

# Large effects of peripheral cues on appearance correlate with low precision

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In a previous study (M. Carrasco, S. Ling, & S. Read, 2004), observers selected one of two Gabors that appeared to have higher contrast (comparative judgment). A peripheral cue preceded one of the Gabors by 120 ms. Results showed that the cue increased the perceived contrast of the adjacent Gabor. We replicated the experiment and found correlations between the precision of judgments and perceptual cueing effects. Larger cueing effects occurred in conditions with less precise judgments and in observers who saw less difference between the stimuli. Further, we asked observers to judge whether the two Gabors were equal or different (equality judgment). This method avoids decision biases but turned out to be less efficient. Cueing effects were absent for equality judgments and trained observers but present for untrained observers with poor ability to discriminate the stimuli. In another experiment, we showed that when observers' responses became more rapid over the course of the experiment, a cueing effect in brightness perception emerged that is unlikely to reflect perceptual changes. Overall, the results show that large effects of peripheral cues on appearance correlate with poor ability to discriminate the stimuli. We suggest that the cue biased observers' decision but did not affect their perception.

Keywords: involuntary attention, visual attention, contrast perception, decision bias, equality judgment

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## Introduction

Cues that precede a task-relevant stimulus have been shown to affect performance. In the present contribution, we will focus on peripheral cues that precede the target by about 100 ms. In classic studies, it has been shown that RTs to stimuli at cued locations are faster than RTs to stimuli at uncued locations (Posner & Cohen, 1984). Because the advantage at the cued location was also observed when there was no incentive to attend to the cue (Jonides, 1981), peripheral cues are believed to trigger involuntary shifts of attention. While there is little doubt about involuntary cueing effects on RT, the situation is less clear for cueing effects on perception. In the present study, we will examine the claim that involuntary attention increases the perceived contrast of sine-wave gratings enveloped by a Gaussian (Gabor stimuli) (e.g., Carrasco, Ling, & Read, 2004; Fuller, Park, & Carrasco, 2009; Fuller, Rodriguez, & Carrasco, 2008).

To study effects of peripheral cues on apparent contrast, Carrasco et al. (2004) asked observers to compare two

Gabor stimuli. In their Experiment 2, one of the Gabors always had a contrast of 22% while the contrast of the other Gabor varied from trial to trial. The constant and variable stimuli are referred to as standard and test stimuli, respectively. Observers indicated which of the two Gabors had a higher contrast. At the same time, they indicated whether the selected grating was tilted to the left or to the right. A cue preceded the target display by 120 ms. When the cue was presented at fixation (i.e., a neutral cue), the test contrast that appeared equal to the standard was 22%, indicating veridical perception. When the cue appeared next to the standard, the test contrast that was perceived as equal had to be increased to 28%. When the cue appeared next to the test, the test contrast had to be lowered to 16% to be perceived as equal to the 22% standard. The results suggest that peripheral cues boost the apparent contrast of cued stimuli because attention was attracted to the cued location.

More recently, the conclusion that attention boosts apparent contrast has been questioned. Carrasco et al. (2004) used a task in which observers had to indicate the stimulus of higher contrast. We will refer to the response

as “comparative judgment” (e.g., Schneider & Komlos, 2008; Valsecchi, Vescovi, & Turatto, 2010). Because observers had to select one of two stimuli, the cue may have biased observers to select the cued stimulus. Schneider and Komlos (2008) asked observers to indicate whether the contrast of the two stimuli was equal, which avoids selection and the associated decision bias. Because cueing effects with equality judgments were absent, they concluded that the cue biased decision processes, rather than perception (see also Valsecchi et al., 2010).

Further, Prinzmetal, Long, and Leonardt (2008) suggested that a guessing bias accounted for effects of peripheral cues on apparent contrast (but see Carrasco, Fuller, & Ling, 2008). In one experiment, they asked observers to judge which of two stimuli had a higher contrast, but sometimes omitted the target stimuli. They observed that participants selected the cued location more often than the uncued location despite the target stimuli being absent. Thus, participants appear to guess that the stimulus with higher contrast is at the cued location.

The goal of the present study was to investigate the relation between cueing effects on appearance and discrimination performance. That is, we will examine the relation between the position of the psychometric function (i.e., the point of subjective equality, PSE) and the width of the psychometric function. Presently, research has focused on PSEs and the hypothesis was that peripheral cues shift the PSEs. So far, the width of the psychometric function has not been taken into account. If the psychometric function is wide, observers’ discrimination performance is poor and they will be unsure about their judgments. If it is narrow, observers are able to better discriminate the stimuli and they will be (relatively) sure about their judgments. In other words, wide functions imply that observers are uncertain about their judgments across a larger range of stimuli. The reasons for wide psychometric functions are not entirely clear. Fluctuating factors such as inattention and stable factors such as low perceptual abilities may contribute. We conjecture that observers who are unsure about the perceptual decision may rely more on extraneous information than observers who are (relatively) sure about the perceptual decision. For instance, observers may rely on the heuristic that “there is higher contrast at the cued location” when unsure about their judgments. Thus, uncertainty may enhance decision biases. In a similar vein, it has been claimed that observers are biased to suspect the target at the cued location when there is uncertainty about the target location, thereby enabling them to exclude noise from the decision (e.g., Shiu & Pashler, 1994).

The predictions of the attention-alters-appearance hypothesis with respect to the width of the psychometric function are less clear. Primarily, attention is believed to boost contrast and to shift the position of the psychometric function. Additionally, the perceptual representation of attended stimuli may improve. However, no effects on the precision of contrast judgments are expected. The reason

is that the contrast judgments always require a comparison between cued and uncued stimuli. Thus, a less precise percept will be compared to a more precise percept and the overall precision should remain unchanged.

## Experiment 1

In the first experiment, we set out to compare cueing effects with stimuli that were exactly as in Carrasco et al. (2004), with the only difference that we varied the type of judgment (see Figure 1) and examined relations between the size of cueing effects and discrimination performance. In one condition, observers were asked to indicate the stimulus of higher contrast (comparative judgment). In another condition, we asked observers to judge whether the two stimuli had the same or a different contrast (see also Schneider, 2006; Schneider & Komlos, 2008; Turatto, Vescovi, & Valsecchi, 2007; Valsecchi et al., 2010). Equality judgments allow for the calculation of points of subjective equality just as comparative judgments (e.g., Freyd & Finke, 1985) but avoid decision biases because no particular stimulus has to be selected.<sup>1</sup> Further, we quantified observers’ capacity to differentiate

