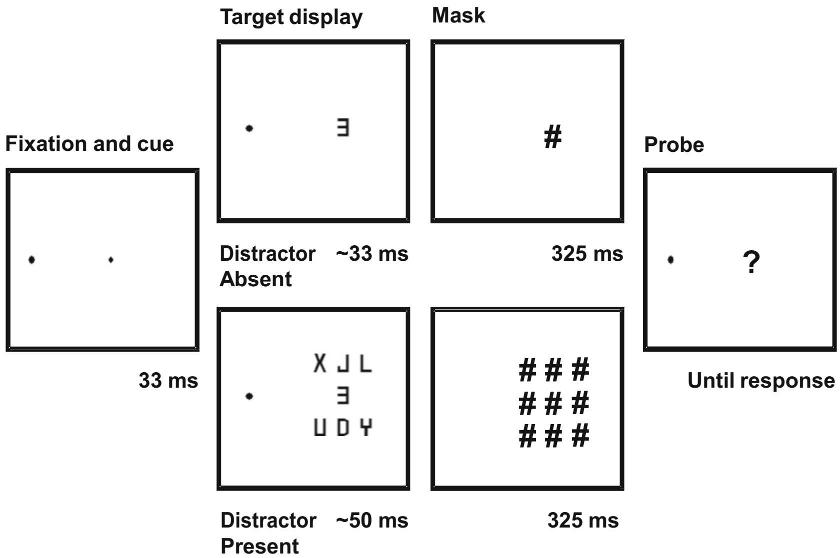

Fig. 1 Schematic of the valid–distractor-absent and valid–distractor-present trials used in Experiment 1. Note that for half of all trials, the target appeared on the opposite side of fixation from the spatial cue (invalid trials). The timing listed below each target display type reflects the mean exposure duration across subjects. Note that the actual exposure durations used for each subject were determined via a staircased timing procedure. The probe item ("?") always appeared at the target location, regardless of the validity of the cue, and stayed on screen until the subjects had reported the identity of the target digit with an unspeeded keypress. Similar displays were used in Experiments 3, 4, and 6

participated in eight blocks of a staircase timing procedure to estimate the exposure durations for valid trials in the main experiment (e.g., Awh et al., 2003; Awh et al., 2005; Stevens et al., 2012; Williamson, Scolari, Jeong, Kim, & Awh, 2009). Here, subjects were presented with a procedure similar to the one described above, with the following important exceptions. The peripheral cue was 100% valid, meaning that no invalid trials were presented. The targets were equally likely to appear with or without distractors. On the first instance of each display type, the stimuli were onscreen for 167 ms (20 frames). In the event of a correct response, the exposure duration was reduced by 8.33 ms (one monitor refresh cycle) on the next trial of the same display type; an incorrect response resulted in the exposure duration increasing by 16.66 ms (two refresh cycles). These trial-by-trial adjustments were made separately for valid–distractor-absent and valid–distractor-present displays, resulting in independent exposure duration estimates for each display type that should conform to a common performance criterion of approximately 68%. The last two blocks of this procedure were checked by eye to ensure that each subject had reached asymptotic performance; if this was not the case, the subject was asked to complete two more blocks. The exposure durations of the final two blocks were averaged together, and these averages were used to set the timing in the subsequent main experiment for both valid conditions, as well as for their (previously unseen) invalid counterparts. In the event that the estimates exceeded 200 ms, the exposure durations were set to this cap in order to reduce the likelihood that subjects could make volitional attentional shifts or eye movements following stimulus display onset (e.g., Itti & Koch, 2001).

The staircase procedure described above has been used in many previous studies (e.g., Awh et al., 2003; Awh et al., 2005; Stevens et al., 2012; Williamson et al., 2009). Given the potential for large individual differences in encoding time between distractor-present and -absent displays, even when they are fully attended, using one duration across subjects or even across display types was likely to result in floor or ceiling effects in one or the other condition. Such floor and ceiling effects could obscure the behavioral measures of attention effects. By ensuring that both valid conditions were at an acceptable accuracy level (approximately 68%), we allowed for both small and large attention effects for each display type (and even for reversals, should they occur). Furthermore, our goal here was to evaluate the presence or absence of biased-competition effects, defined as the difference in attention effect size between distractor-present and -absent displays (see the Analysis section below). Thus, pinning the two valid conditions to a (near) matched accuracy level made comparing attention effects across the two display types much more straightforward, in that we could confidently rely on simple subtraction. Finally, we used the exposure duration estimates determined in the timing procedure for the valid–distractor-absent and valid–distractor-present displays as an operational measure of the strength of interference, described in full detail below.

Analysis

Interference effects We employed a staircase procedure that estimated for each subject the exposure durations needed to obtain criterion performance in distractor-present versus -absent displays when attention was voluntarily and consistently directed to the target location (see the Timing Procedure section above). In addition to compensating for individual differences in perceptual ability, the results of this task serve as an objective measure of distractor interference, or crowding. As we stated in the introduction, the absence of time pressure does not fully ameliorate spatial crowding. However, exposure duration has been shown to mediate the extent of spatial crowding, such that the area of feature integration increases with decreased exposure durations (Tripathy & Cavanagh, 2002). We therefore surmised that stimulus displays with relatively stronger interference would require longer presentation times in order to reach a common performance criterion (this expectation holds for all forms of visual interference effects, not only for those classified as spatial crowding). We used the difference between each subject's valid–distractor-absent and valid–distractor-present exposure durations to calculate the degree to which the distractors interfered with target identification, where comparatively greater interference would result in greater duration differences. Note that although the exposure durations used for the main experimental task were of necessity expressed in monitor refresh rate frames, and thus are rounded to the nearest integer, the analyses reported below utilized the millisecond estimate values prior to rounding.

Attention and biased-competition effects Given that we were interested in attention effects on perceptual sensitivity rather than in decision times, our subjects were explicitly instructed to emphasize accuracy over speed, and were even given an opportunity to change their responses before submitting. Thus, we chose to forgo measuring reaction times (RTs; often used in classic attention studies—e.g., Posner, 1980; Posner, Snyder, & Davidson, 1980), in favor of accuracy as an objective measure of attention effects. The performance accuracy for each condition (valid–distractor absent, valid–distractor present, invalid–distractor absent, and invalid–distractor present) was calculated on a subject-by-subject basis. Attention effects are defined as the difference between valid and invalid performance scores.

The central question posed in this study was whether the presence of external interference elicits larger attention effects than do interference-free displays. We term this the *biased-competition effect*, since this pattern of results is implicitly predicted by the neurally supported theoretical account of the same name. Biased-competition effects are thus defined as the difference between the attention effects for distractor-present and distractor-absent displays, written as

Biased Competition = Distractor Present(Valid – Invalid) – Distractor Absent(Valid – Invalid).

Because our primary focus in this study was to compare attention effect sizes between interference-present and -absent displays, we elected to include a scaled-information Bayes factor analysis for each comparison pertaining to the biased-competition effect, which allows for a direct comparison between the alternative and null hypotheses (Rouder, Speckman, Sun, Morey, & Iverson, 2009). Thus, this offered additional evidence, in conjunction with the traditional p value, as to whether a biased-competition effect was present.

Results and discussion

Interference effects

Across all subjects, the staircase procedure revealed that the valid–distractor-present condition required a longer exposure duration (M = 49.68 ms) to reach the same level of performance than did the valid–distractor-absent condition (M = 32.99 ms), $t(23) = 4.56$, $p = .00014$, $d = 0.93$ (see Fig. 2a). Thus, the letter distractors effectively interfered with digit target processing, even when the target location was precued solely with valid cues.

Attention and biased-competition effects

Figure 2b depicts the mean target identification accuracy in the main experiment as a function of display type (distractor absent vs. distractor present) and the validity of the precue (valid vs. invalid). A two-way analysis of variance (ANOVA) revealed a significant interaction between these two factors (valid–distractor absent, M = 72%; valid–distractor present, M = 71%; invalid–distractor absent, M = 66%; invalid–distractor present, M = 56%), $F(1, 23) = 8.74$, $p = .007$, $d = 0.6$. Strong evidence in favor of a significant biased-competition effect was further given by a Bayes factor analysis: $BF_{10} = 8.02$. For both display types, subjects performed better when the exogenous precue drew their attention to the upcoming target location (attention effects: distractor absent, M = 6%; distractor present, M = 15%). Planned comparisons between the valid and invalid trials revealed that these effects were significant for each display type: distractor absent, $t(23) = 2.63$, $p = .015$, $d = 0.54$; distractor present, $t(23) = 10.02$, $p < .0001$, $d = 2.04$. Importantly, however, the attention effects were greater in the presence of interference, resulting in a significant biased-competition effect, as revealed by the interaction described above between display type and validity (M = 9%).

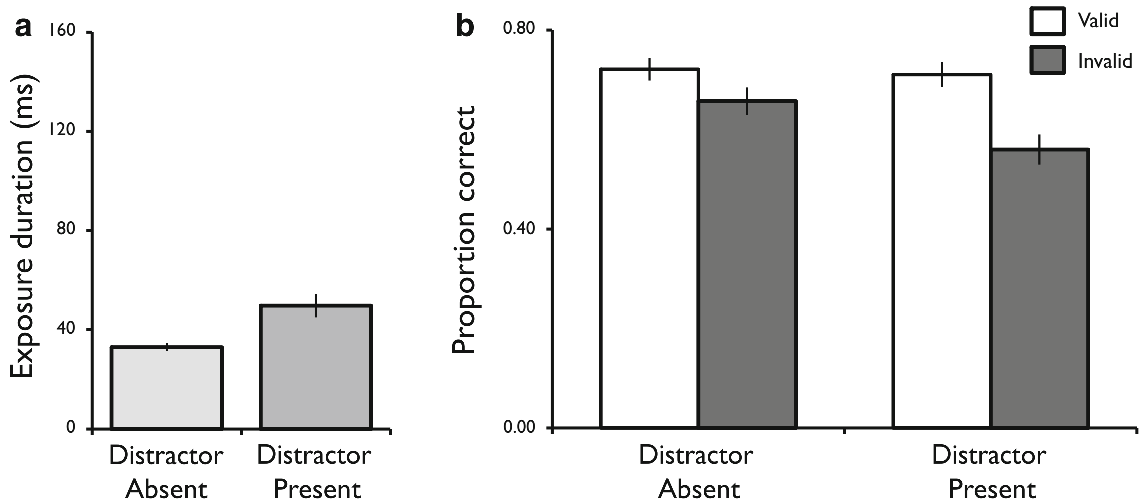

Fig. 2 Results from Experiment 1, in which subjects reported the identity of a parafoveal target digit presented with or without flanking letter distractors. (**a**) Mean exposure durations for valid–distractor-absent and valid–distractor-present trials, as determined by a staircased timing procedure. (**b**) Proportions correct for each of the four conditions (valid–distractor absent, valid–distractor present, invalid–distractor absent, and invalid–distractor present). Error bars represent ± 1 standard error of the mean. Note that because the exposure durations for valid–distractor-absent and valid–distractor-present trials were independently staircased to a common performance criterion, accuracy was expected to be statistically equivalent between these two conditions. Replicating previous findings, the size of the attention effect was significantly greater for distractor-present than for distractor-absent displays

Using number and letter stimuli presented in parafoveal space with a fully exogenous precue, we observed significant attention effects as measured by accuracy in both the presence and absence of external interference. Because the target was presented alone on distractor-absent displays, the attention effects in this condition serve as evidence that covert attention enhanced the target signal. Furthermore, we interpret the increased size of attention effects in interference displays as evidence of distractor suppression that reduced the undue influence from irrelevant stimuli. Thus, the interaction between cueing effects and display type serves as a signature of biased competition.

