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Involuntary attention enhances identification accuracy for unmasked low contrast letters using non-predictive peripheral cues

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Abstract

There is controversy regarding whether or not involuntary attention improves response accuracy at a cued location when the cue is non-predictive and if these cueing effects are dependent on backward masking. Various perceptual and decisional mechanisms of performance enhancement have been proposed, such as signal enhancement, noise reduction, spatial uncertainty reduction, and decisional processes. Herein we review a recent report of mask-dependent accuracy improvements with low contrast stimuli and demonstrate that the experiments contained stimulus artifacts whereby the cue impaired perception of low contrast stimuli, leading to an absence of improved response accuracy with unmasked stimuli. Our experiments corrected these artifacts by implementing an isoluminant cue and increasing its distance relative to the targets. The results demonstrate that cueing effects are robust for unmasked stimuli presented in the periphery, resolving some of the controversy concerning cueing enhancement effects from involuntary attention and mask dependency. Unmasked low contrast and/or short duration stimuli as implemented in these experiments may have a short enough iconic decay that the visual system functions similarly as if a mask were present leading to improved accuracy with a valid cue.

1. Introduction

Cueing paradigms have been implemented as a means of measuring many aspects of visuo-spatial attention. A target stimulus is presented with some probability near to or away from a pre-cue which attracts attention to a spatial location or feature. The observer is required to maintain fixation in the center of the display while covertly attending to the peripheral visual field in search of the target stimulus (Posner, 1980). Attention can be directed voluntarily or involuntarily and there is controversy over the mechanisms by which each form of attention influences the perceptual and decisional processing of attended stimuli.

In a recent publication Kerzel, Gauch, & Buetti (2010) used non-predictive cues and target letters which were either unmasked and low contrast or masked and high contrast. Positive cueing effects were only observed for high contrast masked stimuli, arguing in favor of mask-dependent cueing effects. Interestingly, with unmasked low contrast targets observers performed worse with a valid cue than with an invalid cue. The authors hypothesized that crowding of the cue on the target contributed to the reversed cueing effects and to test this hypothesis they conducted an experiment where the stimuli were presented in the parafovea.

They observed significant cueing effects with unmasked stimuli, but only when stimuli were presented in the parafovea where crowding effects are smaller. Since they only observed cueing effects in the periphery with backward masked stimuli but not unmasked stimuli, they concluded that cueing effects from involuntary attention were dependent on the presence of a post mask and were attributable to a mechanism of improved transfer of stimulus information into visual short term memory (VSTM) as proposed in the mask dependent cueing hypothesis (Liu, Wolfgang, and Smith, 2009).

There are some reports of improved accuracy judgment performance from involuntary attention with unmasked stimuli (Cameron, Tai, & Carrasco, 2002; Carrasco, Giordano,& McElree, 2006; Henderson, 1996; Lu & Dosher, 1998), with some studies reporting improved response accuracy with both masked and unmasked stimuli using the same task (Carrasco, Penpeci-Talgar, & Eckstein, 2000; Carrasco, Williams, & Yeshurun, 2002; Henderson, 1991; Yeshurun & Rashal, 2010). However, recent evidence indicates that cueing effects with unmasked stimuli that are not spatially localized can be confounded by spatial uncertainty (Gould, Wolfgang, & Smith, 2007), bringing into question the validity of some prior conclusions about cueing effects with unmasked stimuli. Recently, Kerzel, Gauch, Buetti (2010) reported cueing effects not due to spatial uncertainty reduction without spatially localizing the target stimuli. The cueing effects were only observed with backward masked stimuli. The present experiments were conducted to determine if target identification accuracy is improved with masked and unmasked stimuli similar to those conducted in Kerzel, Gauch, & Buetti (2010), but utilizing a luminance modulated cue to minimize masking or crowding of the target stimuli.

We hypothesized (similar to their hypothesis) that in their experiments, the high contrast cue stimulus presented in close proximity to the target stimuli interfered with perception of the low contrast target letters. As such, we predicted that a reduction in the cue contrast and an increase in the distance between the cue and target would produce significant positive cueing effects in the peripheral visual field where Kerzel, Gauch, & Buetti (2010) previously did not obtain cueing effects for unmasked stimuli. To obtain support for our hypothesis that cueing effects occur in the periphery with unmasked stimuli, we lowered the contrast of the cue and kept the stimuli in the periphery. A cue with a lower contrast is better suited for low contrast targets, and may produce cueing effects with unmasked stimuli where cueing effects were previously absent. We also tested the effects of the high contrast cue on low contrast targets with masked stimuli, an important condition not investigated in Kerzel, Gauch, & Buetti (2010).