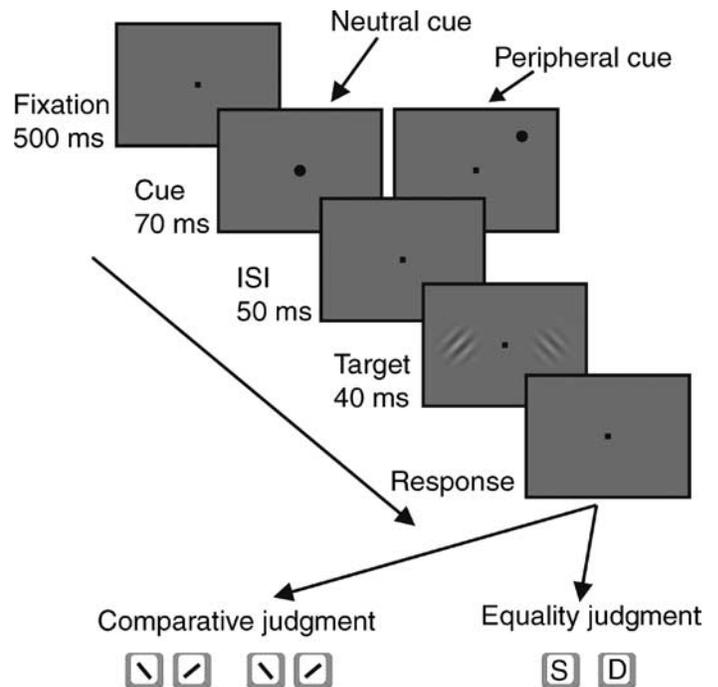


Figure 1. Procedure in Experiment 1 (not drawn to scale). The peripheral cue appeared either above the standard stimulus of 22% contrast or above the test stimulus of variable contrast. For comparative judgments, participants indicated which stimulus had a higher contrast (left stimulus: two keys on the left, right stimulus: two keys on the right) and which orientation it had (see insets in keys). For equality judgments, participants indicated whether the stimuli were the same (“S”) or different (“D”).

between stimuli by analyzing the width of the psychometric functions. Wide psychometric functions indicate large just-noticeable differences or poor discrimination.

## Methods

### Participants

Twelve undergraduate students at the University of Geneva participated for pay and course credit. All procedures were approved by the faculty's ethics committee and in accordance with the 1964 Declaration of Helsinki.

### Apparatus

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 monitor. Background luminance was  $\sim 70$  cd/m<sup>2</sup>. The display had a resolution of  $1024 \times 768$  (horizontal  $\times$  vertical) pixels and was at a distance of 120 cm from the participant. Head movements were restrained by a chin rest.

### Stimuli and procedure

The experimental stimuli were highly similar to those in Carrasco et al.'s (2004) Experiment 2. Participants fixated a black square of  $0.1^\circ$  width. The Gabor patches (sine-wave gratings multiplied by a Gaussian) were presented at  $4^\circ$  to the left or right of central fixation (all distances center to center). The space constant of the Gaussian was set to  $0.43^\circ$ , which produces patches of about  $2^\circ \times 2^\circ$ . The spatial frequency of the sine waves varied randomly between 2 and 4 cycles per degree (cpd) between trials. On each trial, the two patches had the same spatial frequency. The orientation of the sine waves was 45 degrees of rotation, randomly to the left or right. The cue was a filled black circle with a diameter of  $0.3^\circ$ . Peripheral cues were presented  $1.5^\circ$  above one of the Gabors at  $4^\circ$  to the left or right. Neutral cues were presented on the fixation mark. The standard stimulus had a contrast of 22% and the test stimulus was at 6%, 7%, 9%, 11%, 14%, 18%, 22%, 27%, 33%, 41%, 51%, 64%, or 79% contrast (13 increments of about 0.0933 log<sub>10</sub> units). Each trial started with the presentation of the fixation mark for 500 ms (see Figure 1). Then, the cue was presented for 70 ms. After an inter-stimulus interval of 50 ms, the two Gabor patches were shown for 40 ms.

### Design and task

The 208 different combinations of position of the standard stimulus (left, right), position of cue (left, right), cue type (peripheral, neutral), contrast of test stimulus (13 log<sub>10</sub> increments), and spatial frequency (2, 4 cpd) were presented once in each block of trials. Half of the

cues were peripheral and the other half neutral. Mandatory breaks of 1 min were inserted between blocks. In each session, observers completed four blocks. Nine observers completed ten sessions for a total of 8320 trials, one observer completed only 7488 trials, and two others completed 7904 trials.

In separate sessions, subjects performed two different types of judgments. In half of the sessions, observers were told to select the stimulus that had a higher contrast and to indicate its orientation (comparative judgment). Four horizontally aligned keys were used to collect the response (key 1: left middle finger, key 2: left index, key 3: right index, key 4: right middle finger). To indicate which stimulus had a higher contrast, participants responded with the corresponding hand (left stimulus: key 1 or 2, right stimulus: key 3 or 4). To indicate the orientation of the target, the spatially corresponding index or middle finger of the respective hand was used (tilted to left: key 1 or 3, tilted to the right: 2 or 4). In the other half of the sessions, observers were asked to judge whether the two stimuli appeared to be identical or not by pressing one of two designated keys. For both tasks, a single key press was collected per trial. The type of judgment alternated between sessions. Observers were instructed to respond as accurately as possible and to take their time to respond (non-speeded).

## Results

Trials were collapsed across the two possible positions of cue and standard stimulus. We then fitted psychometric functions to the data. For the comparative judgment, we chose to fit a logistic function to the proportion of “test stimulus has higher contrast than standard stimulus” responses,  $y$ :

$$y = 1/(1 + \exp(-(x - a)/b)). \quad (1)$$

For the equality judgment, we chose to fit the proportion of “both stimuli have same contrast” responses,  $y$ , by a scaled logistic distribution:

$$y = c * \exp(-((x - a)/b)^2). \quad (2)$$

The parameter  $x$  is the log<sub>10</sub> contrast of the test stimulus,  $a$  is the point of subjective equality (PSE), and  $b$  is the width of the function. Large widths result in shallow curves. For the logistic distribution, the parameter  $c$  indicates the “height” of the distribution. The relative frequency of “same” responses is determined by the criterion the participant adopts. Conservative participants will respond “same” less frequently than more liberal

participants. Differences in criterion will change the overall number of same responses (“height” of the distribution), but this is independent of the PSE and slope of the curves. The proportion of judgments that the test stimulus has a higher contrast than the standard and the proportion of judgments that the contrast of the two stimuli is the same are shown in Figure 2. The various psychometric parameters are summarized in Figure 3. Analyses were carried out on logarithmic contrast values. However, PSEs (and only PSEs) are reported in percent contrast for clarity.

