Involuntary attention with uncertainty: Peripheral cues improve perception of masked letters, but may impair perception of low-contrast letters

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Improvements of perceptual performance following the presentation of peripheral cues have been ascribed to accelerated accrual of information, enhanced contrast perception, and decision bias. We investigated effects of peripheral cues on the perception of Gabor and letter stimuli. Non-predictive, peripheral cues improved perceptual accuracy when the stimuli were masked. In contrast, peripheral cues degraded perception of low-contrast letters and did not affect the perception of low-contrast Gabors. The results suggest that involuntary attention accelerates accrual of information but are not entirely consistent with the idea that involuntary attention enhances subjective contrast. Rather, peripheral cues may cause crowding with single letter targets of low contrast. Further, we investigated the effect of the amount of uncertainty on involuntary attention. Cueing effects were (initially) larger when there were more possible target locations. In addition, cueing effects were larger when error feedback was absent and observers had no knowledge of results. Despite these strategic factors, location uncertainty was not sufficient to produce cueing effects, showing that location uncertainty paired with non-predictive cues reveals perceptual and not (only) decisional processes.

Keywords: attention, involuntary attention, peripheral cues, perceptual performance, location uncertainty, knowledge of results

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Introduction

There is an ongoing debate about whether involuntary shifts of attention, elicited by non-predictive peripheral cues, enhance perception. On the one hand, there is evidence that involuntary attention improves accuracy on tasks mediated by contrast sensitivity (e.g., Giordano, McElree, & Carrasco, 2009; Liu, Pestilli, & Carrasco, 2005; Montagna, Pestilli, & Carrasco, 2009; Pestilli & Carrasco, 2005; Pestilli, Viera, & Carrasco, 2007; Scolari, Kohnen, Barton, & Awh, 2007) and increases the apparent contrast of cued stimuli (Carrasco, Ling, & Read, 2004; Fuller, Park, & Carrasco, 2009; Fuller, Rodriguez, & Carrasco, 2008). On the other hand, there is evidence that non-predictive cues do not improve perception, whereas predictive cues do (Kerzel, Zarian, & Souto, 2009; Prinzmetal, McCool, & Park, 2005; Prinzmetal, Park, & Garrett, 2005), and that effects of peripheral cues on perceived contrast are due to decision bias (Kerzel, Zarian, Gauch, & Buetti, in press; Prinzmetal, Long, & Leonardt, 2008; Schneider & Komlos, 2008; Valsecchi, Vescovi, & Turatto, 2010) (but see Carrasco, Fuller, & Ling, 2008). In view of the large literature on this topic, the debate about involuntary cueing effects on accuracy measures has to be qualified by at least two factors: the stage at which attentional effects occur (perceptual enhancement vs. decision making) and the type of perceptual enhancement (contrast enhancement, more efficient transfer into visual short-term memory, noise exclusion, etc.).

As to the type of perceptual enhancement, Smith and colleagues (Smith, Lee, Wolfgang, & Ratcliff, 2009; Smith, Ratcliff, & Wolfgang, 2004; Smith & Wolfgang, 2004, 2007; Smith, Wolfgang, & Sinclair, 2004) proposed that benefits after peripheral cueing arise from more efficient transfer into visual short-term memory (VSTM). Smith, Ratcliff et al. (2004) observed cueing effects with high-contrast Gabors that were masked, but not with low-contrast Gabors that were unmasked (mask-dependent cueing effects, see Table 1). They argued that when a mask clears sensory buffers before identification is complete, speeded accrual leads to better performance.

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Stimulus	Location	Voluntary (predictive cues)	Involuntary (non-predictive cues)
Low contrast	Uncertain	Yes	No, except fovea
	Certain	No	
Masked	Uncertain		Yes
	Certain	Yes	

Table 1. Summary of the mask-dependent cueing hypothesis. The table shows whether cueing effects have been observed for various combinations of stimulus type, location uncertainty, and information content of the cue. The column "voluntary" attention summarizes the results of Gould et al. (2007) and Smith, Wolfgang et al. (2004). The results of the present study are indicated in the column "involuntary" attention.

When the stimuli are unmasked, speeded accrual does not improve performance because processing time is unconstrained. While Smith, Ratcliff et al. (2004) used "weakly predictive" cues that we simply refer to as "predictive,"[1] others have reported cueing effects on masked stimuli with non-predictive cues (Exp. 5 in Henderson, 1991; Luck & Thomas, 1999; Exp. 3 in Müller & Rabbitt, 1989). Forcing speeded responses during various time intervals after target onset also shows that the accrual of information is faster at cued locations (e.g., Carrasco & McElree, 2001).

In contrast to the mask-dependent cueing hypothesis, Carrasco, Penpeci-Talgar, and Eckstein (2000) found cueing effects with masked and unmasked stimuli and suggested that contrast enhancement accounted for cueing effects with and without mask. We refer to this hypothesis as "universal" contrast enhancement to denote that the same mechanism is supposed to improve perception of masked high-contrast stimuli and of unmasked low-contrast stimuli. Thus, there is disagreement as to which mechanism accounts for the performance benefit with masked vs. unmasked stimuli. It could either be the same mechanism (contrast enhancement) or it could be different mechanisms (contrast enhancement for low-contrast stimuli and speeded transfer into VSTM for masked stimuli). In addition, the mechanisms are not always mutually exclusive.

Another disagreement concerns the stage at which cueing effects occur. Contrast enhancement and speeded information accrual are forms of perceptual enhancement. A conflicting hypothesis is that cueing effects occur at the level of decision making. Shiu and Pashler (1994) used predictive cues and found cueing effects when masks were shown at non-target locations, but absent when only a single mask was shown at the target location. With multiple mask displays, it was difficult to determine where the target had been presented, resulting in location uncertainty. When there was only a single mask at the target location, there was no uncertainty as to the location of the target. Therefore, Shiu and Pashler concluded that foreknowledge about the target location allows participants to exclude noise from the decision when there was uncertainty about the target location. The absence of cueing effects when there was no noise (i.e., no irrelevant masks) suggests that part of the cueing effect has to be attributed to decision processes and not to sensory enhancement (see also Palmer, Ames, & Lindsey, 1993; Shaw, 1982).