Although we used Awh et al. (2005) as a template for the design of Experiment 1, there were several noteworthy differences. The previous study had presented an interference display on a filled 6 × 6 grid, in which the target could appear in one of four quadrants at a Euclidean distance of 2.6° from fixation and with a 1° spacing between neighboring stimuli. Here we presented six distractors surrounding the target only, which could appear in one of two locations along the horizontal meridian 3.5° away from fixation (and a 1.4° distance from the distractors; see the Stimuli section above). Despite these differences, we observed the same biased-competition pattern reported in the previous study. A similar pattern is also reported in the supplemental material for this article (see Supplementary Exp. 1), in which the interference was reduced to just one letter above and below the target number. Together, these results suggest that the behavioral biased-competition effect generalizes across a range of displays.

Nonetheless, as we described in the introduction, behavioral biased-competition effects are not consistently observed in the literature. In a previous study using oriented Ts as targets (Scolari et al., 2007), we did not find evidence that interference from perceptually similar distractors increased the size of the attention effect. This suggested to us that despite the growing evidence that the biased-competition effect is robust against small changes in number–letter displays, the effect may be susceptible to manipulations in target–distractor similarity. Admittedly, however, observing this effect was not the primary goal of that previous study. Thus, we set out to replicate the observation that biased-competition effects can be eliminated when unfamiliar targets (Vecera & Farah, 1997) are surrounded by perceptually similar distractors.

Experiment 2

In Experiment 2, we employed a design in which high target–distractor similarity should lead to substantially stronger crowding effects (e.g., Baylis & Driver, 1992; Duncan & Humphreys, 1989; Kimchi & Pirkner, 2015; Kooi, Toet, Tripathy, & Levi, 1994; Pelli, Palomares, & Majaj, 2004; Scolari et al., 2007; Treisman, 1991). Subjects reported the orientation of a target T that appeared either alone or flanked by a set of oriented Is. We predicted that the stronger crowding induced by high interstimulus similarity would hinder individuation of the targets and distractors, thereby yielding equivalent attention effects between distractor-present and distractor-absent displays.

Method

The methods used in Experiment 2 were similar to those of Experiment 1, with the following changes:

Subjects A new group of 12 subjects participated in Experiment 2; all were naïve to the purpose of the study. This sample size is within the range of those reported from the relevant studies in Scolari et al. (2007; across Exps. 1–4, sample sizes ranged from 8 to 27, with a mean of 15.25). In all cases, significant differences in accuracy between valid and invalid trials were observed. Furthermore, a pilot study conducted prior to this one also produced large attention effects regardless of whether distractors were present with a sample size of nine subjects (see Supplementary Exp. 2).

All subjects were students from the University of Oregon with normal or corrected-to-normal vision, and each gave written informed consent before participating. All experimental sessions were 90 min in length, and students received partial course credit for their participation.

Stimuli The target was a letter T (subtending 0.70 × 0.70° of visual angle) that was rotated either 0°, 90°, 180°, or 270°, allowing for four possible targets. Each of the six distractors was a randomly selected letter "I" (also subtending 0.70° × 0.70° of visual angle) rotated either 0° or 90°. The stimuli were presented in Arial font, with the target centered approximately 3.5° away from fixation (see Fig. 3a). Each stimulus in the target display was masked by a "window-pane" stimulus (i.e., an open square with a cross centered inside).

Experimental procedure As in Experiment 1, the peripheral cue was wholly uninformative, and the target was equally likely to appear alone (distractor-absent condition) or surrounded by six distractors (distractor-present condition). The most notable changes between this experiment and Experiment 1 were the target and distractor stimuli (see above) and the response mapping. Subjects reported the identity of the target oriented T with an unspeeded button press using the number pad on a standard QWERTY keyboard. Following the spatial configuration of the keys themselves, subjects pressed "5" to report an upright (0°) target, "1" to report a target oriented leftward (90°), "2" to report an upside-down (180°) target, and "3" to report a target oriented rightward (270°). Once the response was made, the target stimulus associated with the subject's button press was displayed in place of the probe. As in Experiment 1, subjects were given the opportunity to change their responses, and they pressed Enter to confirm their answer. After each response, subjects were given written feedback on their single-trial performance. Subjects completed eight blocks of this procedure, for a total of 320 trials.

Timing procedure The timing procedure matched that reported for Experiment 1.

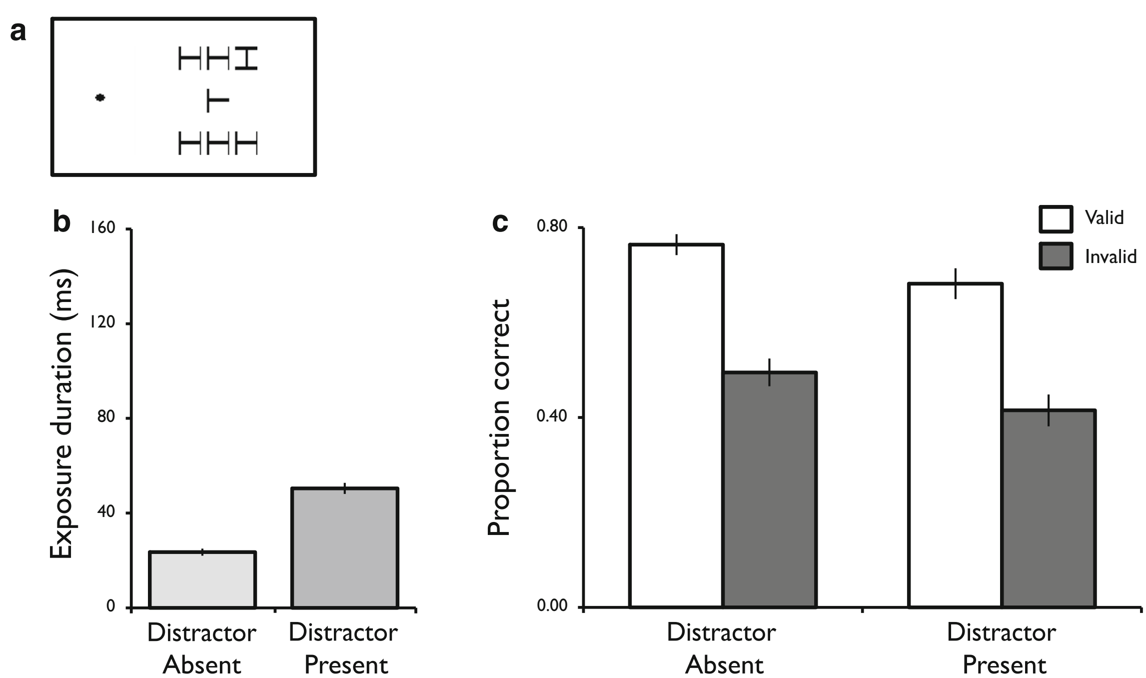

Fig. 3 Results from Experiment 2, in which subjects reported the orientation of a rotated target T presented parafoveally with or without flanking distractors. (**a**) Illustration of the target display used in Experiment 2. (**b**) Mean exposure durations for valid–distractor-absent and valid–distractor-present trials. (**c**) Proportions correct for each of the four conditions (valid–distractor absent, valid–distractor present, invalid–distractor absent, and invalid–distractor present). Error bars represent ± 1 standard error of the mean. In contrast to Experiment 1, the sizes of the attention effect did not differ between display conditions

Analysis The same analyses were performed as in Experiment 1. Notably, we predicted that the biased-competition effects should be equivalent between display types in this experiment, and hence we anticipated accepting the null hypothesis for this comparison. To more rigorously evaluate the evidence for a null result in these instances, as in Experiment 1 we performed a scaled-information Bayes factor analysis that allowed for a direct comparison between the alternative and null hypotheses (Rouder et al., 2009).

Results and discussion

Interference effects Across all subjects, the valid–distractor-present condition required a longer exposure duration (M = 50.43 ms) to reach the same performance criterion as the valid–distractor-absent condition ($M = 23.5$ ms), $t(11) = 9.16$, $p < .0001$, $d = 2.64$ (see Fig. 3b).

Attention and biased-competition effects Figure 3c depicts the mean target identification accuracy in the main experiment as a function of display type and precue validity. Subjects exhibited strong attention effects in both the distractor-absent [$M = 27\%$; $t(11) = 10.91$, $p < .0001$, $d = 3.15$] and distractor-present [$M = 27\%$; $t(11) = 13.06$, $p < .0001$, $d = 3.77$] conditions. However, there was no difference in the sizes of the effects across display conditions, $F(1, 11) = 0.034$, $p = .86$, $d = 0.05$, $BF_{01} = 3.54$, and hence no biased-competition effect.

As in Experiment 1, we used an uninformative peripheral cue to manipulate the locus of exogenous spatial attention. Whereas we had observed the behavioral signature of biased competition in the first experiment, the spatial-cueing effects between distractor-present and distractor-absent displays were equivalent in Experiment 2. A similar result—equivalent attention effects across display types—was observed in Supplementary Experiment 2 (see the supplemental material). Reliable attention effects in the distractor-absent display point to a signal enhancement effect of spatial cueing, similar to (albeit larger than) that observed in Experiment 1. However, the equivalent attention effects between distractor-present and -absent displays suggest that attention did not reduce influences from external interference in Experiment 2.

The absence of distractor suppression coupled with the considerably large attention effects (a 12% increase from Exp. 1 for distractor-present displays) may lead one to surmise that the distractors had no deleterious impact on performance. Despite the equally large attention effects across displays, however, it is clear that the highly similar distractors impeded target processing. Subjects needed significantly more time to encode flanked targets than to encode those presented alone. Indeed, interference was stronger here than in Experiment 1 (judging by the increased difference in exposure durations between that display types[1]), in line with past work showing that crowding is amplified as similarity between the targets and flankers increases (e.g., Baylis & Driver, 1992; Duncan & Humphreys, 1989; Kimchi & Pirkner, 2015; Kooi et al., 1994).