### Points of subjective equality

PSEs (see Figure 3A) were subjected to a three-way, within-participants ANOVA (2 judgment  $\times$  2 spatial frequency  $\times$  3 cue type). The interaction of judgment and cue type,  $F(2, 22) = 11.01$ ,  $p < 0.001$ , showed that cueing effects were present with the comparative judgment but absent with the equality judgment. The interaction of spatial frequency and cue type,  $F(2, 22) = 7.09$ ,  $p = 0.004$ , showed that cueing effects were larger with 4 cpd than with 2 cpd. None of the remaining main effects or interactions reached significance ( $ps > 0.2$ ). To follow up on the significant interactions, we ran one-way ANOVAs to test for effects of cue type for each combination of spatial frequency and judgment. A significant cueing effect could only be confirmed with the comparative judgment and a spatial frequency of 4 cpd,  $F(2, 22) = 5.98$ ,  $p = 0.008$  (remaining  $ps > 0.2$ ). At 4 cpd, a test stimulus of 19.2% contrast appeared equal to a 22% standard stimulus when the test was cued, and a 24.3% test stimulus appeared equal to a 22% standard stimulus when the standard was cued. These effects are far smaller than those reported by Carrasco et al. (2004): In their study, the PSEs for 4 cpd were 16% when the test was cued and 28% when the standard was cued. Possibly, the additional equality judgment in our experiment reduced the size of the cueing effect for the comparative judgment. Alternatively, the better discrimination performance of our observers may account for the reduction (see below). The smaller cueing effects with 2 cpd seem to replicate Figures 5a and 5b in Carrasco et al. However, modulations of cueing effects by spatial frequency were not formally tested in their study.

One may argue that estimations of the PSEs with equality judgments were not reliable. Consequently, the resulting variability of PSEs prevented cueing effects from reaching significance. To counter this argument, we calculated the standard deviation of PSEs between neutral, test cued, and standard cued for each combination of spatial frequency, task, and participant (see Figure 3B). Effects of cueing, as well as unreliable measurements, will increase the variability between the three conditions. A two-way ANOVA (judgment  $\times$  spatial frequency) showed that standard deviations were higher with 4 cpd than with 2 cpd,  $F(1, 11) = 9.67$ ,  $p = 0.01$ , but the interaction of task

and spatial frequency,  $F(1, 11) = 6.75$ ,  $p = 0.025$ , showed that the increase with 4 cpd was only observed with the comparative judgment. Inspection of Figure 3B confirms that standard deviations were about the same in conditions that did not produce reliable cueing effects. In contrast, the standard deviation of PSEs with the comparative judgment and 4 cpd was larger, which reflects the effect of the cue. Thus, increased variability of PSEs with equality judgments cannot explain the absence of reliable cueing effects.

Next, we investigated whether observers’ PSE over- or underestimated the true contrast of the standard stimulus in the neutral condition. A one-sample  $t$ -test compared the PSEs against the true contrast of 22%. There was an underestimation in the neutral condition with equality judgments and 2 cpd (PSE of 20.9%),  $t(11) = 2.98$ ,  $p = 0.013$ , which is marginally significant after Bonferroni correction (four  $t$ -tests lower the significance level to 0.0125). The remaining PSEs in neutral conditions were not different from the true contrast,  $ps > 0.19$ .

### Width of psychometric functions

Mean widths are graphed in Figure 3C. A three-way ANOVA (judgment  $\times$  spatial frequency  $\times$  cue) was conducted. The psychometric functions were wider with equality than comparative judgments (0.26 vs. 0.11),  $F(1, 11) = 217.02$ ,  $p < 0.001$ , showing that observers were less precise to judge whether two objects were similar than to decide which had the higher contrast. Psychometric functions were wider with 4 cpd than with 2 cpd (0.2 vs. 0.17),  $F(1, 11) = 11.89$ ,  $p = 0.005$ . The mean width was large with test cued, intermediate with neutral cues, and small with standard cued (0.2, 0.19, and 0.17, respectively),  $F(2, 22) = 8.3$ ,  $p = 0.002$ . The interaction of cue type and type of judgment approached significance,  $F(2, 22) = 3.43$ ,  $p = 0.051$ , indicating that the decrease in width when the standard was cued was more pronounced with equality judgments (comparative: 0.12, 0.11, and 0.10, equality: 0.27, 0.27, and 0.24, for test cued, neutral, and standard cued, respectively). Finally, the interaction of spatial frequency and cue type was significant,  $F(2, 22) = 4.57$ ,  $p = 0.022$ , suggesting that the effects of cue type were larger with 4 cpd than with 2 cpd (2 cpd: 0.18, 0.18, and 0.16; 4 cpd: 0.22, 0.2, and 0.18 for test cued, neutral, and standard cued, respectively). These results suggest that cueing and spatial frequency changed not only the position of the psychometric curve but also its shape. In particular, functions were wider with 4 cpd. We remind that only this condition produced cueing effects on apparent contrast (PSEs).

We found some further indications that the width of the psychometric function and PSEs were not completely independent. First, our psychometric functions look a lot steeper than those in Figures 5a and 5b in Carrasco et al. (2004). Note that we displayed the same range from 5% to