Thus, there is some agreement that *voluntary* attention combined with location uncertainty leads to cueing effects partly because foreknowledge makes it easier for participants to base their judgments on the correct object(s) (Gould et al., 2007; Palmer et al., 1993; Prinzmetal, McCool et al., 2005; Shaw, 1982; Shiu & Pashler, 1994). The question addressed in the present research is whether *involuntary* attention combined with location uncertainty has similar effects. With non-predictive cues, there is no foreknowledge of the target location because the cue appears with equal probability at all possible target locations. Thus, there is no strategic benefit of attending to the target location. Nonetheless, the possibility has been raised that non-predictive cues bias observers' judgments about which target contains the target stimulus (Prinzmetal, Long et al., 2008; Prinzmetal, McCool et al., 2005) and prime responses to targets appearing at the cued location (Prinzmetal, Ha, & Khani, 2010). Therefore, we expect the cue to bias observers to report their perceptions at the cued location. Better performance at the cued location should result despite the cue being non-informative. We refer to this hypothesis as the location bias hypothesis.

The location bias hypothesis makes the prediction that cueing effects should always occur when there is location uncertainty, even when cues are non-predictive. We tested this hypothesis with stimuli that were either of low contrast and unmasked, or of high contrast and masked. As laid out above, Smith and Ratcliff (2009) hold that only masked stimuli benefit from attention whereas others hold that masked and unmasked stimuli benefit equally (e.g., Carrasco et al., 2000). If the location bias hypothesis or the universal contrast enhancement hypothesis were true, we should always find cueing effects. Conditions in which we do not find cueing effects do not support these hypotheses.

A further goal of the present research was to investigate how decision biases operate. The basic idea is that observers rely more on the cued location despite there being no incentive to do so. If so, what are the factors that determine the weight given to the cued location? One factor may be the amount of location uncertainty, which we manipulated by changing the set size. In visual tasks, performance decreases with set size (e.g., Treisman & Gelade, 1980), but this effect gets smaller when valid cues indicate the target location(s) (e.g., Cameron, Tai, Eckstein, & Carrasco, 2004; Morgan, Ward, & Castet, 1998; Palmer et al., 1993), suggesting that valid cues increase the signal-to-noise ratio. While effects of valid cues in visual search are well studied, little is known about how set size affects involuntary cueing under conditions of location uncertainty. It may be that cueing effects increase the more uncertainty there is. For instance, Luck and Thomas (1999) showed that involuntary cueing effects were larger when uncertainty about the target location was created by presenting masks at non-target locations than when there was no location uncertainty because only a single mask was presented at the target location. In one experiment, we increased uncertainty by doubling the possible target locations from two to four. In another experiment, we increased uncertainty by not providing feedback. Without feedback, observers may not notice that it does not make sense to attend to the cued location and may attribute a larger weight to the cued location.

In all experiments, we investigated involuntary cueing effects with large samples of subjects. In a previous study (Kerzel et al., 2009), we failed to replicate a study that reported involuntary cueing effects with a small group of observers (Liu et al., 2005). One possible explanation for the failure to replicate is a sampling error in Liu et al. (2005). We believe that large sample sizes have the advantage that idiosyncratic strategies cancel out to reveal what is truly "reflexive" or "automatic." After all, trying not to pay attention to a salient event may be as difficult as not to think of a white bear (Wegner, Schneider, Carter, & White, 1987). Note that studies on voluntary attention avoid this problem. However, we acknowledge that our view is not universally accepted in the community and that a small-sample approach certainly does have its merits.

Experiment 1: Orientation judgments, low contrast

In a previous study (Kerzel et al., 2009), we did not observe cueing effects with location uncertainty and non-informative cues, which contradicts the location bias and contrast enhancement hypotheses. Kerzel et al. presented a non-predictive peripheral cue that was followed by two low-contrast Gabor stimuli. One of the Gabors was tilted and observers had to indicate its orientation. The other Gabor was vertical and served as a distractor. The presence of a distractor may have required observers to perform a (minimal) search in order to locate the target. Prinzmetal et al. (2010) observed that cueing effects on reaction times (RTs) change as a function of distractor presence. Similarly, distractors may make the task more difficult, which has been shown to result in weaker involuntary cueing effects on RTs, presumably because the tendency to respond to stimuli at the cued location decreases (Prinzmetal, Zvinyatskovskiy, Gutierrez, & Dilem, 2009). Thus, distractor stimuli may camouflage involuntary cueing effects because the task is more difficult or the set size is larger (one vs. two). Here, we presented only a single, low-contrast Gabor to put the location bias and contrast enhancement hypothesis to a fairer test (see Figure 1A).

Methods

Participants

In all experiments reported here, undergraduate students at the University of Geneva participated for course credit. All procedures were approved by the faculty's ethics committee and were in accordance with the 1964 Declaration of Helsinki. In Experiment 1, 12 students participated.

Apparatus

In all experiments, stimuli were generated by a VISAGE system (Cambridge Research Systems, Rochester, UK) and presented at a refresh rate of 100 Hz on a 21-inch CRT. The display had a resolution of 1024 × 768 (horizontal × vertical) pixels. The background luminance was ~70 cd/m^2. Head movements were restrained by a chin rest.