Although the stimuli were arguably the most pertinent difference between Experiments 1 and 2, there were other noteworthy differences. The numbers of target and distractor alternatives were reduced in Experiment 2, and the discrimination required of the subjects was different. To enable a more direct comparison between experiments, Experiment 3 employed the same number–letter displays used in Experiment 1. Here we increased the influence of the letter distractors by moving the whole display into peripheral space, a manipulation known to increase the strength of visual crowding (Bouma, 1970). We predicted that this would eliminate the biased-competition pattern observed in Experiment 1, while holding constant the stimuli employed as targets and distractors.

Experiment 3

In Experiment 2, the behavioral signature of biased competition was absent; attention effects were equivalent in the presence and absence of distractors, unlike in Experiment 1. Although we suggested that stronger crowding might have disrupted effective suppression of the distractors, this factor was confounded with changes in the type of stimuli and the kind of discrimination required of subjects. Thus, in Experiment 3 we sought to increase crowding using the same stimuli and discrimination task as in Experiment 1. The display was presented in peripheral (5.6° eccentricity) rather than parafoveal (3.5° eccentricity) space, to increase the strength of visual crowding (Bouma, 1970, 1973; Kimchi & Pirkner, 2015; Pelli et al., 2004). We hypothesized that the stronger crowding would impair distractor suppression by preventing target–distractor individuation, thereby yielding equivalent attention effects across displays.

Method

The methods used in Experiment 3 were similar to those of Experiment 1, with the following changes:

Subjects A total of 23 new subjects participated in Experiment 3. All of the subjects were students from the University of Oregon with normal or corrected-to-normal vision and gave written informed consent before

[1] Although a between subjects t test comparing crowding strength for Experiments 1 and 2 did not reach significance [$t(34) = 1.823$, $p = .077$], a scaled-information Bayes factor analysis weakly favored the alternative hypothesis, $BF_{10} = 1.41$.

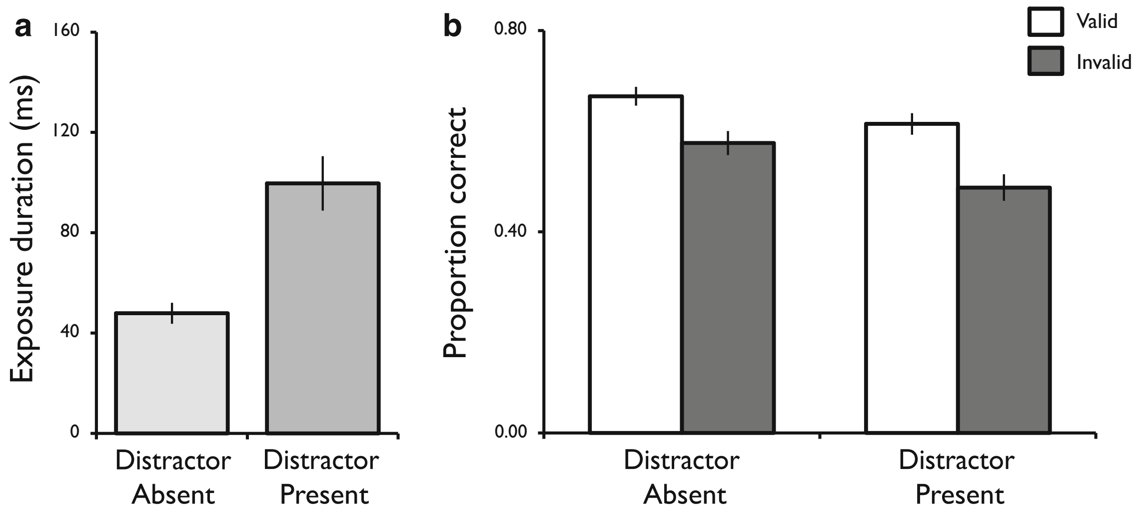

Fig. 4 Results from Experiment 3, in which subjects reported the identity of a peripheral target digit presented with or without flanking letter distractors. (**a**) Mean exposure durations for valid–distractor-absent and valid–distractor-present trials. (**b**) Proportions correct for each of the four conditions (valid–distractor absent, valid–distractor present, invalid–distractor absent, and invalid–distractor present). Error bars represent ± 1 standard error of the mean. In contrast to Experiment 1, the sizes of the attention effect did not differ between display conditions

participating. All experimental sessions were 90 min in length, and each student received partial course credit for participation.

Stimuli The stimuli matched exactly those used in Experiment 1, except that the target display was now centered 5.6° from fixation.

Experimental procedure The procedure matched that of Experiment 1.

Timing procedure The timing procedure matched that of Experiment 1.

Analysis The same analyses were employed here as in Experiment 1.

Results and discussion

Interference effects Consistent with both Experiments 1 and 2, exposure durations were estimated to be significantly longer for the valid–distractor-present condition ($M = 99.72$ ms) than for the valid–distractor-absent condition ($M = 47.92$ ms), $t(22) = 5.73$, $p < .0001$, $d = 1.19$ (see Fig. 4a). Given that interference should be amplified for far—relative to close—displays, we next compared the size of the crowding effects observed here to those observed in Experiment 1. This post-hoc analysis revealed that by virtue of positioning the display farther in the periphery, we succeeded in increasing the size of the crowding effect [heteroscedastic between-subjects t test[2]: $t(29.046) = 3.6$, $p = .001$, $d = 1.34$, where $a = .017$ following a conservative Bonferroni correction to account for multiple statistical tests, since a similar comparison is made in Exp. 5 below].

Attention and biased-competition effects Figure 4b depicts the mean target identification accuracy in the main experiment as a function of display type and precue validity. Again, subjects exhibited strong attention effects in both the distractor-absent ($M = 9\%$), $t(22) = 5.03$, $p < .0001$, $d = 1.049$, and distractor-present ($M = 13\%$), $t(22) = 5.90$, $p < .0001$, $d = 1.23$, conditions. However, despite using the same stimuli as in Experiment 1—albeit presented at a greater eccentricity—there was no difference in the size of the effects across display conditions (biased-competition effect: $M = 3.4\%$), $F(1, 22) = 2.51$, $p = .13$, $d = 0.33$. Evidence in favor of the null hypothesis was further provided, albeit weakly, via the Bayes factor analysis: $BF_{01} = 1.49$. Although these results indicate that biased competition was effectively absent, a post-hoc between-subjects comparison of the sizes of the effects across Experiments 1 and 3 did not reach significance, $t(45) = 1.407$, $p = .17$, $d = 0.42$, $BF_{01} = 1.44$.

This experiment used a design and procedure nearly identical to those of Experiment 1, with the exception of the peripheral position of the stimulus display. Just by moving the stimuli farther from fixation, we eliminated the behavioral signature of biased competition. The larger eccentricity increased crowding strength, in line with the known link between eccentricity and crowding (Bouma, 1970). This explanation is further supported by the significantly larger interference effects observed here than in Experiment 1. We concluded that, similar to Experiment 2, increased crowding prevented

[2] The variances between groups were not homogeneous via Levene's test for equality of variances, $p = .019$.

target–distractor individuation and thereby prevented the resolution of distractor interference by spatial attention. Unlike in Experiment 2, though, the attention effects were comparable in size to those reported in Experiment 1. This provides evidence against the possibility that biased competition is absent only when signal enhancement alone produces large attention effects (as was the case in Exp. 2).

Although we reported no differences in the attention effect sizes between display conditions in Experiment 3, this pattern was not significantly different from the biased-competition pattern observed in Experiment 1. This null result is not too surprising, because we were relying on a between-subjects comparison of a relatively small effect. Thus, in Experiment 4 we presented both parafoveal and peripheral stimulus displays to a single set of subjects, to provide a more sensitive test of whether the biased-competition effect varies as a function of display eccentricity.

Experiment 4

In Experiment 4, the subjects viewed single-digit or number–letter displays (intermixed) presented at either a close (3.5°, as in Exp. 1) or a far (5.6°, as in Exp. 3) eccentricity. The order of the eccentricity conditions was blocked (and counterbalanced between subjects), allowing subjects to maintain stable attention sets with respect to the expected target locations over the course of the experiment. We predicted that the biased-competition effect would only be observed when the display was presented at a relatively close eccentricity.

Method

The methods used in Experiment 4 were similar to those from Experiments 1 and 3, with the following changes:

Subjects Twenty-three subjects participated in Experiment 4. All subjects were students from the University of Oregon with normal or corrected-to-normal vision and gave written informed consent before participating. All experimental sessions were 90 min in length, and each student received partial course credit for participation. Two subjects were removed from the analyses: one due to experimental error, and a second because she reported after the session that she had not been wearing her prescription glasses, which made the task difficult. All analyses included the remaining 21 subjects.

Stimuli The targets and distractors exactly matched those used in Experiments 1 and 3. The stimulus display was centered either 3.5° from fixation (close condition) or 5.6° from fixation (far condition).

Experimental procedure Each subject completed two experimental tasks: four blocks of 32 trials each of the close-eccentricity condition, and four blocks of the far-eccentricity condition; the order of conditions was counterbalanced across subjects. See the Experimental Procedure section in Experiment 1 for all other design and procedural details relating to this experiment.

Timing procedure Subjects completed between five and 11 blocks of the timing procedure for each of the eccentricity conditions. For most of the subjects, the timing procedures and main experimental tasks were interleaved, with the relevant timing procedure preceding the corresponding experimental task (for two subjects, both timing procedures were completed first, before starting the main experiment). See the Experiment 1 Timing Procedure section for all other details relating to this task.

Analysis The same analyses were employed here as in Experiment 1.

Results and discussion

Interference effects Just as we saw in Experiment 1, exposure durations were significantly longer for valid–distractor-present displays (M = 50.86 ms) than for valid–distractor-absent displays (M = 34.54 ms) at the close eccentricity, $t(20) = 4.42$, $p = .00026$, $d = 0.96$. This was true for the far-eccentricity condition, as well (valid–distractor present, M = 145.31 ms; valid–distractor absent, M = 63.58 ms), $t(20) = 8.92$, $p < .0001$, $d = 1.95$. The crowding effect was significantly greater for the far than for the close displays, $F(1, 20) = 58.52$, $p < .0001$, $d = 1.67$ (see Fig. 5a), consistent with our comparison between Experiments 1 and 3 (see the Exp. 3 Results section), and in line with the known properties of visual crowding.