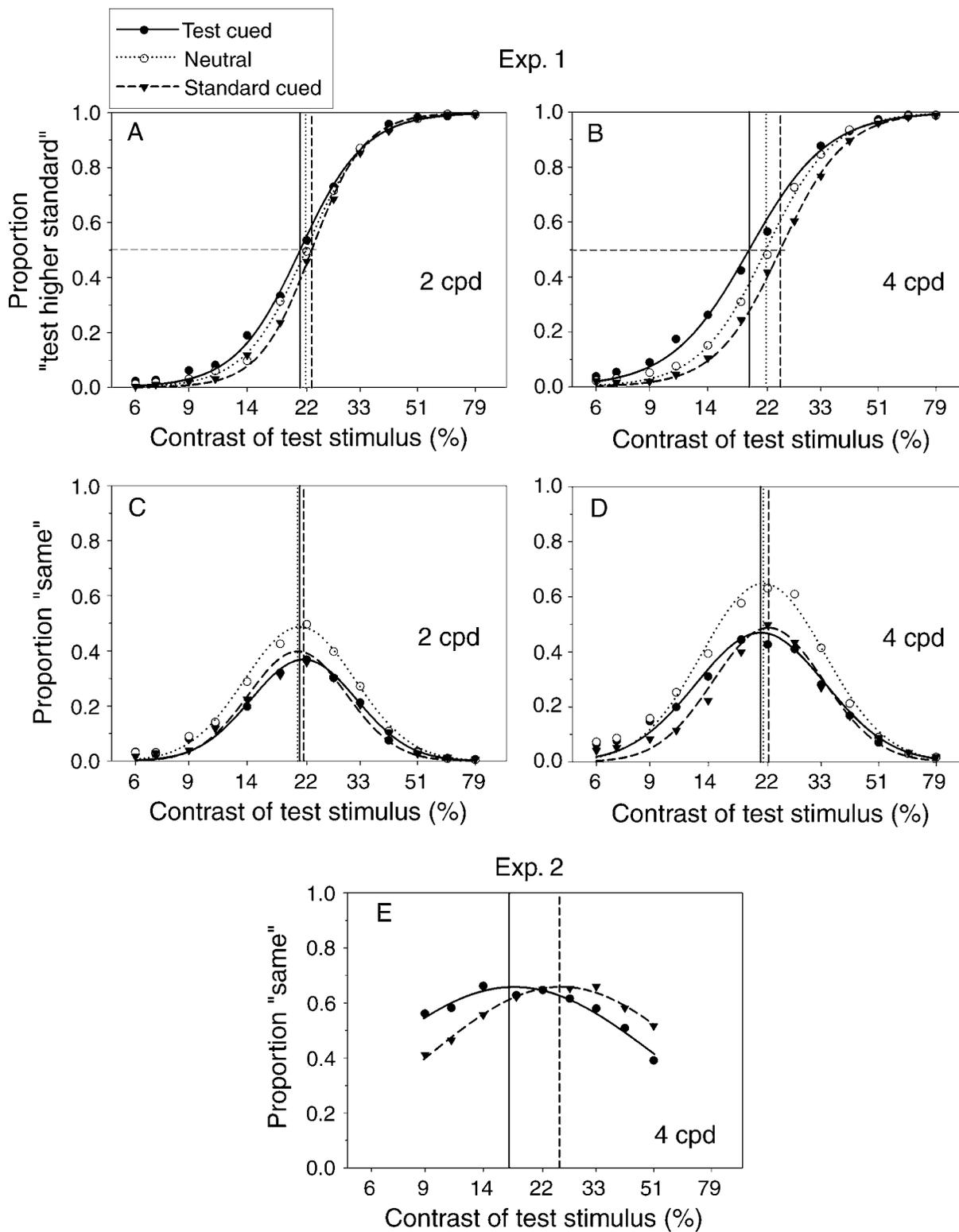


Figure 2. Results of Experiments 1 and 2. (A, B) The mean proportion of judgments that the contrast of the test stimulus is higher than the contrast of the standard stimulus in Experiment 1. (C–E) The mean proportion of judgments that the contrast of the test stimulus is the same as the contrast of standard stimulus in (C, D) Experiments 1 and (E) 2. The spatial frequency was either 2 or 4 cpd. The points of subjective equality are indicated by vertical lines. Error bars are omitted for clarity.

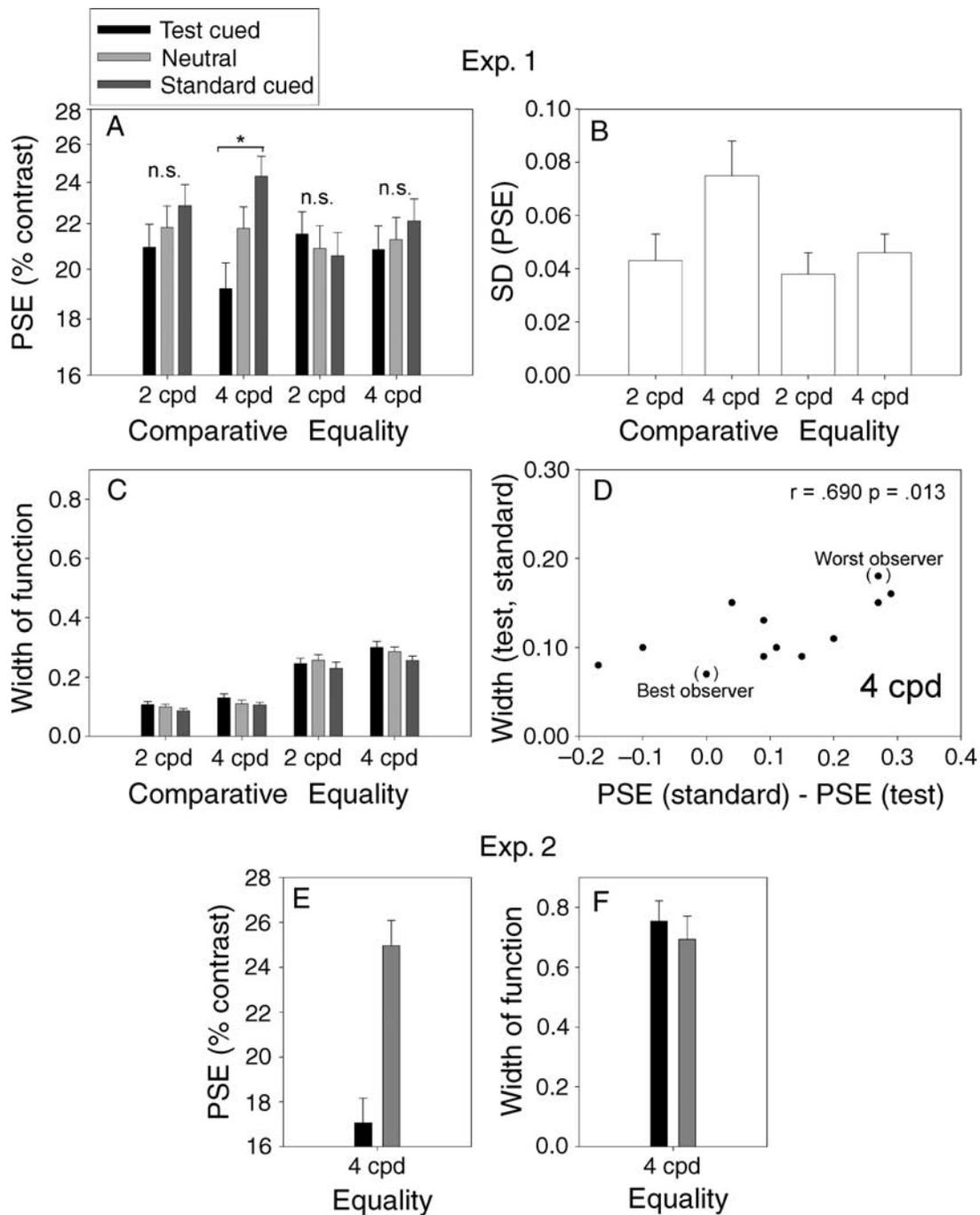


Figure 3. Results of Experiments 1 and 2. (A) The mean points of subjective equality (PSE) in percent contrast for each spatial frequency (2 and 4 cpd) and judgment type (comparative, equality). In all other plots, the log<sub>10</sub> values are shown. (B) The standard deviation of PSEs for each combination of spatial frequency and judgment type. (C) The mean width of the psychometric curves (parameter  $b$  in Equations 1 and 2). (D) The correlation between the width of the psychometric function (average of standard cued and test cued) and cueing effects (difference between standard cued and test cued). Note that wide functions indicate poor discrimination. Functions of the best and worst observers are displayed in the icon on the JOV website. (E) The PSEs and (F) the widths in Experiment 2. Error bars denote the between-participant standard error.