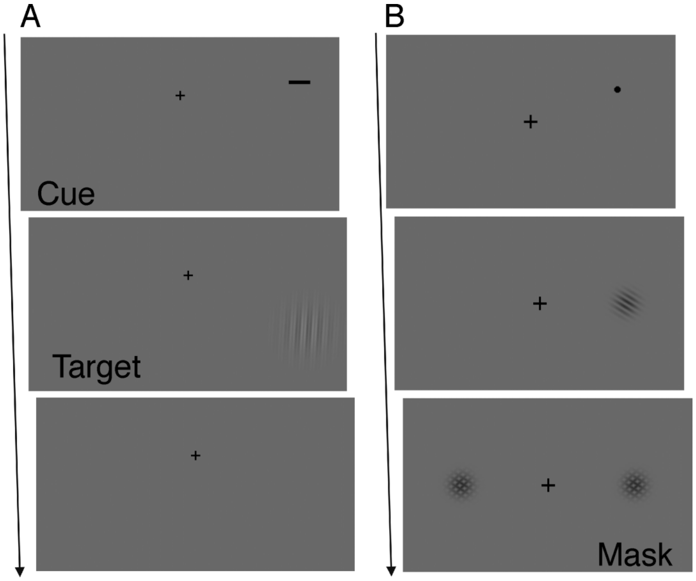

Figure 1. Illustration of experimental stimuli in Experiments 1 and 2. The stimuli are drawn to scale, but the contrast is different. (A) A low-contrast, unmasked Gabor used in Experiment 1. (B) A high-contrast, masked Gabor used in Experiment 2. In both cases, observers' task was to judge the orientation of the Gabor stimuli.

Stimuli

The stimuli were viewed from a distance of 90 cm. A black, 0.3° fixation cross was presented in the center of the screen. The cue was a black, 1 × 0.15° (width × height) line that was presented 5.5° to the left or right and 0.6° above central fixation. Target and distractor were presented 5.5° to the left and right (center to center) and 2.5° below central fixation. As in Liu et al. (2005), target and distractor were Gabor patches (sine wave multiplied by Gaussian) with compound sine waves of 2 and 6 cycles per degree (cpd) at 5% Michelson contrast (i.e., each spatial frequency had a contrast of 2.5%). The space constant of the Gaussian was 1. The cue was presented for 50 ms, and after an empty interval of 40 ms, the target was presented for 90 ms. The stimuli are very similar to those used by Liu et al. (2005) with the exception that our cue was black (less than 1 cd/m^2) and we did not present an additional vertical distractor.

Procedure

Participants' task was to indicate the orientation of the grating by pressing a spatially corresponding key. In this and all the following experiments, participants were instructed to respond as accurately as possible and to take their time to respond. A beep sound was presented after a wrong response. Before the experiment started, we ran a 2-down-1-up staircase (aiming at 71% correct threshold) to familiarize the subjects with the task. Participants completed between 88 and 158 trials for 20 reversals of a single staircase. The staircase was visually inspected and an orientation of 4° or lower was used in the experiment. The possible combinations of target location, cue location, and target orientation (left or right) were repeated to yield 256 trials.

Results and discussion

Proportion correct and median RT were calculated for each condition and participant. A summary of the experimental results is shown in Figure 2 and Table 2. Analysis of proportion correct showed that the difference between invalid and valid trials (0.79 vs. 0.78) was not reliable, $p = 0.57$. RTs were longer in invalid than valid trials (786 vs. 735 ms), $t(11) = 3.85$, $p = 0.003$. The mean orientation of the Gabor was 3°.

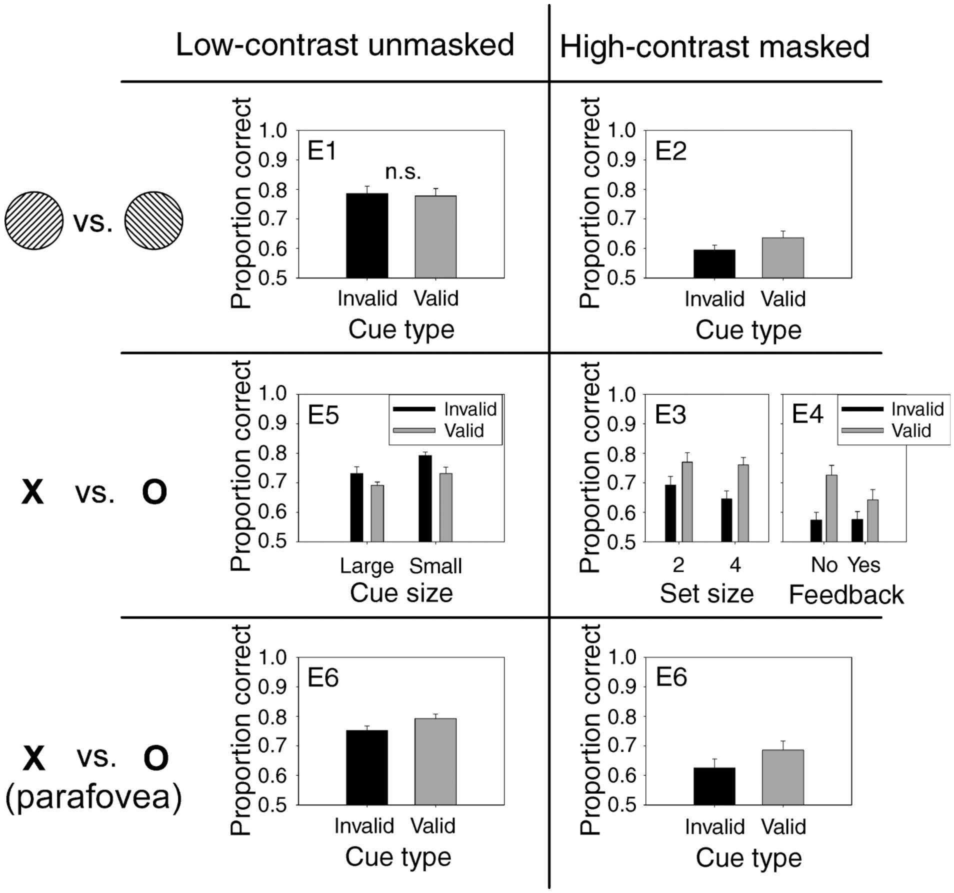

Figure 2. Results from Experiments 1–6. The stimuli were either of low contrast and unmasked or of high contrast and masked. The task was either orientation or letter discrimination. Differences between valid and invalid conditions were significant unless noted otherwise (n.s. for Experiment 1). Experiments are referred to as E1, E2, etc. for Experiment 1, 2, etc.