Attention and biased-competition effects Figure 5b depicts the mean target identification accuracy in the main experiment as a function of display eccentricity (close vs. far), display type (distractor present vs. distractor absent), and precue validity (valid vs. invalid). A repeated measures ANOVA produced a significant three-way interaction between these variables of interest, $F(1, 20) = 7.461$, $p = .013$, $d = 0.6$. Attention effects for the two nearly identical distractor-absent conditions were equivalent (close eccentricity, M = 3.3%; far eccentricity, M = – 2.1%), $t(20) = 1.6$, $p = .13$, $d = 0.35$, whereas the attention effects for the two distractor-present conditions differed significantly (attention effects: close eccentricity, M = 13%; far eccentricity, M = – 3.6%), $t(20) = 6.81$, $p < .0001$, $d = 1.49$.

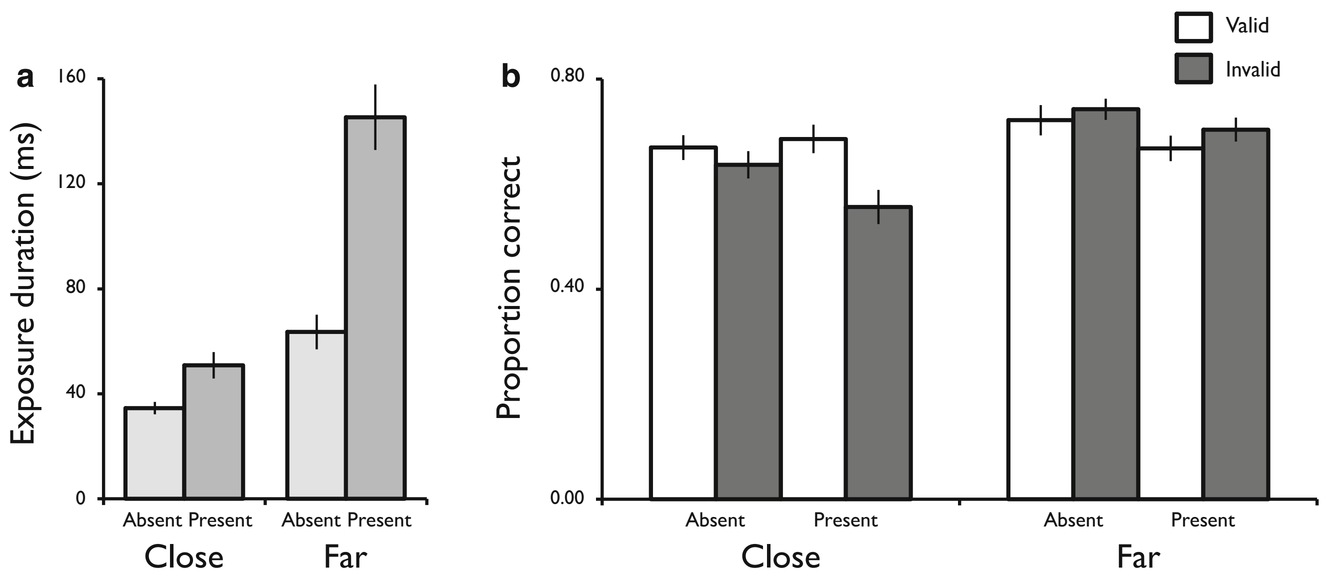

Fig. 5 Results from Experiment 4, in which subjects reported the identity of a parafoveal ("close") or peripheral ("far") target digit presented with or without flanking letter distractors. (**a**) Mean exposure durations for valid–distractor-absent and valid–distractor-present trials for each of the two eccentricity conditions. (**b**) Proportions correct for each of the four conditions (valid–distractor absent, valid–distractor present, invalid–distractor absent, and invalid–distractor present) for both eccentricity conditions. Error bars represent ± 1 standard error of the mean. We observed a significant biased-competition effect (i.e., greater attention effect for distractor-present than for distractor-absent displays) for close displays but not for far displays, and this interaction was significant

Planned comparisons also revealed a significant attention effect for distractor-present displays at a close eccentricity, $t(20) = 5.079$, $p < .0001$, $d = 1.11$, but not for their distractor-absent counterparts, $t(20) = 1.115$, $p = .278$, $d = 0.24$, resulting in a significant biased-competition effect ($M = 10\%$), $F(1, 20) = 4.797$, $p = .041$, $d = 0.48$, $BF_{10} = 1.82$. Conversely, attention effects were equivalently absent for both distractor-present, $t(20) = 1.632$, $p = .118$, $d = 0.36$, and distractor-absent, $t(20) = 0.677$, $p = .51$, $d = 0.15$, displays presented at a far eccentricity (biased-competition effect, $M = -1.5\%$; no interaction), $F(1, 20) = 0.138$, $p = .71$, $d = 0.081$, $BF_{01} = 4.65$.

Experiment 4 was designed as a within-subjects test of Experiments 1 and 3, and we replicated the pattern of biased-competition effects reported across both earlier experiments. Namely, biased competition was only observed when the targets were presented relatively close to fixation, when crowding was thus reduced. In the far eccentricity condition, in which stronger crowding impeded target–distractor individuation, cueing effects were equivalent in the presence or absence of distractors. That said, a curious finding was that cueing effects were not observed in the distractor-absent displays and in far-eccentricity distractor-present displays, in contrast to other studies reported here and in the literature. We do not have a firm explanation for why cueing effects did not emerge in these conditions, except to note that such effects for lone-target displays are often quite modest, particularly when perceptual task demands are low (e.g., Dosher & Lu, 2000; Grindley & Townsend, 1968; Shiu & Pashler, 1994), as was the case with our high-contrast single-digit stimuli.

The absence of a cueing effect in distractor-present displays is less common and raises the possibility that long exposure durations would inadvertently eliminate the effect. By setting exposure durations based on individual estimates, we ensured that stimulus encoding time differences would not influence attention effects. However, we also ran the risk of reducing or eliminating attention effects if the durations were unduly long, especially if subjects were given sufficient time to disengage from an invalidly cued location and to shift attention to the target location before the display offsets. Fortunately, there were wide individual differences in encoding times: Estimates ranged from 56.66 to 320.6 ms for the validly cued peripheral distractor-present displays in Experiment 4 (note that the durations used in the main experiment were restricted to 200 ms or less; see the Experiment 1 Timing Procedure section). This variability lent itself well to a post-hoc split-half analysis on the data, allowing us to determine whether subjects with relatively short and long exposure duration estimates showed attention effect size differences. The 11 subjects with the shortest exposure durations required on average 104.56 ms to identify a validly cued crowded target at the performance criterion, which is comparable to the estimate for the full group of subjects from Experiment 3, $t(32) = 0.29$, $p = .77$, $d = 0.10$. Despite the shorter exposure durations used for these subjects, the attention effect remained absent ($M = -4.3\%$) and did not differ from that in the other half of subjects, with exposure duration estimates averaging 190.25 ms (M = – 2.8%), $t(19) = 0.32$, $p = .75$, $d = 0.15$. This analysis ruled out longer exposure duration estimates, in and of themselves, as being responsible for the absent cueing effect. We thus concluded that these findings still fall in line with our hypothesis that the interaction between cueing effects and interference is eliminated when target–distractor individuation is impeded.

Experiment 5

Experiments 1–4 produced results consistent with our prediction that the amplification of cueing effects in the presence of distractors can be eliminated when visual crowding impedes target–distractor individuation. This was demonstrated by manipulating crowding strength in two ways. Increased target–distractor similarity and increased eccentricity of targets yielded amplified crowding effects, as shown by the threshold durations from the staircased timing procedure. In turn, increased crowding effects eliminated the interaction between spatial-cueing effects and the level of interference in the display. Although there is ongoing debate regarding the specific consequences of visual crowding (e.g., Agaoglu & Chung, 2016; Ester, Klee, & Awh, 2014; Ester, Zilber, & Serences, 2015; Gheri & Baldassi, 2008; Greenwood et al., 2009, 2010; Harrison & Bex, 2015; Parkes et al., 2001; Strasburger, 2005; Wolford, 1975), researchers generally agree that visual properties across crowded stimuli are erroneously integrated in some fashion (Pelli et al., 2004). This motivated our hypothesis that the behavioral signature of biased competition—amplified attention effects in the presence of distractors—is contingent on the individuation of targets and distractors.

If our object-based account of biased competition is correct, any kind of visual interference that is not perceived as a distinct object from the target should fail to yield increased attention effects, as compared to a clean display. Thus, to generalize the earlier findings, we created displays in which number targets were embedded within a speckled noise pattern that was not perceived as a distinct distractor object. Even though this noise mask produced interference similar to that evoked by the distractors in the earlier studies, we predicted that subjects would perceive the target and noise as a single, integrated signal, and that attention effects in this study should be equivalent between the clean and noise displays.

Method

Subjects Twenty subjects participated in Experiment 5.

Stimuli The single-digit targets used in Experiments 1, 3, and 4 were included here at the original (parafoveal) eccentricity; however, the targets were embedded in a noise mask (i.e., random speckled patterns that were not intended to elicit a percept of a discrete distractor element) on interference trials. One of four possible speckled patterns was randomly selected and presented simultaneously with the target on noise-present trials (see Fig. 6a). The target was presented alone on noise-absent trials.

Experimental procedure See Experiment 1 for a description of the procedure.

Timing procedure See Experiment 1 for a description of the timing procedure.

Analysis See Experiment 1 for a description of the analyses.

Results and discussion

Interference effects Exposure durations were estimated to be significantly longer for valid–noise-present trials (M = 74.15 ms) than for valid–noise-absent trials (M = 36.03 ms), $t(19) = 6.44$, $p < .0001$, $d = 1.44$ (see Fig. 6b). We next compared the sizes of the interference effects observed here to those observed in Experiment 1. This analysis revealed that the interference in these noise-present displays was stronger than that observed in the distractor-present displays of Experiment 1 [between-subjects t test: $t(42) = 3.19$, $p = .003$, $d = 0.98$, where $a = .017$, following a conservative Bonferroni correction to account for multiple statistical tests since a similar comparison was made in Exp. 3 above].

Attention and biased-competition effects Figure 6c depicts the mean target identification accuracy in the main experiment as a function of display type and precue validity. Subjects exhibited strong attention effects in both the noise-absent (M = 6%), $t(19) = 2.20$, $p = .04$, $d = 0.49$, and noise-present (M = 9%), $t(19) = 3.92$, $p = .001$, $d = 0.88$, conditions. Furthermore, we observed no difference in the size of the effects across display conditions (biased-competition effect: M = 3%), $F(1, 19) = 1.14$, $p = .3$, $d = 0.24$, $BF_{01} = 2.63$.