100% contrast in Figure 2. Consistent with our idea that guessing contributes to the cueing effects on PSEs, we also observed smaller cueing effects than Carrasco et al. Further, we correlated cueing effects with slope values. Cueing effects on PSEs were indexed by the difference

between standard cued and test cued. Function widths were averaged across these two conditions. A significant positive correlation emerged only with 4 cpd stimuli and comparative judgments,  $r(10) = 0.690$ ,  $p = 0.013$  (see Figure 3D). In general, participants with steep psychometric functions

would be considered accurate observers, because they notice smaller differences along the relevant dimension. Figure 3D shows that the most accurate observer with extremely steep psychometric functions showed virtually no cueing effect, while the least accurate observer with shallow curves showed a large cueing effect. Thus, less accurate observers with shallow slopes are also those with large cueing effects.

Finally, we examined the scaling parameter  $c$  of equality judgments. High values indicate that participants adopted a more liberal criterion for “same” responses. Overall, participants were rather reluctant to judge a stimulus as “same” (low  $c$  values), probably because the majority of test stimuli differed strongly from the standard and required a “different” response. A two-way ANOVA (spatial frequency  $\times$  cue) indicated that participants were more liberal with a spatial frequency of 4 than 2 cpd (0.535 vs. 0.418),  $F(1, 11) = 8.44$ ,  $p < 0.014$ . In addition, they judged “same” more often with neutral cues (0.567, 0.419, and 0.443 for neutral, test cued, and standard cued, respectively),  $F(2, 22) = 46.83$ ,  $p < 0.001$ . The interaction approached significance,  $F(2, 22) = 3.30$ ,  $p = 0.056$ , indicating that the difference between neutral and peripheral cues was larger with 4 cpd than with 2 cpd. Further, we did not observe significant correlations between the scaling parameter and the size of the cueing effect, suggesting that the criterion for “same” was independent of differences in PSEs.

### Proportion correct

For tilt judgments (performed with comparative judgments), proportions of correct responses were close to ceiling and not analyzed any further. Mean proportions correct were 0.979 and 0.965 for 2 cpd and 4 cpd, respectively, and 0.968, 0.973, and 0.975 for uncued selected, neutral, and cued selected, respectively.

## Discussion

We examined the hypothesis that peripheral cues increase the perceived contrast of stimuli preceded by non-predictive peripheral cues. Our results show that this hypothesis needs to be qualified. First, cueing only affected the PSEs of 4 cpd gratings but not the PSEs of 2 cpd gratings. Second, cueing effects were only obtained for comparative judgments but not for equality judgments, which replicates an earlier study (Schneider & Komlos, 2008). Therefore, our first conclusion is that effects of involuntary attention on appearance are far less general than previously claimed. We are not aware of any theory of attention that predicts peripheral cueing effects with 4 cpd, but not 2 cpd, or that predicts effects of attention to depend on the type of judgment. However, the data may be nicely summarized by saying that large peripheral

cueing effects on appearance correlate with poor observer performance. First, the 4 cpd condition was more difficult than the 2 cpd condition as shown by flatter psychometric functions. Consistent with our hypothesis, cueing effects were also larger in the 4 cpd condition than in the 2 cpd condition. Second, participants with wide psychometric functions who did not see small differences between the stimuli showed larger cueing effects. Our interpretation is that participants relied upon the cues to guide their judgment of contrast when they were uncertain about the answer. Equality judgments reduce the decision bias because they do not involve stimulus selection but imply a “holistic” comparison.

Further, the ability to discriminate between two stimuli by equality judgment was lower than by comparative judgment (see also Fetterman, Dreyfus, & Stubbs, 1996). Similarly, Turatto et al. (2007) noted that observers were unable to discriminate a difference in PSE obtained by comparative judgment in a task employing equality judgments. Therefore, it seems that equality judgments are a less efficient method because observers’ ability to discriminate between stimuli is underestimated. Possibly, there are more “difficult” points along the psychometric function with equality than with comparative judgments. For the comparative judgment, there is one “difficult” decision point along the psychometric function, namely when the two stimuli are in fact identical. For the equality judgment, there are two such points, when one stimulus is just low enough to be different from the other, and also when that stimulus is just high enough to be different. In addition, we noted a small bias to underestimate contrast with 2 cpd with equality judgments and neutral cues. Nonetheless, equality judgments have the merit of avoiding selection of a single stimulus.

## Experiment 2

In Experiment 1, participants worked through a large number of trials (more than 7488) and may therefore be considered “trained.” In Experiment 2, we reexamined equality judgments in the 4 cpd condition with untrained observers. To preview the results, untrained observers’ performance on the task was abysmal, with psychometric functions twice as wide as those of the trained observers. The question is whether the cueing effect would appear with equality judgments when discrimination performance is extremely poor.

## Methods

### Participants

Nineteen undergraduate students at the University of Geneva participated for course credit.

### Apparatus, stimuli, procedure, and design

These were the same as in [Experiment 1](#) with the following exceptions. Only the equality task and the 4 cpd stimuli were run. The neutral condition was also not included. The standard stimulus had a contrast of 22% and the range of test stimulus contrasts was adjusted to the dynamic range observed in [Experiment 1](#), from 9% to 51% in nine increments on a log<sub>10</sub> scale. To facilitate the task, the orientation of the two Gabors was vertical.

### Design and task

The 36 different combinations of position of the standard stimulus (left, right), position of cue (left, right), and contrast of test stimulus (9 log<sub>10</sub> increments) were presented once in each block of trials. Mandatory breaks of 1 min were inserted after five consecutive blocks (i.e., after 180 trials). In a single session, observers completed 19 blocks for a total of 684 trials. The first 180 trials were training during which no cue was presented and acoustic error feedback was given for physically same stimuli and extremely different stimuli. The last 504 trials provided data. Observers were asked to judge whether the two stimuli appeared to be identical or not by pressing one of two designated keys. Observers were instructed to respond as accurately as possible and to take their time to respond (non-speeded).