	N	Cueing effect
Orientation		
Exp. 1, low-contrast unmasked	12	−0.01 ± 0.013, n.s.
Exp. 2, high-contrast masked	16	0.04 ± 0.017
Letters, high-contrast masked		
Exp. 3, set size 2	20	0.08 ± 0.016
Exp. 3, set size 4	20	0.12 ± 0.019
Exp. 4, no feedback	14	0.15 ± 0.019
Exp. 4, feedback	13	0.07 ± 0.067
Letters, low-contrast unmasked		
Exp. 5, salient cue	16	−0.04 ± 0.018
Exp. 5, less salient cue	8	−0.06 ± 0.015
Reduced eccentricity of 1.5°		
Exp. 6, high-contrast masked letters	8	0.06 ± 0.14
Exp. 6, low-contrast unmasked letters	16	0.04 ± 0.018

Table 2. Experimental results. The cueing effect is the difference between valid and invalid conditions. It was significantly different from zero unless noted otherwise (n.s.). Means and between-subject standard error are given in the format *M* ± *SE*.

There was no cueing effect on accuracy, which does not support the location bias and universal contrast enhancement hypotheses. In contrast, Gould et al. (2007) reported reliable effects of predictive cues on orientation judgments with low-contrast Gabors and location uncertainty. Thus, reliable cueing effects emerge with location uncertainty when there is a strategic benefit in attending to the cued location (as in Gould et al., 2007), but not when there is no strategic benefit because the cues do not provide any foreknowledge about the target location (as in the present experiment).

Experiment 2: Orientation judgments, masked stimuli

In Experiment 2, we continued with the orientation judgment task but masked the stimuli. To make the experiment comparable to the remaining experiments, we created a mask that combined all possible target features. The target was a lowered sine wave that varied from medium gray to black at an orientation of 45° from vertical. The mask was a plaid that combined the two possible target orientations (see Figure 1B).

Methods

Sixteen students participated. Participants viewed the stimuli at a distance of 47 cm. The target and mask appeared at 4° to the left or right of fixation. The cue was presented 1.5° above the possible target location and was a black disk of 0.3° diameter. The lowered sine wave had a spatial frequency of 4° cpd and was enveloped by a Gaussian with a space constant of 0.5°. The Weber contrast was 100%. The cue was presented for 100 ms and was immediately followed by the target. Target duration was 70 ms at maximum. The mask consisted of the two possible target orientations and was created by superimposing the two possible target shapes and retaining the smaller luminance value of the two gratings (i.e., the minimal luminance was retained). Before the experiment started, participants completed one staircase (2-down-1-up) with 20 reversals, which took between 79 and 169 trials. The staircase procedure adapted target presentation time and not orientation. With our mask and range of presentation times, it was difficult to discriminate the tilt of the grating even with extremely large tilts. If the threshold procedure indicated a threshold below 70 ms, this value was selected; otherwise, the presentation time was set to 70 ms (to avoid eye movements with longer presentation times). As in the previous experiment, there were 256 trials.

Results

Analysis of proportion correct showed that responses were less accurate with invalid than with valid cues (0.59 vs. 0.64), $t(15) = 2.42$, $p = 0.029$. RTs were longer with invalid than valid cues (899 vs. 859 ms), $t(15) = 3.09$, $p = 0.008$, ruling out speed-accuracy trade-off. The mean target presentation time was 65 ms.

All of the hypotheses listed in the Introduction section predict cueing effects in the present experiment: The location bias account because of location uncertainty, the universal contrast enhancement hypothesis because of contrast enhancement, and the mask-dependent cueing hypothesis because of the masked target displays. However, Experiments 1 and 2 taken together only support the mask-dependent cueing account, because the other hypotheses would have predicted cueing effects in both experiments, but we only observed cueing effects in Experiment 2. Further, Experiment 2 confirms that mask-dependent cueing effects may occur in a task that is structurally similar to Experiment 1 (orientation judgments on sine-wave gratings).

In the following experiments, we changed the type of stimulus to letters. Presently, most research on the mask-dependent cueing and contrast enhancement has used Gabor stimuli (e.g., Cameron, Tai, & Carrasco, 2002; Carrasco, Williams, & Yeshurun, 2002; Gould et al., 2007; Smith, Ratcliff et al., 2004), whereas most research on decision biases or priming has used letter stimuli (e.g., Prinzmetal, McCool et al., 2005; Shaw, 1982; Shiu & Pashler, 1994). In particular, we do not know of any study that has looked at low-contrast letters. Most studies employing letter stimuli used masks.

Experiment 3: Letter discrimination, masked stimuli

In the remaining experiments, we presented variants of Henderson's (1991) paradigm (see Figure 3). Observers were shown a peripheral cue that resembled an underline for 100 ms. Then, the target appeared either at the cued location (valid trial) or at a different location (invalid trial) for 70 ms. Subsequently, all possible target locations were masked. Observers were shown either two or four possible target locations in separate blocks of trials.