Here, we compared the attention effects across conditions in which a target was presented alone or embedded within a speckled noise pattern. As we saw when we increased the strength of visual crowding, the attention effects were equivalent across display conditions. In another study (see Supplementary Exp. 3), we replicated this pattern using a different stimulus set (a rotated target T, as in Exp. 2). We take the results of this experiment as further evidence that attention failed to resolve external interference that could not be individuated into discrete distractor elements. That said, a post-hoc between-subjects comparison of the biased-competition effects in Experiments 1 and 5 did not reach significance,

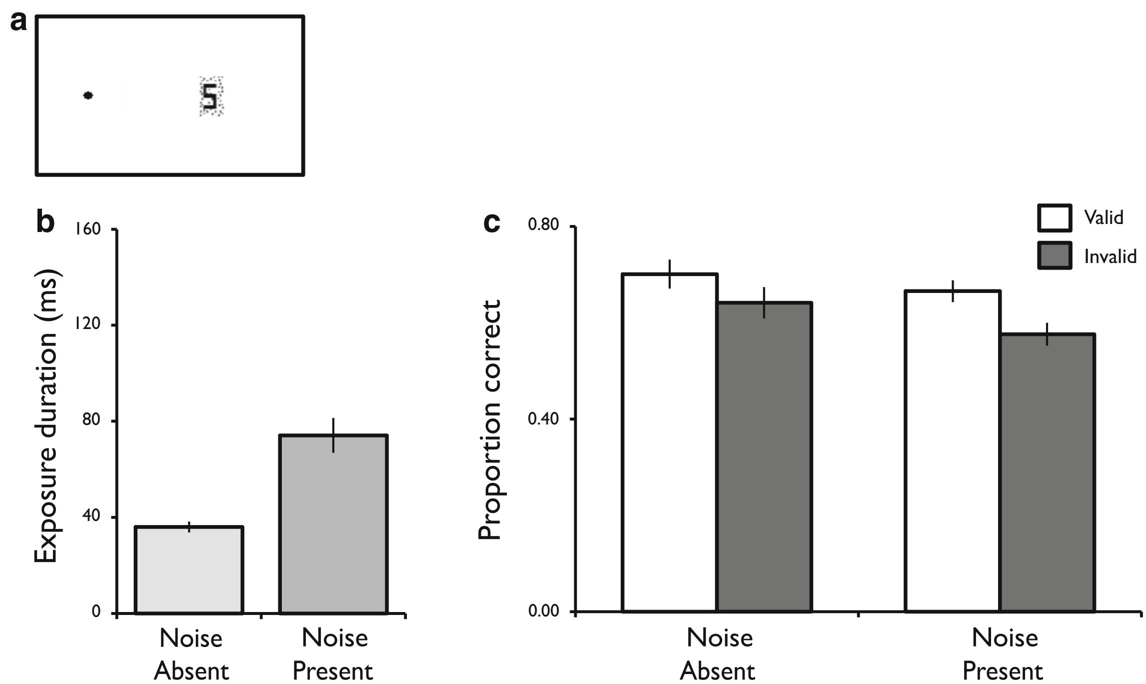

Fig. 6 Results from Experiment 5, in which subjects reported the identity of a parafoveal target digit presented alone or embedded within a speckled noise pattern. (**a**) Illustration of the target display used in Experiment 5. (**b**) Mean exposure durations for valid–noise-absent and valid–noise-present trials. (**c**) Proportions correct for each of the four conditions (valid–noise absent, valid–noise present, invalid–noise absent, and invalid–noise present). Error bars represent ± 1 standard error of the mean. In contrast to Experiment 1, the sizes of the attention effects did not differ between display conditions

$t(42) = 1.36$, $p = .18$, $d = 0.42$, $BF_{01} = 1.48$. Thus, Experiment 6 was conducted to test this prediction with a more sensitive within-subjects design.

Experiment 6

In Experiment 6, subjects were presented with digit targets either flanked by letter distractors or embedded in speckled noise, allowing us to make a within-subjects comparison of the biased-competition effects with the two display types. We predicted significantly larger attention effects in the presence of letter distractors than for a target presented alone, but that interference from a speckled noise mask would yield a cueing effect similar to that with the lone-target displays.

Method

Subjects Fifteen naïve subjects participated in Experiment 6. All subjects were students from the University of Oregon with normal or corrected-to-normal vision and gave written informed consent before participating. The experimental sessions were 90 min in length, and each student received partial course credit for their participation.

Stimuli The target was a single digit. The distracting elements were either letters, identical to those used in Experiment 1, or speckled noise patterns, identical to those used in Experiment 5.

Experimental procedure Subjects viewed the digit targets either alone or in the presence of interference (intermixed), where interference was defined as either flanking letter distractors (as in Exp. 1) or embedded noise patterns (as in Exp. 5). Subjects completed one timing task followed by one experimental task for each of the two interference conditions, for a total of four unique tasks. The order of the interference conditions was counterbalanced across subjects.

Timing procedure See the Experiment 4 Method for a description of the timing procedure.

Analysis See the Experiment 1 Method for a description of the analyses.

Results and discussion

Interference effects Exposure durations on valid trials were significantly longer in the presence of flanking letter distractors ($M = 48.95$ ms) than when there were no distractors ($M = 31.14$ ms), $t(14) = 3.44$, $p = .004$, $d = 0.89$. This was true for the embedded-noise task, as well (noise present, $M = 53.02$ ms; noise absent, $M = 29.29$ ms), $t(14) = 6.03$, $p < .0001$, $d =$

1.56. The strength of the interference did not differ between the two types of interference, $F(1, 14) = 1.40$, $p = .256$, $d = 0.31$ (see Fig. 7a).

Attention and biased-competition effects Figure 7b depicts the mean target identification accuracy in the main experiment as a function of interference type (letter distractors vs. embedded noise), display type (interference present vs. absent), and precue validity (valid vs. invalid). A repeated measures ANOVA produced a marginally significant three-way interaction between these variables of interest, $F(1, 14) = 4.41$, $p = .054$, $d = 0.54$. Because the interaction was marginal, we conducted an additional scaled-information Bayes factor analysis (Rouder et al., 2009); the results favored the alternative hypothesis, $BF_{10} = 1.68$. Attention effects for the two identical lone-target conditions were equivalent (intermixed with trials in which interference was defined as flanking letters, $M = 3\%$; or in which interference was defined as embedded noise patterns, $M = 2\%$), $t(14) = 0.57$, $p = .58$, $d = 0.15$. Conversely, the attention effects for the two interference conditions differed significantly (flanking letters, $M = 16\%$; embedded noise, $M = 7\%$), $t(14) = 3.42$, $p = .0041$, $d = 0.88$. Planned comparisons revealed a significant attention effect for flanking letter distractor displays, $t(14) = 7.97$, $p < .0001$, $d = 2.058$, but not for their distractor-absent counterparts, $t(14) = 1.20$, $p = .25$, $d = 0.31$, and these patterns were significantly different from each other (biased-competition effect, $M = 12.4\%$), $F(1, 14) = 25.68$, $p < .0001$, $d = 1.31$, $BF_{10} = 274.2$. Although within-subjects t tests revealed that attention effects were similarly absent in lone-target displays, $t(14) = 0.75$, $p = .47$, $d = 0.19$, and significant in interference displays, $t(14) = 3.44$, $p = .004$, $d = 0.89$, for the embedded-noise task, we found no significant interaction between display types (biased-competition effect, $M = 5.4\%$), $F(1, 14) = 3.611$, $p = .078$, $d = 0.49$. A scaled-information Bayes factor analysis similarly, albeit weakly, indicated the absence of an interaction: $BF_{10} = 0.807$.

Overall, the results of Experiment 6 confirmed the qualitative pattern observed between Experiments 1 and 5. We found a significant biased-competition effect using a parafoveal number–letter display, but no such effect when flanking letter distractors were replaced with embedded speckled noise patterns. The degree to which the target and the external interference are treated as a uniform object is likely increased in the case of embedded noise, given their spatial overlap. We argue that when stimuli are integrated into a single percept, external interference cannot be appropriately marked as irrelevant, leading to a failure to suppress distracting information. In this case, the attentional system may instead enhance the pooled representation of all elements, in a manner similar to that in interference-absent displays.

Although we suspected that the integration of relevant and irrelevant elements should be strongest with embedded-noise displays, as compared to our previous crowding manipulations, the interaction between the attention effects in the presence and absence of interference was only marginally significant. Similarly, the biased-competition effect for the embedded-noise display, although not statistically reliable, was trending toward a positive effect. Thus, to more

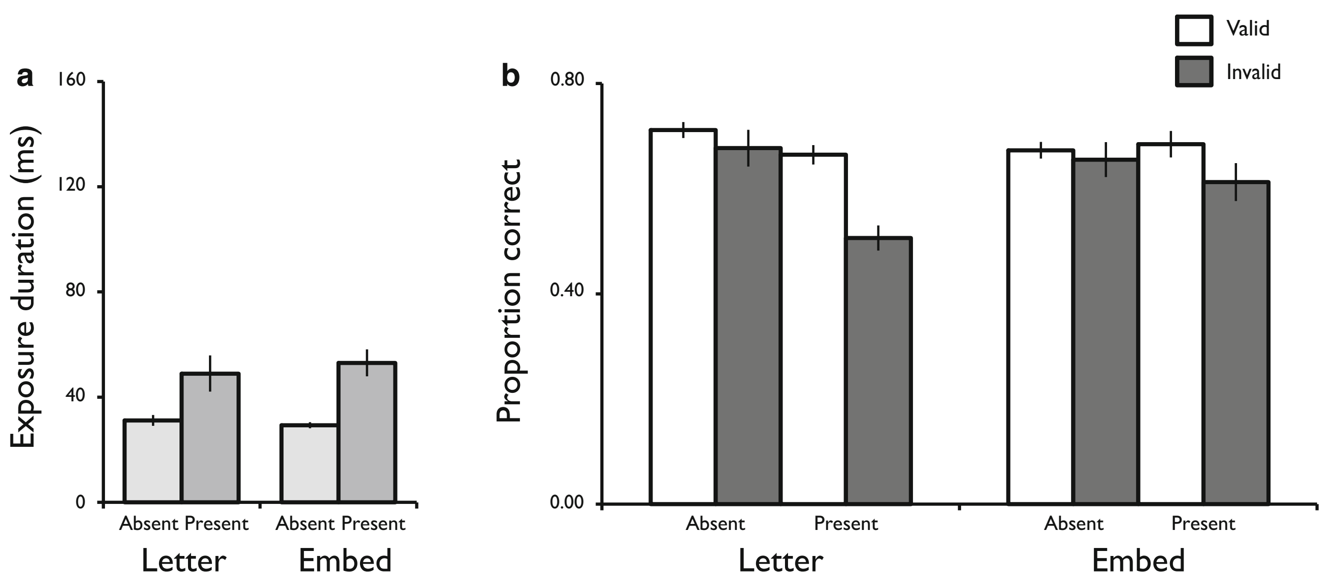

Fig. 7 Results from Experiment 6, in which subjects reported the identity of a parafoveal target digit presented with or without interference, defined as flanking letter distractors (as in Exp. 1) or as embedded noise (as in Exp. 5). (**a**) Mean exposure durations for valid–interference-absent and valid–interference-present trials for each of the two noise type conditions. (**b**) Proportions correct for each of the four conditions (valid–interference absent, valid–interference present, invalid–interference absent, and invalid–interference present) for both interference conditions. Error bars represent ± 1 standard error of the mean. We observed a significant biased-competition effect (i.e., greater attention effect for interference-present than for interference-absent displays) for letter distractor displays but not for embedded noise displays, and this interaction was marginally significant