## Results

Two participants had extremely shallow curves (widths larger than 2 log<sub>10</sub> units) and were removed from analysis, leaving 17 participants in the final sample. [Figure 2E](#) shows the proportions of “same” judgments, and [Figures 3E](#) and [3F](#) shows the PSEs and widths, respectively. The mean width and height of psychometric functions was 0.72 and 0.63, respectively. When the test was cued, a test contrast of 17% was sufficient to match the standard of 22%. When the standard was cued, a test contrast of 25% was perceived as equal. The difference between test cued and standard cued was significant (17% vs. 25%),  $t(16) = 2.41$ ,  $p = 0.029$ . The width and the height of the distributions did not differ between test cued and standard cued,  $ps > 0.27$ . Inspection of [Figures 2](#) and [3](#) suggests that the performance of untrained subjects in [Experiment 2](#) was considerably worse than the performance of trained subjects in [Experiment 1](#). To evaluate the difference, we ran an independent-samples  $t$ -test on the widths of the psychometric functions, averaged across test cued and standard cued. The average width was larger in [Experiment 2](#) than in [Experiment 1](#) (0.72 vs. 0.28 log<sub>10</sub> units),  $t(17.8) = 6.36$ ,  $p < 0.001$ . The fit of the psychometric model to the data was mediocre (mean  $R^2$  of 0.697), confirming that performance was highly

variable (mean  $R^2$  was better than 0.9 in the previous experiment).

## Discussion

The results show that cueing effects with equality judgments reemerge when observers see very little differences between the stimuli. The fact that the trained observers in the previous experiment who had much better discrimination performance (and more reliable estimates of their PSEs) did not show cueing effects supports the notion that poor ability to discriminate correlates with large changes in appearance. The fact that we obtained cueing effects with same–different judgments is also somewhat at odds with Schneider and Komlos’ (2008) claim that same–different judgments are bias-free. Rather, the present results suggest that biases may be more complex than previously thought. Carrasco et al. (2004) tested whether the cue induced a bias to select the cued side by reversing the judgment (the instruction was to “select stimulus of lower contrast” instead of “select stimulus of higher contrast”). They found that the basic increase in perceived contrast persisted. However, it may also be that the cue is associated with a tendency to attribute “more of something” to the cued location. After all, the cued stimulus is preceded by another stimulus, resulting in “more” stimulation at the cued location. If the association producing the bias was “more contrast at the cued location,” reversing the question is of not much help and this may also explain why the cueing effect persisted to some degree with “same–different” judgments.

## Experiment 3

[Experiment 1](#) showed that a task that avoided selection did not produce cueing effects. In [Experiment 3](#), we used comparative judgments and investigated a dimension that has previously been shown to be unaffected by cueing, notably brightness (Prinzmetal, Nwachuku, Bodanski, Blumenfeld, & Shimizu, 1997). Prinzmetal et al. (1997) and Schneider (2006) went to great lengths to show that above-threshold brightness contrast was not affected by attentional manipulations (dual vs. single task, valid vs. invalid cues). Here, we presented two Gaussians and asked observers to press the key corresponding to the brighter stimulus.

## Methods

### Participants

Fourteen undergraduate students at the University of Geneva participated for course credit.

### Apparatus, stimuli, procedure, and design

These were the same as in [Experiment 1](#) with the following exceptions. We removed the sine-wave grating and only presented the Gaussians. Gaussians were brighter than the background and luminance (Weber) contrast was 22% for the standard and 7%, 11%, 18%, 22%, 27%, 41%, and 64% for the test stimulus. The 56 different combinations of position of the standard stimulus (left, right), position of cue (left, right), cue type (peripheral, neutral), and contrast of test stimulus (7 increments) were repeated twice in each block of 112 trials. In a single 1-h session, observers completed 9 blocks for a total of 1008 trials. Mandatory 1-min breaks were inserted between blocks. Observers were told to select the stimulus that appeared brighter and to indicate its location by pressing a spatially compatible key with the left or right index. Observers were instructed to respond as accurately as possible and to take their time to respond (non-speeded). A short practice block (less than 5 min) preceded the experiment.

### Results

Preliminary analysis showed that PSEs changed over the course of the experiment.<sup>2</sup> We therefore analyzed the data in seven overlapping bins of 224 trials each that were centered on trial number 112, 224, 336, 448, 560, 672, 784, and 896. We calculated the difference between the PSEs of standard cued and test cued (i.e., the cueing effect on PSEs), as well as the mean slope and median RT for these two conditions. The resulting means are presented in [Figures 4B, 4D, and 4F](#). We then carried out one-way ANOVAs with bin as a factor. The cueing effect increased as the experiment progressed,  $F(7, 91) = 3.88, p < 0.001$ . [Figure 4B](#) shows that it was reliable after about 672 trials, but far from significant in the first 336 trials. In contrast, mean width did not change across bins (see [Figure 4D](#)),  $F(7, 91) = 1.28, p = 0.27$ . [Figure 4F](#) shows that RTs decreased by ~220 ms as the experiment progressed,  $F(7, 91) = 16.33, p < 0.001$ . When all trials were considered, the effect of cue type on PSEs approached significance,  $F(2, 26) = 3.16, p = 0.059$ . The PSE was 20.7% when the test was cued, 21.6% with neutral cues, and 22.4% when the standard was cued.

Next, we analyzed the first block of 336 trials and the last block of 336 trials in more detail. This was motivated by inspection of [Figure 4B](#), which shows cueing effects in the last part of the experiment, but none in the first. A two-way ANOVA (2 blocks, 3 cue types) on PSEs revealed a significant interaction between block and cue type (see [Figure 4A](#)),  $F(2, 26) = 4.83, p = 0.016$ . Follow-up one-way ANOVAs showed that the effect of cueing was not significant in the first block,  $F(2, 26) = 0.05, p = 0.955$ , but highly significant in the last block,  $F(2, 26) = 6.65, p = 0.005$ .

A two-way ANOVA (2 blocks, 3 cue types) on the widths of the psychometric functions (see [Figure 4C](#)) revealed a tendency for wider psychometric functions in the last than in the first block (0.123 vs. 0.107),  $F(1, 13) = 4.00, p = 0.067$ . The effect of cue type approached significance,  $F(2, 26) = 2.83, p = 0.077$ , indicating narrower functions when the standard was cued (0.12, 0.12, and 0.103 for test cued, neutral, and standard cued, respectively). The interaction between block and cue type,  $F(2, 26) = 3.622, p = 0.041$ , showed that functions widened from the first to the last block for neutral cues and when the standard was cued (0.104 to 0.137 for neutral, and 0.095 to 0.11 for standard cued), but not when the test was cued (0.122 and 0.122). Thus, the absence of cueing effects in the first block did not occur because participants performed poorly in the first part of the experiment. Quite to the contrary, performance was slightly better at the start than toward the end. As in [Experiment 1](#), we correlated the cueing effect in PSEs (standard cued–test cued) with the mean width of the two conditions. [Figure 4E](#) shows that the two measures were significantly correlated in the last block,  $r(12) = 0.557, p = 0.039$ . No significant correlation emerged in the first block,  $p > 0.8$ .

### Discussion

We confirmed that peripheral cues increased subjective brightness (contrast) when we adapted Carrasco et al.'s (2004) paradigm to measure the same dimension as in Prinzmetal et al.'s (1997) study. This is revealing because another study reported the opposite result (Tsal, Shalev, Zakay, & Lubow, 1994), which was not replicated in Prinzmetal et al., but no study so far reported an increase of brightness (or brightness contrast) for above-threshold stimuli. Brightness perception around threshold may be affected by cueing (Schneider, 2006), but Prinzmetal et al. (2008) suggested that guessing accounts for these effects (but see Carrasco et al., 2008; Ling & Carrasco, 2007).