Methods

Twenty students participated. The experimental stimuli were highly similar to those in Henderson (1991). Participants fixated a black cross of 0.5° width. Target and masks were presented at an eccentricity of 9.7° (center to center). The target letters were X (0.91° × 0.99°, width × height) and O (0.95° × 0.99°) in Arial. The cue was a horizontal bar (1.23° × 0.27°) at a vertical distance of 0.45° (edge to edge) below the target letter. The mask was the compound of the letters X and O. All stimuli were black (less than 1 cd/m^2) and the Weber contrast was 100%. Each trial started with the presentation of the fixation mark for 1 s. Then, the cue was presented for 100 ms. The target followed immediately without blank interval and was presented for 70 ms. The mask was presented at all possible target positions until a response was recorded. There were either two or four possible target locations. The two locations were left and right of central fixation. The four locations were at the corners of a square centered on central fixation.

The number of possible target locations was blocked. Block order was counterbalanced across subjects. The possible combinations of target location, cue location, and target letter (X or O) were repeated to yield 320 trials per block. The cue was non-predictive. That is, the target had a probability of 50% to occur at the cued location with two possible target locations and a probability of 25% with four possible target locations. Observers were instructed to discriminate the target by pressing one of two designated keys. The experiment was preceded by 20–50 practice trials.

Results

Inspection of the scatter plots (see Figure 4) shows that performance varied strongly between subjects because the stimuli were not individually adjusted. Nonetheless, cueing effects were present from very poor to very good discrimination performance, confirming the robustness of the effect.

A two-way, within-participant ANOVA (validity × set size) showed that performance was worse with invalid than with valid cues (0.67 vs. 0.77), $F(1, 19) = 40.86$, $p < 0.001$. The interaction of validity and set size reached significance, $F(1, 19) = 4.98$, $p = 0.038$, showing that the difference between valid and invalid was greater with four than with two possible target locations (0.12 vs. 0.08). The cueing effect was significantly different from zero with both set sizes, $ts(19) > 4.88$, $ps < 0.001$. Posthoc, we decided to examine whether effects of validity and set size changed over the course of the experiment. Therefore, we divided the data into the first and second blocks of trials (i.e., 160 trials for each block) and ran a three-way ANOVA (block × validity × set). In addition to the results of the above ANOVA, we observed an effect of block, $F(1, 19) = 6.77$, $p = 0.018$, showing that performance improved from 0.71 in the first block to 0.73 in the second block. More importantly, there was a significant three-way interaction, $F(1, 19) = 5.15$, $p = 0.035$. To follow-up on this interaction, we tested for the modulation of the cueing effect by set size in each block separately. The cueing effect was larger with set size four than set size two in the first block (0.13 vs. 0.07), $t(19) = 3.73$, $p = 0.001$, but not in the last block (0.10 vs. 0.09), $p = 0.645$.

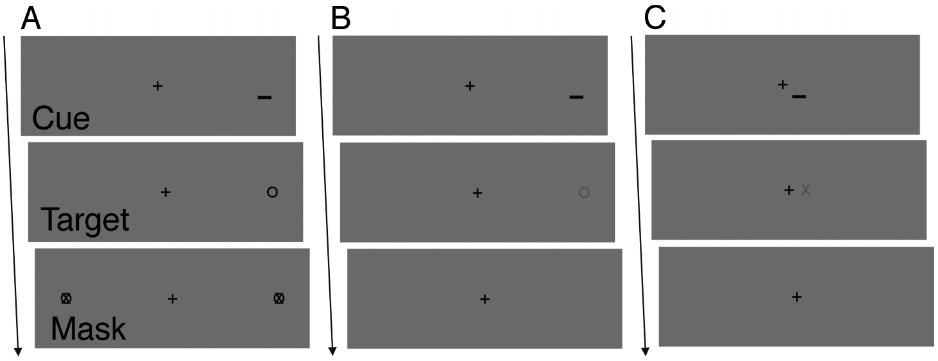

Figure 3. Illustration of experimental stimuli in Experiments 3, 5, and 6. The stimuli are drawn to scale, but the contrast is different. (A) A masked letter used in Experiment 3. (B, C) Unmasked letters of low contrast used in Experiment 5. The eccentricity of cue and target was 9.7° in (A) and (B) and 1.5° in (C).

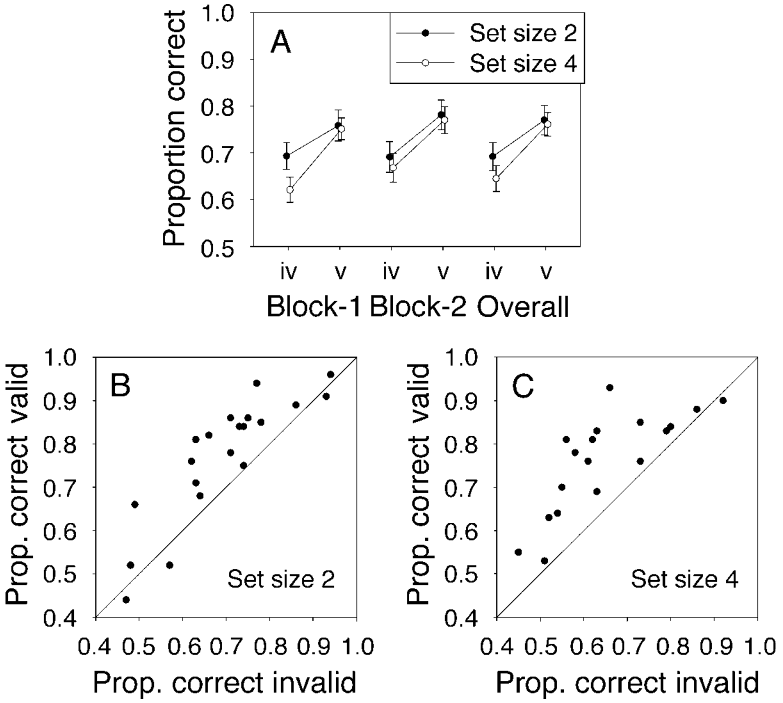

Figure 4. Results of Experiment 3. (A) Proportions correct as a function of validity (iv = invalid, v = valid), set size, and block (first, second, overall). Error bars represent the standard error of the mean. (B, C) Individual proportions correct with set sizes two and four, respectively. One point represents one participant's performance in invalid and valid trials.