rigorously evaluate the evidence for a null result, we conducted a Bayes factor analysis that allowed for a direct comparison of the alternative and null hypotheses (Rouder et al., 2009). Though each of these comparisons resulted in values that provided relatively weak evidence in favor of one alternative over the other, they nonetheless conformed to our interpretations of the traditional p values. It is also worth noting that the sizes of the embedded-noise attention effect were consistent across Experiments 5 and 6, as measured by Cohen's d (0.88 and 0.89, respectfully). It seems, then, that the potentially marginal interaction between attention effects in the noise-present and -absent conditions is driven mainly by the noise-absent trials. Notably, the noise-absent conditions were entirely equivalent in design and procedure across the two experimental tasks completed by each subject, and statistically, the attention effects between the two were equivalent. We therefore ran a repeated measures ANOVA, again comparing the attention effects between display conditions, this time substituting the noise-absent values for the equivalent condition intermixed with flanking-distractor trials. We observed no reliable interaction, $F(1, 14) = 2.196$, $p = .16$, $d = 0.38$, and this conclusion was echoed by the Bayes factor ($BF_{01} = 1.45$).

Meta-analysis: Individual differences in crowding susceptibility

To further test our claim that exogenous attention fails to suppress irrelevant external signals when they are effectively integrated with the target, we conducted a meta-analysis correlating each subject's interference effect and biased-competition effect. We predicted an inverse relationship between these factors across all display types, in which large interference effects would reflect substantial target–distractor integration, and small biased-competition effects would reflect inadequate interference suppression.

The relationship between interference strength and biased competition was assessed via a simple linear regression, including the data from 121 subjects across seven independent experiments: Experiments 1–3 and 5, and three supplementary experiments that followed a methodological design very similar to those included here (see the supplementary materials for a description of the methods and the results for each of the three supplementary experiments). Experiments 4 and 6 were excluded from this meta-analysis because each subject participated in two tasks manipulating different aspects of the stimulus display (i.e., the eccentricity of the target, in Exp. 4, and the type of interference presented, in Exp. 6), and there was no obvious choice to include the data from one task over the other (while including data from both would violate the assumption of independent samples). Note, however, that all the conditions included in Experiments 4 and 6 were nonetheless represented in the meta-analysis. Because we were concatenating data across experiments utilizing flanking-distractor and embedded-noise displays, we have opted to relabel the conditions with the all-encompassing terms "interference present" and "interference absent" in the Results and Discussion below.

Results and discussion

A linear regression revealed a moderate and robust negative relationship between the strength of interference and the size of biased-competition effects: $R = -.22$, $t(119) = 2.44$, $p = .016$ (see Fig. 8). Thus, subjects who could more easily disambiguate the target from irrelevant elements also showed greater evidence that attention resolved the competitive interactions between stimuli.

Because we had objectively measured interference effects with individual exposure duration estimates that were utilized during the main experiment, it was possible that exposure duration, and not the strength of interference, predicted the presence or absence of biased-competition effects. According to this argument, longer exposure durations lead directly to reduced attention effects (and thereby to reduced biased-competition effects) because subjects were given sufficient time to disengage from any interference and process the target. Our most obvious evidence arguing against this explanation was the biased-competition effect itself. That is, if exposure duration could explain attention effect sizes, then we should have seen larger effects when interference was absent than when it was present, given the significantly shorter exposure durations. With the exception of Supplementary Experiment 3, we never observed larger attention effects when the target was presented alone, even when the biased-competition effect was absent, nor was this pattern reported by Awh et al. (2005). Furthermore, when we analyzed together all five experiments that had failed to produce a measurable biased-competition effect (Exps. 2, 3, 5, and Supplementary Exps. 2 and 3), the attention effects between the interference-present and -absent conditions were equivalent (interference present, $M = 14.9\%$; interference absent, $M = 14.9\%$), $t(76) = -0.014$, $p = .99$, $d = 0.0016$. The fact that the attention effects for lone-target displays rarely exceeded those for interference displays, despite a wide range of exposure duration differences, suggests to us that the effects we observed were most likely due to a common attention mechanism across display types rather than to the durations themselves. Specifically, we argue that when an interference display is not readily segregated into its relevant and irrelevant component parts, the observer must rely on signal enhancement in a manner that is consistent with lone-target displays, whereby the signal of the entire display is amplified (we return to this point below).

Nonetheless, the concern remains valid that longer exposure durations specifically in the interference-present conditions could reduce or eliminate attention effects. As we described previously, this is particularly an issue given that we were targeting transient, exogenous attention with an

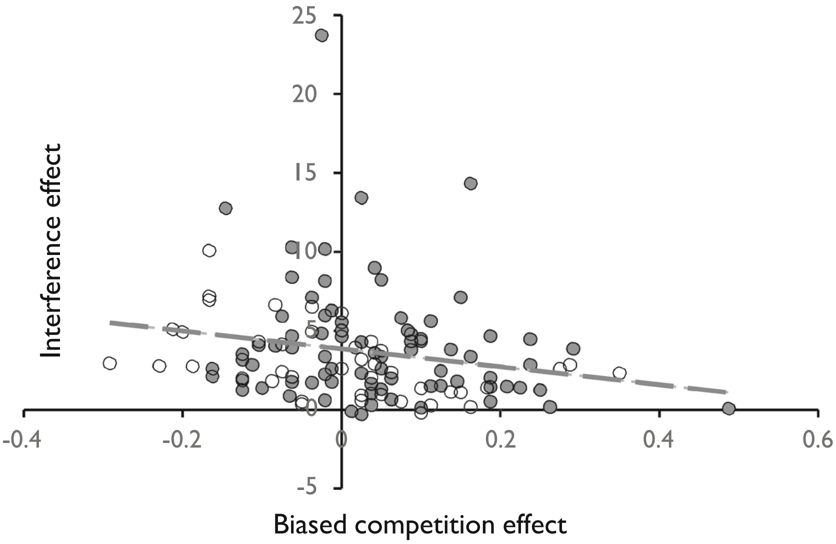

Fig. 8 Correlation between the size of the interference effect (defined as the difference between valid–interference-present and valid–interference-absent display exposure duration estimates) and the size of the biased-competition effect (defined as the difference in attention effect sizes between interference-present and interference-absent displays) for 121 individuals across four of the experiments described in the main text (filled circles) and three supplementary experiments (open circles). A simple linear regression revealed a significant negative relationship, indicating that subjects who were better able to individuate target items from the distractor elements exhibited larger biased-competition effects

uninformative peripheral cue. If the duration were set too long on invalid trials, subjects might have enough time to disengage from the cued location and shift attention to the other (target) location. This would result in smaller attention effects due to improved performance on invalid trials. It is worth highlighting again that the timing procedure used to estimate exposure durations only included valid trials, meaning that any shifts of attention that could happen after stimulus onset did not contribute in any way to these estimates. Furthermore, when we removed all subjects from the meta-analysis whose estimates exceeded 150 ms in the interference-present conditions ($N = 3$),[3] the inverse relationship qualitatively improved, $R = -.31$, $t(116) = 3.46$, $p = .00076$, contrary to the predictions of this alternative account.

To further investigate whether our results were driven solely by longer exposure durations, we reexamined our meta-analysis. First, we sorted all included 121 subjects on the basis of their exposure durations for the interference-present conditions, and next correlated the interference effects with the biased-competition effects for only the 61 subjects with the shortest durations. In this analysis, every experiment (1–3, 5, and Supplemental Exps. 1–3) was represented by at least four subjects, and the exposure duration estimates ranged from 23 to 54 ms. If exceedingly long exposure durations in the interference-present condition accounted for the absent biased-competition effects, then we would expect that the relationship observed in our meta-analysis would be driven primarily by the excluded 60 subjects, and that such a relationship should be absent or considerably weaker here. Instead, we observed a very robust inverse relationship, $R = -.31$, $t(59) = -2.51$, $p = .015$. Furthermore, when we considered only subjects with exposure duration estimates of 100 ms or greater ($N = 15$), we still observed a significant attention effect in the presence of interference ($M = 9\%$), $t(14) = 6.07$, $p < .0001$, $d = 1.57$. Finally, and perhaps most convincingly, exposure durations from interference-present conditions alone failed to significantly predict individual biased-competition effects across all 121 subjects, $R = -.15$, $t(119) = -1.64$, $p = .104$. Overall, we are confident that long exposure durations, in and of themselves, cannot account for the observed inverse relationship.

We argue that in the face of strong interference, relevant and irrelevant elements in a visual display become perceptually integrated and, due to this excessive integration, attention fails to inhibit the irrelevant signals. This is evident by the fact that when the strength of interference was increased, the attention effects on interference-present displays were not significantly different from those on lone-target trials. Instead, attention may unduly enhance the irrelevant elements along with the target. To the extent that signal enhancement is deployed for both display types, one might surmise that we should observe poorer performance in the presence of interference when concurrent distractor suppression is absent, even despite the timing procedures that were designed to equate task difficulty. As we noted above, when we failed to observe biased competition, attention effects (defined as valid – invalid performance)

[3] With the removal of these subjects (all from Exp. 3), a significant inverse relationship also emerged when only the experiments reported the main text were included: $R = -.26$, $t(74) = -2.33$, $p = .023$. Thus, this result does not critically depend on the inclusion of the three supplementary experiments.

were decidedly not smaller for the interference-present conditions. However, when we consider valid trials only, we do notice a consistent, albeit negligible, difference in line with this prediction. Although the differences in accuracy between valid–interference-absent and valid–interference-present trials rarely reached significance within an individual experiment [Exp. 3 and the letter noise display in Exp. 6 being the exceptions: $t(22) = 2.091$, $p = .048$, $d = 0.44$, and $t(14) = 2.19$, $p = .046$, $d = 0.57$, respectively], most did conform to this qualitative pattern. We thus conducted a post-hoc analysis, in which we compared the accuracies between valid–interference-absent and valid–interference-present conditions across all experiments included in the linear regression described above. Here we observed significantly better performance on valid–interference-absent trials (valid–interference absent, $M = 71\%$; valid–interference present, $M = 66\%$), $t(120) = 3.51$, $p = .00063$, $d = 0.32$; this was similarly true for a comparison of the invalid trials (invalid–interference absent, $M = 60\%$; invalid–interference present, $M = 53\%$), $t(120) = 4.27$, $p < .0001$, $d = 0.39$. This indicates that even when attention was preallocated to the target location, irrelevant signals interfered with target identification. These results are consistent with a perceptual pooling of signals across targets and external interference.