At the beginning of the experiment, observers took their time to respond and cueing effects on PSEs were absent. Over the course of the experiment, observers accelerated, probably because they noticed that thinking about the decision did not help much, or they simply wanted to get the experiment over with (remember that there were 1008 trials, which is a lot for a single session). The higher speed decreased the precision of judgments slightly and resulted in cueing effects in PSEs that were not present at the beginning. All of these factors suggest that cueing effects on PSEs were caused by a decision bias, rather than by perceptual changes. If the cue had changed perception, why were these effects absent in the first block? Perceptual discrimination was certainly not worse in the first block. Overall, RTs in the last block were in the range of a speeded choice task (~450 ms). It seems therefore

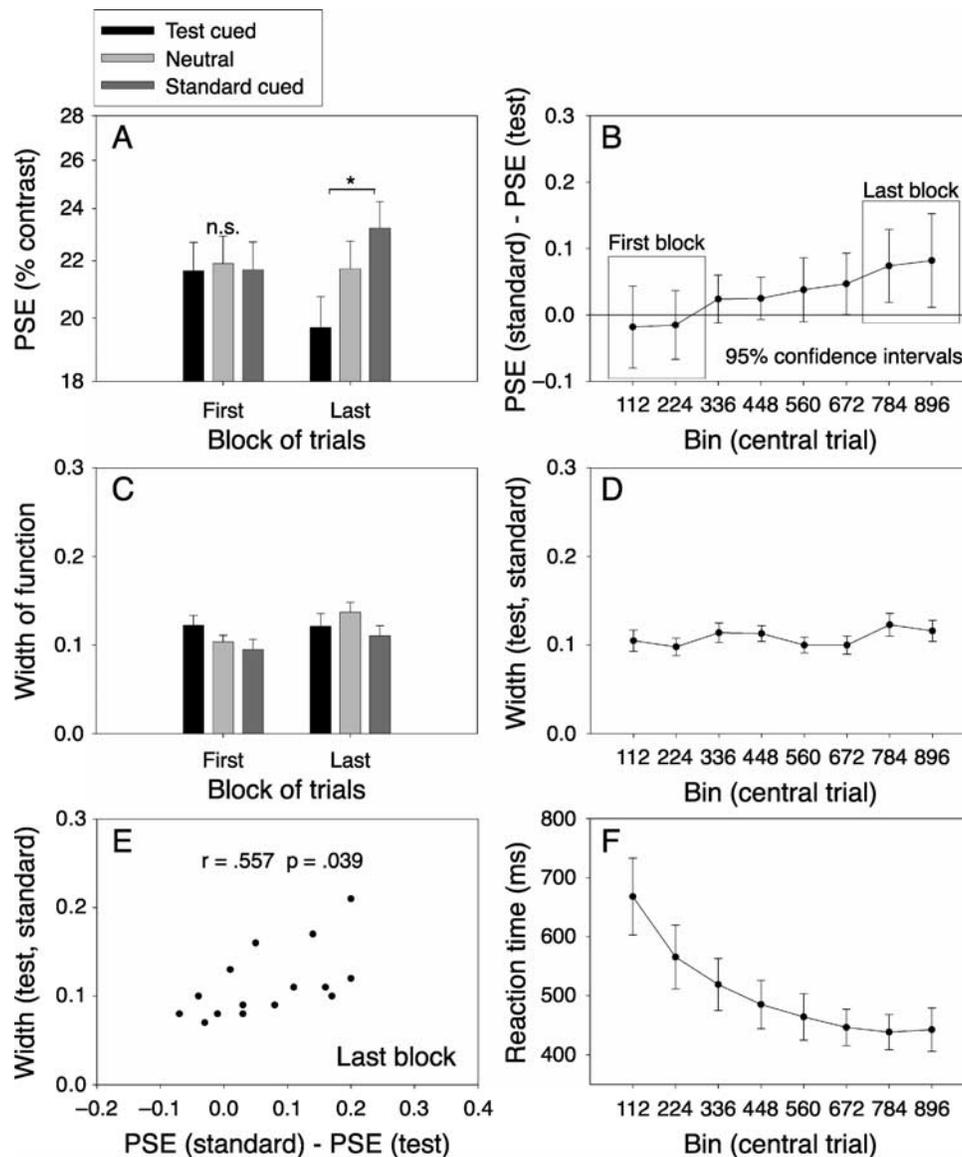


Figure 4. Results of Experiment 3. Error bars denote the between-participant standard error unless noted otherwise. (A) The PSEs in the first and last blocks of 336 trials. (B) The time course of the cueing effect on PSEs (difference between standard cued and test cued). Bins are centered on the indicated trial number, and in this panel, error bars show 95% confidence intervals. (C) The width of the psychometric function in the first and last blocks of trials. (D) The mean slope (averaged across test cued and standard cued) was fairly stable. (E) The correlation between width of the psychometric function and cueing effect on PSEs in the last block. (F) RTs (averaged across test cued and standard cued) decreased considerably during the experiment.

safe to conclude that participants responded not only as accurately as possible but also as rapidly as possible. The latter violates the instruction to take their time to respond. Thus, just telling participants to prioritize accuracy over speed does not guarantee compliance with these instructions. Once participants decided to respond as fast as possible, they selected the cued location more often, which is consistent with the suggestion that the cue increases the readiness to respond to stimuli at this location (cf. Prinzmetal, McCool, & Park, 2005).

## General discussion

We examined the effects of involuntary attention on the position (PSEs) and width of psychometric functions. First, Experiment 1 showed that cueing effects on PSEs were absent for equality judgments when observers were trained and discrimination performance was good. When observers were untrained and discrimination performance was bad, cueing effects on PSEs emerged with equality

judgments. Further, we replicated cueing effects on PSEs with 4 cpd and comparative judgments, but not with 2 cpd, and found that psychometric functions were wider in the condition that had yielded involuntary cueing effects. In addition, we observed that individuals with poor discrimination performance showed larger cueing effects than observers with good discrimination performance. Finally, when participants in [Experiment 3](#) switched from a strategy that prioritized accuracy to a strategy that prioritized speed, cueing effects on PSEs emerged. Overall, the results may be summarized by saying that less precise or faster responses lead to larger cueing effects on appearance (i.e., PSEs).