Further, we analyzed median RTs. The two-way, within-subject ANOVA (set size × validity) showed that RTs were longer in invalid than valid trials (787 vs. 759 ms), $F(1, 19) = 10.17$, $p = 0.005$, ruling out speed-accuracy trade-off. No further effects reached significance.

Discussion

We observed involuntary cueing effects on perceptual accuracy. Discriminating between the masked letters X and O was easier when the target location was cued. The larger cueing effect with four possible target locations has to be attributed to decision processes. However, the effect of set size was rather volatile. It disappeared after about 160 trials, which means that after some training, observers gave the same weights to cued and uncued locations regardless of set size. Thus, there were some strategic adjustments that influence the size of the cueing effects. In contrast, the increase of 2% in perceptual performance between the first and second blocks was—while significant—rather small. It should be noted that experiments with RT as the main dependent variable have shown both similar and opposite results. When observers had to search for a target letter and report its shape, the effect of a peripheral cue increased when more elements had to be searched (Prinzmetal et al., 2010). The explanation was that the peripheral cue attracted attention and started a serial search at the cued location, which produced larger benefits when more items were to be searched. In contrast, the cueing effect in RTs decreases with increasing display size when target discrimination did not require serial search because the other display locations were empty (Mordkoff, Halterman, & Chen, 2008; Prinzmetal et al., 2010). In the present study, there was only a single target stimulus and the other display locations were empty, but only until all display positions were filled. Thus, it is difficult to compare the present results to those obtained with clearly visible targets and RT as dependent variable because it is not clear whether the present displays are more like "empty" or "filled" displays.

Experiment 4: Letter discrimination, feedback

Classically, the notion of uncertainty refers to the spatial location of the target. However, it has recently been shown that observers can learn to weigh cues differently when they are given feedback about their performance. Droll, Abbey, and Eckstein (2009) showed that observers learn the predictive value of cues (presentation time of 2 s simultaneous with the stimuli) and direct their responses more frequently to predictive cues than to less predictive cues. Presently, we are only interested in non-predictive cues. Observers were told before the experiment that the cues were non-predictive, and there should not be any learning because there was nothing to learn. Nonetheless, there is the possibility of an implicit bias to consider the cued locations as task-relevant. In the absence of feedback (as in Henderson, 1991, 1996), this bias may be more pronounced than when observers know the results of the perceptual decision. In other words, performance feedback may help them notice that it does not make sense to give a higher weight to the cued location.

Methods

Twenty-seven undergraduate students participated. Apparatus, stimuli, procedure, and design were the same as in the preceding experiment with the following exceptions. A different cue was used. Instead of the horizontal line below the letters, a square of 0.59° width was shown at 0.45° above the letter (edge to edge). We changed the cue because we worried that the underline may have resulted in a perceived cue–target compound (i.e., the underlined letters X and O) that was easier to discriminate or that attracted attention because it was familiar. However, we observed essentially the same results with the square such that familiarity can be excluded as a cause for the involuntary cueing effects. The set size was two throughout.

The different combinations of cue position, target position, and target identity were repeated in random order to yield 192 trials. For 14 observers, no error feedback was given. For 13 observers, a beep indicated when the judgment was incorrect (as in all other experiments reported in this paper).

Results

A two-way, mixed-factors ANOVA (feedback × validity) was run on mean proportion correct and median RTs. Mean proportion correct was lower with invalid than valid cues (0.58 vs. 0.69), $F(1, 25) = 41.45$, $p < 0.001$. Cue validity interacted with feedback, $F(1, 25) = 6.16$, $p = 0.02$, showing that the difference between valid and invalid trials was smaller with feedback than without (0.07 vs. 0.15). The cueing effect was significant with feedback (0.58 vs. 0.64), $t(12) = 2.37$, $p = 0.036$, and without feedback (0.57 vs. 0.73), $t(13) = 7.8$, $p < 0.001$. Another ANOVA on RTs confirmed slower RTs with invalid than valid cues (952 vs. 800 ms), $F(1, 25) = 22.14$, $p < 0.001$, and a significant interaction between validity and feedback, $F(1, 25) = 9.65$, $p = 0.005$. The cueing effect was smaller with feedback than without (52 vs. 252 ms) but significant both with feedback (824 vs. 773 ms), $t(13) = 3.86$, $p = 0.002$, and without feedback (1079 vs. 827 ms), $t(13) = 4.14$, $p = 0.001$.

Discussion

We observed that involuntary cueing effects are stronger when no performance feedback was given. This shows that observers use the feedback to decrease the weight given to the cued location. A priori, participants prioritize information from the cued location, but they may learn to better (but not fully) ignore the cue when they have knowledge of results. As for the time course of set-size effects in Experiment 1a, the present results confirm that decision processes do play a role in involuntary cueing effects. Taken together, however, Experiments 1–4 suggest that decision processes only modulate cueing effects but are not sufficient to generate them.

Experiment 5: Letter discrimination, low contrast

Experiments 5 clarifies whether the same involuntary cueing effects are obtained for masked stimuli as with low-contrast, unmasked stimuli. We used the same stimuli as in the preceding experiment but left out the mask and reduced the contrast of the target letters so they were difficult to discriminate (see Figure 3B). The experiment was run in two versions. In one group of participants, we used the same cue as above. In another group of participants, we used a smaller and therefore less salient cue.

Methods

Twenty-four undergraduate students participated. The methods were the same as in Experiment 3 with the following exceptions. No masks were presented. Before the experiment started, the contrast yielding 71% correct responses was determined by an adaptive procedure (2-down, 1-up). Participants completed six staircases with 16 reversals each, which took 345 trials on average (ranging from 317 and 379 trials). Then, the last six reversals of each block were averaged. After each block of 80 trials in the main experiment, the contrast was increased by 0.06 log10 units in the following block if proportion correct was below 0.625 or decreased by the same amount if it was above 0.875.