Next, we set out to determine whether the presence or absence of a biased-competition effect on an individual level mediated the pattern above. First, we sorted all subjects on the basis of the size of their biased-competition effects, and then compared the accuracy differences between the valid–interference-absent and valid–interference-present trials from the one-third of subjects with the smallest effect sizes to those from the one-third of subjects with the largest effect sizes ($N = 40$ for each group). Those who did not exhibit a biased-competition effect ($M = -10.8\%$) showed significant differences in performance accuracy across the two valid conditions (valid–interference absent, $M = 74\%$; valid–interference present, $M = 67\%$), $t(39) = 4.46$, $p < .0001$, $d = 0.71$. Conversely, those who exhibited the largest biased-competition effects ($M = 17.1\%$) did not show accuracy differences between the valid conditions (valid–interference absent, $M = 72\%$; valid–interference present, $M = 71\%$), $t(39) = 0.57$, $p = .57$, $d = 0.09$, and these patterns were marginally different from each other, $F(1, 78) = 3.81$, $p = .055$, $d = 0.44$. Thus, subjects who failed to exhibit a biased-competition effect also demonstrated a larger degree of undue distractor interference, even when attention was accurately cued to the target location. These results are consistent with our argument that target–distractor integration leads to failed or insufficient external interference suppression. Instead, attention enhances, at least partially, the neural representations of irrelevant elements.

General discussion

The biased-competition model proposes that space-based selection improves the fidelity of behaviorally relevant input by filtering out unwanted clutter, hence reducing its impact on target processing. Thus, attention should show the greatest facilitatory effect in the presence of irrelevant elements. Although this pattern of results has been produced in many behavioral studies (e.g., Awh et al., 2005; Shiu & Pashler, 1994; reviewed in Beck & Kastner, 2009), we noted exceptions to the model's predictions (e.g., Lu & Dosher, 1998; Scolari et al., 2007). We therefore set out to determine the boundary conditions in which biased-competition effects would be elicited.

We predicted that exogenous spatial attention would resolve interference only under conditions in which the target and nontarget elements are effectively represented as distinct objects. We tested this hypothesis by systematically manipulating the strength of visual crowding—a phenomenon known to hinder target–distractor individuation—or by generating interference with embedded noise patterns intended to preclude a percept of individuated distractor elements. In all cases in which we presented a number–letter stimulus display in parafoveal space (Exps. 1, 4, and 6 and Supplementary Exp. 1), increased cueing effects in the presence of interference as compared to lone-target displays suggested that attention had helped to resolve visual interference. However, increased visual crowding (Exps. 2–4 and Supplementary Exp. 2) and integrated noise masks (Exps. 5–6 and Supplementary Exp. 3) eliminated this biased-competition effect.

In light of these experimental results, we wish to highlight two important conclusions. First, our accuracy-based measure was sensitive enough in almost all cases (with exceptions in Exps. 4 and 6; we return to this point below) to detect relatively small exogenous attention effects driven by signal enhancement. This is the most compelling explanation of cueing effects in lone target trials. In the absence of external irrelevant elements, space-based attention largely enables identification of a target stimulus by improving its associative signal and/or reducing internal noise (e.g., Carrasco, 2011). We argue when targets and distractors are perceptually integrated into a single object—as is the case under crowded conditions (Pelli et al., 2004)—signal enhancement operates on the full display in the absence of concurrent distractor suppression. Consistent with this assertion, in cases in which crowding was sufficiently strong, we generally found that attention effects on interference-present trials were equivalent to those on interference-absent trials, in line with the hypothesis that common mechanisms drove cueing effects. Notably, the claim that irrelevant elements are erroneously enhanced in highly crowded displays is further supported by (1) consistently longer stimulus exposure durations required on interference-present trials (derived from our staircasing procedure), and

(2) a small but overall significant performance decrement on valid–interference-present trials as compared to their lone target counterparts. Thus, when signal enhancement is the primary mode of selection, it may be more effective with displays that lack strong interference.

Second, we wish to highlight the wide differences across experiments in stimulus encoding time, particularly for interference displays, as measured by exposure duration estimates. The amount of interference generated by distracting elements varied between subjects, even for a single display type. We suspect when external interference for a given subject is particularly high—regardless of how it is defined—its signal is not sufficiently suppressed (and as we described above, subsequently enhanced). We took advantage of this large variability in encoding time across subjects to examine the relationship between interference and biased competition. A significant negative relationship emerged between the two factors: Individuals who exhibited relatively weaker interference effects also showed larger attention effects on interference-present trials than on trials in which interference was absent. These results suggest that exogenously driven spatial attention resolves visual interference only under specific display conditions: The relevant and irrelevant input must be individuated for distracting influences to be muted. The degree to which individuation is successful appears to be governed in part by individual differences.

The studies described in this article suggest a critical boundary condition for the resolution of visual interference via spatial attention. Across six experiments, we interpret the results to show that attention resolves interference from competing distractors only when they can be individuated into discrete elements. This hypothesis may unify seemingly disparate results in the literature (e.g., Awh et al., 2005; Lu & Dosher, 1998; Scolari et al., 2007; Shiu & Pashler, 1994). We argue here that when crowding is sufficiently strong, the target and distractors are effectively integrated into a single percept, or object (see Pelli et al., 2004), precluding biased processing toward only the relevant elements in the display. Consistent with our interpretation, Chen et al. (2018) recently showed, in a clever neuroimaging study, that selective attention successfully suppressed signals from distracting flankers in weakly crowded displays, but not strongly crowded ones, in area V4. Furthermore, when a pooling model was applied, they found that relatively more weight was given to the unattended flankers within the strong crowding context.

Throughout this article, we have used the term "individuation" to refer to the process by which the target is selected as a unique object apart from surrounding distractors, and target–distractor "integration" in cases when this process fails, resulting at times in an incoherent percept. A large body of crowding research is specifically dedicated to investigating what form integration takes. Two broad models have received support in the literature: Pooling models propose that the perceptual result of crowding is a weighted average of all visual features (Agaoglu & Chung, 2016; Greenwood et al., 2009, 2010; Harrison & Bex, 2015; Parkes et al., 2001), whereas substitution models assert that individual feature values are accessible, but their specific locations and spatial relationships to each other are confusable (Ester et al., 2014; Ester et al., 2015; Gheri & Baldassi, 2008; Strasburger, 2005; Wolford, 1975). We remain purposefully agnostic with regard to this debate, since these data cannot distinguish between the two; nor can either hypothesis be easily tested with our stimulus sets. None of our irrelevant items were associated with alternative response choices, precluding a straightforward test of substitution, and similarly, it is unclear what a subject would report as the average of a target number and set of six distracting letters. It is worth noting, however, that the relationship we are asserting between space-based attention and interference strength is orthogonal to this interesting question.

In hindsight, the data presented here are consistent with an object-based modulation of space-based attention. A long line of research has demonstrated that the selection of space may be governed, at least in part, by the presence of object contours: When attention is directed to only a part of an object, it has been shown to extend to the object boundaries such that irrelevant space is also selected (e.g., Abrams & Law, 2000; Baylis & Driver, 1993; Duncan, 1984; Egly, Driver, & Rafal, 1994; Moore, Yantis, & Vaughan, 1998). Although demonstrations of object-mediated space-based attention are numerous, rarely do they convincingly show that such selection is automatic by explicitly discouraging an attentional spread (Scolari, Ester, & Serences, 2014; but see Kramer & Jacobson, 1991; Scholl, Pylyshyn, & Feldman, 2001). To the extent that crowded target and distractor elements are pooled into a single object representation, as described above, the present study meets this challenge: The full stimulus display includes task-irrelevant information, the selection of which impedes target identification. Although we cannot determine from these experiments how much of the stimulus display is encompassed by the focus of attention on any given trial, it is clear from the estimated exposure durations and overall accuracy differences between corresponding interference-present and interference-absent trials that at least some distracting input is included in the selected region. Furthermore, the disparate findings in Experiments 1 and 2 suggest that this is not simply due to a limited attentional resolution per se, because both stimulus displays occupied the same spatial region. A more parsimonious explanation is that the high interstimulus similarity in Experiment 2 elicited stronger target–distractor integration. Thus, the locus of space-based attention may be governed, at least in part, by appropriate object-based segregation. This is somewhat complementary to Vecera's (2000) biased-competition account of object-based segregation and attention. Although Vecera argued biased competition facilitates object-based segregation, we argue that proper segregation is a necessary precursor to biased competition.

Descriptions of the biased-competition model generally focus on the perceptual consequences of sufficient distractor suppression, whereby target identification is facilitated when external interference is excluded from processing. Similarly, spatial crowding—as was manipulated in this study—is a perceptual phenomenon that is not fully resolvable even in the absence of time pressure, given stable fixation (Bouma, 1970; Pelli et al., 2004). Thus, in the present study, we deliberately used unspeeded accuracy as our dependent measure. In most cases, accuracy-dependent measures were sufficient to detect attention effects, even for interference-absent conditions. However, in the few cases in which no attention effects were observed (i.e., Exps. 4 and 6), it is possible that our measure was simply too coarse to detect them, and that speeded responses would have produced detectable effects in RT. It remains an open question whether attention to perceptually integrated target–distractor displays results in a larger reduction in decision times—as measured by RT differences between valid and invalid trials—than in interference-absent displays.

In each of the experiments reported here, we made use of an uninformative, peripheral precue. Thus, our results may be specific to transient, exogenous spatial attention, whereas notable key differences between this and sustained, endogenous attention preclude sweeping generalizations beyond involuntary mechanisms. For example, whereas Lu and Dosher (1998) found no evidence for distractor exclusion in embedded-noise displays in an exogenous attention task, the same group (Dosher & Lu, 2000) observed larger attention effects in the presence of external interference using the same class of stimuli and an endogenous, central cue. Other evidence suggests that endogenous and exogenous attention are best conceived of as independent systems, given differences in their temporal dynamics, perceptual consequences, and neural mechanisms (e.g., Carrasco, 2011; Corbetta & Shulman, 2002; Hein, Rolke, & Ulrich, 2006). Nonetheless, the two systems do share commonalities, and both have been shown to exhibit perceptual facilitation consistent with the biased-competition account. Thus, whether the results reported here would hold with manipulations of endogenous attention is an interesting question for future research.