We believe that these results lend some credibility to the hypothesis that cueing effects on appearance result from guessing strategies. This hypothesis claims that the cue biases observers to select the cued stimulus. The present study supports this hypothesis and qualifies it in two ways. First, the present study shows that observers who were less certain or paid less attention to the perceptual decision relied more on extraneous information. This was true for single conditions (e.g., 2 cpd vs. 4 cpd) and across observers (i.e., correlation between width of psychometric function and cueing effect). We believe that this correlation between the size of cueing effects and the precision of judgments favors the decision bias account. Second, the decision bias may be more complex than previously thought. The cueing effect with equality judgments shows that the cue does not (only) bias observers to select the cued stimulus, because there is no single stimulus to select in equality judgments. Rather, we suggest that the cue induced observers to associate the cued stimulus with “more” along a quantitative dimension (i.e., more contrast) because the cue represents “more” stimulation.

It would be desirable to move away from our correlational design to an experiment in which we manipulated task difficulty (i.e., the width of the psychometric function) intentionally. Obviously, this would only be possible by changing the stimuli or creating a dual task situation. Whatever the outcome of such an experiment would be, critics would always claim that the observed differences are due to changes in the deployment of attention, not task difficulty. Thus, the correlational approach of the present study certainly has its weaknesses, but there are very few alternatives and if the results are viewed in the context of previous work (see below), our conclusions do not seem farfetched.

Further, we do not believe that reversing the judgments (i.e., asking which target has a lower contrast, e.g., Carrasco et al., 2004) solves the problem of decision biases. As outlined above, decision biases may be more complex than a simple bias to respond with a spatially corresponding key press (i.e., left cue favoring left responses and right cue favoring right responses). For instance, one may argue that the cue is associated with a

judgment that there is “more” of something, which would make the response reversal useless. Similarly, showing that the cue only has an effect at certain SOAs (Carrasco et al., 2004) is not convincing because decision biases also have a time course (Danziger & Rafal, 2009; Spalek, 2007).

Supporting evidence for the decision bias account comes from studies that have reported no effect of non-informative, peripheral cues on the perception of low-contrast stimuli. If involuntary attention boosted perceived contrast, discrimination of low-contrast stimuli should improve. However, Kerzel, Zarian, and Souto (2009) have not replicated effects of non-predictive peripheral cues on orientation discrimination with low-contrast stimuli (see e.g., Giordano, McElree, & Carrasco, 2009; Liu, Pestilli, & Carrasco, 2005; Pestilli, Viera, & Carrasco, 2007). Further, it has been noted that predictive peripheral cues did not change perceptual sensitivity to unmasked, low-contrast stimuli, whereas sensitivity improved when masks were used (Kerzel, Gauch, & Buetti, *in press*; Smith & Ratcliff, 2009; Smith, Ratcliff, & Wolfgang, 2004). These results contradict previous reports of enhanced perception at the cued location for masked and unmasked stimuli (Cameron, Tai, & Carrasco, 2002; Carrasco, Penpeci-Talgar, & Eckstein, 2000), which may be accounted for by decision processes and not by perceptual enhancement (Gould, Wolfgang, & Smith, 2007). Similarly, Prinzmetal and colleagues found that involuntary attention has no effect on the perception of letters, lines, or faces (Prinzmetal, Leonhardt, & Garrett, 2008; Prinzmetal et al., 2005; Prinzmetal, Park, & Garrett, 2005), which is also incompatible with the idea that non-predictive cues change perception.

In light of the failure to obtain effects of non-predictive peripheral cues on perceptual accuracy with low-contrast stimuli, Carrasco et al.’s (2004) finding of enhanced perceived contrast is puzzling. Even if biased guessing accounted only for part of the changes in appearance (as suggested by Anton-Erxleben, Henrich, & Treue, 2007), a paradigm that involves the selection of either a cued or uncued stimulus will always be plagued by decision biases. To provide more convincing evidence for changes of appearance, alternative paradigms would be preferable. Besides equality judgments, delayed match-to-sample procedures, as in Prinzmetal et al. (1997), may avoid decision biases. More precisely, Prinzmetal et al. (1997) asked observers to indicate the luminance of a gray disk on a response palette that was visible throughout the experiment. The task avoids decision biases because participants were not asked to choose one of two stimuli. Rather, only one stimulus was presented at a time, and participants were asked to adjust a mouse cursor to the target’s luminance. As mentioned above, results obtained with this procedure do not support the hypothesis that attention alters appearance. Presently, there is no support for the attention-changes-appearance hypothesis from

paradigms other than comparative judgments. Future research should provide broader evidence for the claim.

While the present study casts some doubts on changes of appearance due to peripheral cues, we do not doubt that attention may affect perception. There is ample evidence that voluntary attention improves perceptual performance (e.g., Bashinski & Bacharach, 1980; Cheal & Gregory, 1997; Cheal & Lyon, 1991; Doshier & Lu, 2000; Kerzel et al., 2009; Lu & Doshier, 2000; Luck, Hillyard, Mouloua, & Hawkins, 1996; Experiment 1 in Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989). Mechanisms such as external noise reduction or signal enhancement may underlie these attentional effects (e.g., Gould et al., 2007).

There is an apparent contradiction between our conclusions and neurophysiological studies showing that attention increases the gain of the neural response (e.g., Martinez-Trujillo & Treue, 2002; Reynolds, Pasternak, & Desimone, 2000; Stormer, McDonald, & Hillyard, 2009; Treue & Maunsell, 1996). Increases in neural gain lead to the straightforward prediction that subjective experience is altered when stimuli are attended. While this is a reasonable assumption, accepting it would also have some adverse effects: The appearance of the visual world would change as we shift visual attention from one object to the next. This is undesirable, as suggested by numerous efforts of our visual system to preserve the impression of a stable world (mechanisms of perceptual constancy for size, color, luminance, etc.). One may also ask the question whether changes in appearance serve the ultimate goal of attention: to select objects for action (Neumann, van der Heijden, & Allport, 1986). The most important job to accomplish in this respect is the gating of sensory information. Therefore, it may be that the amplification of neural responses does not affect the nature of the representation as much as the likelihood of reaching consciousness or working memory (e.g., Reeves & Sperling, 1986; Smith & Ratcliff, 2009). In other words, neural gain control may affect the prevalence of attended stimuli in capacity-limited channels. Improvements in speed and accuracy that do not need to be based on changes in appearance will result.

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## Footnotes

<sup>1</sup>The RTs of same–different judgments have been widely studied in the 1980s in a debate on dimensional comparisons (e.g., Farell, 1985; Ratcliff & Hacker, 1981), but we do not think this literature is relevant for the present study in which we focus exclusively on psychometric functions and not on RTs.

<sup>2</sup>It would have been interesting to run a similar analysis in Experiment 1. However, this was not possible for two reasons: First, only half of the observers started with the comparative judgment. Experiment 3 showed that after a single session, participants are already as fast as they can get. Second, there were far more conditions (208 instead of 56), such that it was not possible to reliably determine PSEs within different periods of a single session.

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