The experiment was run in two versions. In the first version with 16 participants, the same cue (dimensions: 1.23° × 0.27°) was used as in Experiment 3. Additionally, a smaller and therefore less salient cue was used with eight participants. The size of the cue was reduced to 0.68° × 0.05°, which decreased the surface occupied by the cue by a factor of ~10 from 0.33 to 0.03 deg^2.

Results

With the large cue, responses were more accurate with invalid than with valid cues (0.73 vs. 0.69), $t(15) = 2.23$, $p = 0.04$. RTs did not differ between invalid and valid trials (670 vs. 679 ms), $p = 0.523$. The mean contrast in the main experiment was 6.5%.

With the small cue, responses were more accurate with invalid than with valid cues (0.79 vs. 0.73), $t(7) = 2.23$, $p = 0.004$. RTs did not differ between invalid and valid trials (791 vs. 849 ms), $p = 0.182$. The mean contrast in the main experiment was 6%.

Discussion

Surprisingly, perception of low-contrast, unmasked stimuli was worse at the cued location than at the uncued location. In the previous experiments, perception of masked stimuli showed the opposite pattern: better performance at the cued than at the uncued location. Because we used the same stimulus dimensions and eccentricity as in Experiments 3 and 4, we conclude that non-predictive, peripheral cues affect the perception of stimuli limited by the available processing time differently from stimuli limited by low contrast. Even a less salient cue produced a similar reduction of performance at the cued location.

Experiment 6: Letter discrimination, small eccentricity

In the final experiment, we aimed at clarifying why performance was worse at the cued location, and not just unaffected by the cue as predicted by the mask-dependent cueing account. To clarify whether crowding caused the decrease of performance at the cued location, we reduced the eccentricity of the stimuli. Crowding occurs when a target stimulus is flanked by distractor stimuli in peripheral vision and the ratio between stimulus-to-stimulus distance (center to center) and eccentricity is smaller than 0.5 (e.g., Bouma, 1970; Pelli, Palomares, & Majaj, 2004). For our letter stimuli, this ratio was 0.11 and it is likely that crowding occurred. Therefore, we reduced the eccentricity of the letters to 1.5°, which brings up the ratio to 0.72 (see Figure 3C).

Methods

Twenty-four undergraduate students participated. Apparatus, stimuli, procedure, and design were the same as in the preceding experiment with the exception that the eccentricity was reduced to 1.5°. One group of participants ($N = 8$) saw the masked letters with the large cue. Another group of participants ($N = 16$) saw the low-contrast stimuli with the small cue because the small cue seemed to have produced more reliable reversals of cueing (see Table 2).

Results

We replicated the involuntary cueing effect with masked stimuli: Responses were less accurate with invalid than with valid cues (0.63 vs. 0.69), $t(7) = 4.46$, $p = 0.003$. RTs did not differ between invalid and valid trials (950 vs. 863 ms), $p = 0.117$.

We also found involuntary cueing effects with low-contrast stimuli. Responses were less accurate with invalid than with valid cues (0.75 vs. 0.79), $t(15) = 2.28$, $p = 0.038$. RTs were longer with invalid than with valid cues (667 vs. 627 ms), $t(15) = 2.5$, $p = 0.024$. The average threshold was 3% Weber contrast.

Discussion

When we reduced the eccentricity of low-contrast letter stimuli, impaired performance at the cued location that we observed in Experiment 5 turned into improved performance. For masked stimuli, the positive cueing effect was unchanged. The most important goal of the present experiment was to test whether the reversed cueing effects in Experiment 5 were due to crowding and the present experiment provides a clear answer. Because the inter-object-to-eccentricity ratio was increased from 0.11 to 0.76 in the present experiment, crowding was effectively ruled out and the reversed cueing effect disappeared. The benefit at cued location with low-contrast letter stimuli is inconsistent with the mask-dependent cueing hypothesis but supports the universal contrast enhancement and location bias accounts. To pinpoint contrast enhancement as the source of the cueing effect, future research would have to use a paradigm in which target location is certain, for instance by highlighting the target position by a luminance pedestal (e.g., Smith, Ratcliff et al., 2004) or markers (e.g., Dosher & Lu, 2000; Gould et al., 2007). This would require careful monitoring of eye movements because the stimuli are very close to the fovea and foreknowledge of the target location will easily elicit small eye movements.

While we can only speculate about the origin of the cue-induced improvement in parafoveal vision, we would like to point out that the role of attention may not be the same at all eccentricities. Roberts, Delicato, Herrero, Gieselmann, and Thiele (2007) showed that attention increased the summation area in peripheral vision but decreased the summation area in central vision. Experimentally, Roberts et al. measured the length tuning of cells and found that attention decreased the preferred line length in central vision but increased the preferred line length in peripheral vision. Roberts et al. also conjectured that the changed tuning in the parafovea may result in higher subjective contrast, because high contrast also decreases the preferred line length. While these conjectures still need empirical support, the differential effect of attention on length tuning provides a useful framework for understanding the difference between Experiments 5 and 6.

General discussion

We set out to test three hypotheses about the effects of peripheral cues on perception. The location bias account holds that peripheral cues bias observers to report their perception at the cued location when they are unsure about which location contained the target. Therefore, cueing effects should occur regardless of stimulus type as long as there is uncertainty about the target location. The hypothesis of universal contrast enhancement states that peripheral cues enhance the perception of masked and low-contrast stimuli by increasing the perceived contrast. In contrast, the mask-dependent cueing hypothesis claims that cueing effects only occur with masked stimuli because the principal effect of attention is to accelerate the accrual of information in visual short-term memory. In our experiments, there was always uncertainty about the target location and the cue was always non-predictive.