Author Note Data collection occurred at the Department of Psychology, University of Oregon, Eugene, Oregon, USA. We thank Jun Ishikawa for help with data collection. M.S. thanks the Texas Tech University Women Faculty Writing Group. This work was funded by NIMH Grant 2R01MH087214-06A1 to E.A. The authors have no commercial relationships to declare.

References

Abrams, R. A., & Law, M. B. (2000). Object-based visual attention with endogenous orienting. *Attention, Perception, & Psychophysics*, *62*, 818–833. https://doi.org/10.3758/BF03206925

Agaoglu, M. N., & Chung, S. T. (2016). Can (should) theories of crowding be unified? *Journal of Vision*, *16*(15), 10. https://doi.org/10.1167/16.15.10

Awh, E., Matsukura, M., & Serences, J. T. (2003). Top-down control over biased competition during covert spatial orienting. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 52–63. https://doi.org/10.1037/0096-1523.29.1.52

Awh, E., Sgarlata, A. M., & Kliestik, J. (2005). Resolving visual interference during covert spatial orienting: Online attentional control through static records of prior visual experience. *Journal of Experimental Psychology: General*, *134*, 192–206.

Baylis, G. C., & Driver, J. (1992). Visual parsing and response competition: The effect of grouping factors. *Perception & Psychophysics*, *51*, 145–162. https://doi.org/10.3758/BF03212239

Baylis, G. C., & Driver, J. (1993). Visual attention and objects: Evidence for hierarchical coding of location. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 451–470. https://doi.org/10.1037/0096-1523.19.3.451

Beck, D. M., & Kastner, S. (2005). Stimulus context modulates competition in human extrastriate cortex. *Nature Neuroscience*, *8*, 1110–1116. https://doi.org/10.1038/nn1501

Beck, D. M., & Kastner, S. (2009). Top-down and bottom-up mechanisms in biasing competition in the human brain. *Vision Research*, *49*, 1154–1165. https://doi.org/10.1016/j.visres.2008.07.012

Bles, M., Schwarzbach, J., De Weerd, P., Goebel, R., & Jansma, B. M. (2006). Receptive field size-dependent attention effects in simultaneously presented stimulus displays. *NeuroImage*, *30*, 506–511. https://doi.org/10.1016/j.neuroimage.2005.09.042

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

Bouma, H. (1973). Visual interference in the parafoveal recognition of initial and final letters of words. *Vision Research*, *13*, 767–782.

Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research*, *51*, 1484–1525. https://doi.org/10.1016/j.visres.2011.04.012

Cheal, M. L., & Gregory, M. (1997). Evidence of limited capacity and noise reduction with single-element displays in the location-cuing paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, *23*, 51–71.

Chen, N., Bao, P., & Tjan, B. S. (2018). Contextual-dependent attention effect on crowded orientation signals in human visual cortex. *Journal of Neuroscience*, *38*, 8433–8440.

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, *3*, 201–215.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*, 193–222. https://doi.org/10.1146/annurev.ne.18.030195.001205

Dosher, B. A., & Lu, Z.-L. (2000). Noise exclusion in spatial attention. *Psychological Science*, *11*, 139–146. https://doi.org/10.1111/1467-9280.00229

Duncan, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology: General*, *113*, 501–517. https://doi.org/10.1037/0096-3445.113.4.501

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, *96*, 433–458. https://doi.org/10.1037/0033-295X.96.3.433

Egly, R., Driver, J., & Rafal, R. D. (1994). Shifting visual attention between objects and locations: evidence from normal and parietal lesion subjects. *Journal of Experimental Psychology: General*, *123*, 161–177. https://doi.org/10.1037/0096-3445.123.2.161

Ester, E. F., Klee, D., & Awh, E. (2014). Visual crowding cannot be wholly explained by feature pooling. *Journal of Experimental Psychology: Human Perception and Performance*, *40*, 1022–1033. https://doi.org/10.1037/a0035377

Ester, E. F., Zilber, E., & Serences, J. T. (2015). Substitution and pooling in visual crowding induced by similar and dissimilar distractors. *Journal of Vision*, *15*(1), 4. https://doi.org/10.1167/15.1.4

Gheri, C., & Baldassi, S. (2008). Non-linear integration of crowded orientation signals. *Vision Research*, *48*, 2352–2358.

Greenwood, J. A., Bex, P. J., & Dakin, S. C. (2009). Positional averaging explains crowding with letter-like stimuli. *Proceedings of the National Academy of Sciences*, *106*, 13130–13135.

Greenwood, J. A., Bex, P. J., & Dakin, S. C. (2010). Crowding changes appearance. *Current Biology*, *20*, 496–501. https://doi.org/10.1016/j.cub.2010.01.023

Grindley, G. C., & Townsend, V. (1968). Voluntary attention in peripheral vision and its effects on acuity and differential thresholds. *Quarterly Journal of Experimental Psychology*, *20*, 11–19.

Harrison, W. J., & Bex, P. J. (2015). A unifying model of orientation crowding in peripheral vision. *Current Biology*, *25*, 3213–3219.

Hein, E., Rolke, B., & Ulrich, R. (2006). Visual attention and temporal discrimination: Differential effects of automatic and voluntary cueing. *Visual Cognition*, *13*, 29–50.

Itti, L., & Koch, C. (2001). Computational modelling of visual attention. *Nature Reviews Neuroscience*, *2*, 194–203. https://doi.org/10.1038/35058500

Kastner, S., De Weerd, P., Desimone, R., & Ungerleider, L. G. (1998). Mechanisms of directed attention in the human extrastriate cortex as revealed by functional MRI. *Science*, *282*, 108–111. https://doi.org/10.1126/science.282.5386.108

Kimchi, R., & Pirkner, Y. (2015). Multiple level crowding: Crowding at the object parts level and at the object configural level. *Perception*, *44*, 1275–1292.

Kooi, F. L., Toet, A., Tripathy, S. P., & Levi, D. M. (1994). The effect of similarity and duration on spatial interaction in peripheral vision. *Spatial Vision*, *8*, 255–279.

Kramer, A. F., & Jacobson, A. (1991). Perceptual organization and focused attention: The role of objects and proximity in visual processing. *Perception & Psychophysics*, *50*, 267–284. https://doi.org/10.3758/BF03206750

Lu, Z.-L., & Dosher, B. A. (1998). External noise distinguishes attention mechanisms. *Vision Research*, *38*, 1183–1198. https://doi.org/10.1016/S0042-6989(97)00273-3

Moore, C. M., Yantis, S., & Vaughan, B. (1998). Object-based visual selection: Evidence from perceptual completion. *Psychological Science*, *9*, 104–110. https://doi.org/10.1111/1467-9280.00019

Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Frontiers in Cognitive Neuroscience*, *229*, 342–345.

Neisser, U., & Becklen, R. (1975). Selective looking: Attending to visually specified events. *Cognitive Psychology*, *7*, 480–494. https://doi.org/10.1016/0010-0285(75)90019-5

Parkes, L., Lund, J., Angelucci, A., Solomon, J. A., & Morgan, M. (2001). Compulsory averaging of crowded orientation signals in human vision. *Nature Neuroscience*, *4*, 739–744. https://doi.org/10.1038/89532

Pelli, D. G., Palomares, M., & Majaj, N. J. (2004). Crowding is unlike ordinary masking: Distinguishing feature integration from detection. *Journal of Vision*, *4*(12), 12. https://doi.org/10.1167/4.12.12

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*, 3–25. https://doi.org/10.1080/00335558008248231

Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General*, *109*, 160–174. https://doi.org/10.1037/0096-3445.109.2.160

Reynolds, J. H., & Chelazzi, L. (2004). Attentional modulation of visual processing. *Annual Review of Neuroscience*, *27*, 611–647. https://doi.org/10.1146/annurev.neuro.26.041002.131039

Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. (2009). Bayesian *t* tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin & Review*, *16*, 225–237. https://doi.org/10.3758/PBR.16.2.225

Scholl, B. J., Pylyshyn, Z. W., & Feldman, J. (2001). What is a visual object? Evidence from target merging in multiple object tracking. *Cognition*, *80*, 159–177. https://doi.org/10.1016/S0010-0277(00)00157-8

Scolari, M., Ester, E. F., & Serences, J. T. (2014). Feature- and object-based attentional modulation in the human visual system. In K. Nobre & S. Kastner (Eds.), The Oxford handbook of attention (pp. 573–600). Oxford: Oxford University Press.

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), 7. https://doi.org/10.1167/7.2.7

Shiu, L.-P., & Pashler, H. (1994). Negligible effect of spatial precuing on identification of single digits. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 1037–1054. https://doi.org/10.1037/0096-1523.20.5.1037

Simons, D. J., & Levin, D. T. (1998). Failure to detect changes to people during a real-world interaction. *Psychonomic Bulletin & Review*, *5*, 644–649.

Stevens, A. A., Maron, L., Nigg, J. T., Cheung, D., Ester, E. F., & Awh, E. (2012). Increased sensitivity to perceptual interference in adults with attention deficit hyperactivity disorder. *Journal of the International Neuropsychological Society*, *18*, 511–520.

Strasburger, H. (2005). Unfocussed spatial attention underlies the crowding effect in indirect form vision. *Journal of Vision*, *5*(11), 8. https://doi.org/10.1167/5.11.8

Treisman, A. (1991). Search, similarity, and integration of features between and within dimensions. *Journal of Experimental Psychology: Human Perception and Performance*, *17*, 652–676. https://doi.org/10.1037/0096-1523.17.3.652

Tripathy, S. P., & Cavanagh, P. (2002). The extent of crowding in peripheral vision does not scale with target size. *Vision Research*, *42*, 2357–2369. https://doi.org/10.1016/S0042-6989(02)00197-9

Vecera, S. P. (2000). Toward a biased competition account of object-based segregation and attention. *Brain and Mind*, *1*, 353–384.

Vecera, S. P., & Farah, M. J. (1997). Is visual image segmentation a bottom-up or an interactive process? *Perception & Psychophysics*, *59*, 1280–1296. https://doi.org/10.3758/BF03214214

Williamson, K., Scolari, M., Jeong, S., Kim, M.-S., & Awh, E. (2009). Experience-dependent changes in the topography of visual crowding. *Journal of Vision*, *9*(11), 15. https://doi.org/10.1167/9.11.15

Wolford, G. (1975). Perturbation model for letter identification. *Psychological Review*, *82*, 184–199. https://doi.org/10.1037/0033-295X.82.3.184