We did not consistently observe better performance at the cued location. Improvements in performance were absent with low-contrast Gabors (Experiment 1) and low-contrast letters (Experiment 5). Thus, location uncertainty was not sufficient to produce reliable cueing effects. However, we observed in Experiments 3 and 4 that cueing effects were greater with more uncertainty. In Experiment 3, cueing effects were (initially) larger with a set size of four than with a set size of two. In Experiment 4, cueing effects were larger when no performance feedback was given. Thus, decision biases may modulate cueing effects but are not sufficient to generate them. Recently, Prinzmetal, Long et al. (2008) suggested that peripheral cues biased observers to select the cued location when the task was to indicate the stimulus with a higher contrast (but see Carrasco et al., 2008). A point in favor of their hypothesis was that observers tended to report that the cued position contained the stimulus of higher contrast even when no stimulus had been presented. When applied to the present study, one would predict that observers report their perception at the cued location when in doubt about the target's identity, which should result in improved accuracy at the cued location. This was not consistently the case. Thus, decision biases seem restricted to situations in which the task of the observer was to decide which one of two stimuli has a certain property (i.e., higher contrast). That is, a comparison between two stimuli. The present experiments did not involve a comparison between stimuli but implied the identification of a single stimulus. Thus, the occurrence of decision biases depends on the nature of the task.

Further, our data do not entirely support the hypothesis of universal contrast enhancement. In its strictest form, the hypothesis would predict that peripheral cues trigger exactly the same contrast enhancement with masked as with low-contrast stimuli. The different results obtained with low-contrast and masked stimuli are incompatible with this hypothesis. A modified version of the universal contrast enhancement hypothesis may claim that contrast enhancement occurs unless some other, unrelated process interferes with perception of the stimuli. In the present case, one may argue that contrast enhancement did not occur with low-contrast stimuli because crowding occurred. The results of Experiment 6 provide some evidence that crowding was indeed making discrimination of low-contrast stimuli at the cued location more difficult. However, it is not clear why there should have been no crowding with masked stimuli. A study by Scolari et al. (2007) showed that crowding does occur for stimuli whose visibility was limited by the presentation of masks,[2] and that peripheral cues improved performance at the cued location. Further, an influential theory (Intriligator & Cavanagh, 2001) holds that crowding results from the limited resolution of attention and resolution is not expected to differ very much as a function of stimulus type. Therefore, the opposite effects of the same cues point to different processes underlying cueing effects with low-contrast and masked stimuli. Further, the universal contrast enhancement hypothesis has difficulty to explain why there was no improvement for the Gabor stimuli in Experiment 1. In Experiment 1, the ratio of inter-object distance to eccentricity was 0.56, which makes crowding very unlikely. Despite the sufficiently large spacing, cueing effects were absent.

Overall, the data are in line with the mask-dependent cueing hypothesis by Smith et al. (e.g., Smith, Ratcliff et al., 2004). Peripheral cues improved the perception of masked stimuli but not unmasked, low-contrast stimuli. The present research complements previous studies by showing that mask-dependent cueing also holds for non-predictive cues and with location uncertainty. Gould et al. (2007) reported significant positive cueing effects with location uncertainty and low-contrast stimuli. The present study shows that these effects only occur when the cues provide foreknowledge about the target location (as in Gould et al., 2007) but not when the cues are non-predictive (as in the present study). This is consistent with studies showing different behavioral and neural signatures of voluntary and involuntary attention (Esterman et al., 2008; Landau, Esterman, Robertson, Bentin, & Prinzmetal, 2007; Prinzmetal, Leonhardt, & Garrett, 2008; Prinzmetal, Long et al., 2008; Prinzmetal, McCool et al., 2005; Prinzmetal, Park et al., 2005). In and of itself, however, location uncertainty does not lead to cueing effects. A point that needs further investigation is why cueing effects occurred for low-contrast stimuli close to the fovea when target location was uncertain. For our present purposes, it was sufficient to pinpoint masking as the cause of the worse performance at the cued location. Future research should examine the differences between parafoveal and peripheral cueing effects (see Yeshurun & Carrasco, 1998 for an example). Presently, most research has dealt with peripheral cues and targets.

Overall, the present study shows that studies with location uncertainty that presumably confound decision and perception provide results that are consistent with studies that isolate perceptual processing by eliminating location uncertainty (Smith & Ratcliff, 2009; Smith, Ratcliff et al., 2004; Smith & Wolfgang, 2007; Smith, Wolfgang et al., 2004). Thus, conditions with location uncertainty reflect more than just decision biases, at least when the cues provide no information about the target location. Finally, the results are not fully consistent with the notion that peripheral cues enhance performance in all tasks mediated by contrast sensitivity (e.g., Giordano et al., 2009; Liu et al., 2005; Pestilli & Carrasco, 2005; Pestilli et al., 2007; Scolari et al., 2007).

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Footnotes

[1] Gould, Wolfgang, and Smith (2007) used three possible target orientations relative to the target. The target had a probability of 0.5 to occur at the cued location and of 0.25 at each of the other two locations. They describe their cues as "weakly predictive," but we prefer to make a categorical distinction between non-predictive and predictive cues.

[2] Scolari et al. (2007) refer to their stimuli as "low-contrast stimuli" (p. 5). However, Weber fractions of 12% are rather high. If the low contrast had been limiting performance, the presentation of masks would not have been necessary. Contrast would need to be much lower to limit performance. For instance, thresholds were around 6% in the present study, which is in the same range the thresholds for letters reported by Strasburger (2005). In addition, the physical contrast of masked stimuli should not be equated with the subjective contrast. In the present study, the letters had a Weber contrast of 100%, but because we used a very efficient mask, perception of the letters was very difficult and the letters were certainly not perceived as having a high contrast.

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