We tested this hypothesis in four experiments with low visibility letters and non-predictive cues. Robust cueing effects were observed with unmasked stimuli using a low contrast cue in two experiments with different temporal parameters. These cueing effects were obtained across a full range of contrast levels covering performance levels from chance guessing to near 100% accuracy. Two additional control experiments confirmed that the high contrast cue is forward masking the low contrast targets, thereby lowering target discriminability. The results indicate improved accuracy judgment performance from involuntary attention capture at two different temporal durations without any dependence on backward masking.

2.1. Experiment 1: Low contrast letter identification with full contrast cue

The first experiment was conducted to verify that cueing effects are absent with the stimulus parameters utilized in the 5th experiment of Kerzel, Gauch, & Buetti (2010). We conducted the same task but used the method of constant stimuli rather than a staircase procedure to test for cueing effects across a range of target contrasts since some researchers have argued that cueing effects only occur near detection threshold (Kerzel et al., 2010; Kerzel, Zarian, Souto, 2009; Schneider, 2006). It was hypothesized that no cueing effects would be observed using a full contrast cue in close proximity to the low contrast targets as reported in Kerzel, Gauch, & Buetti, (2010) since our experimental parameters are nearly identical to theirs.

2.2. Methods

2.2.1 Participants—In each of the experiments reported here, subjects were recruited from the local public community, consisting of students and non-students alike. Recruitment and experimental procedures were approved by the University of California affiliated Institutional Review Board ethics committee. Six subjects (3 male and 3 female; ages ranged from 19 to 32) participated in the experiments, five of which were naïve observers, and one was the primary author. All participants signed an informed consent and were financially compensated for their time.

2.2.2 Apparatus—In all experiments, stimuli were generated, presented, and responses recorded using the WinVis Psychophysical Testing platform, a toolbox for Matlab. Stimuli were presented on a 17 inch Sony Trinitron CRT monitor at a refresh rate of 100 Hz. The display resolution was 1024×768 pixels. The background was grey with an approximate luminance of 13 cd/m^2. Subjects were positioned in an Eyelink II eye tracker with a chin and forehead rest. Subject’s eyes were positioned 50cm from the display resulting in 2.1 × 2.1 min square pixels. Subjects were told that eye movements were being recorded during each trial and to avoid making eye movements during a trial. The experiment was conducted in moderate brightness indoor lighting conditions.

2.2.3 Stimuli—Monitor luminance linearity was achieved using an 8 bit gamma correcting look up table. A 25% contrast fixation circle 0.2° in size was presented at the center of the screen at the beginning of each trial (Figure 1). The duration of the fixation circle was randomly selected from 1.5–3.0 sec for each trial to prevent the subject from being able to predict the cue onset. The fixation target was removed during target presentation, whereas in Kerzel, Gauch, & Buetti (2010) the fixation stimulus was a plus sign and remained displayed throughout the entire experiment. The cue was a full contrast black horizontal line (1.23° × 0.27°) presented 9.7° from fixation. In Kerzel, Gauch, & Buetti (2010) two cue sizes were tested, but the results were identical with significantly higher accuracy for invalid cue trials than valid cue trials. Similarly, we presented the same cue stimulus characterized as “large” in their experiments and the target stimulus was also presented at 9.7° eccentricity and 0.45° (edge to edge) above the cue, along the horizontal meridian. The target letters were each 1° × 1° in size. Following the offset of the fixation point, the cue was displayed for 100ms, followed by the presentation of the target for 70ms. After the target offset, there was 100ms of blank screen, after which the subject was text prompted, “What was the target letter?” The contrasts tested in this experiment were 6.3%, 7.8%, 9.2%, 10.6%, and 12.1% (relative to the background luminance). Pilot studies indicated that the range of 6–12% contrast covered performance from chance guessing to near 100% correct letter identification.

2.2.4 Procedure—Subjects were instructed to complete the task at their own preferred pace and to take breaks between each 40-trial run as often as desired to maintain a consistent attentive state. After each stimulus presentation, the subject used a keypad to indicate the observed letter, either an ‘O’ or an ‘X’. A response initiated the next trial.

Each run consisted of 40 trials (totaling 2–3 minutes for a full 40-trial run) with 50% of the trials having valid cues and 50% with invalid cues. Each data collection session lasted 1 hour, and each subject participated in a total of 4 hours per experiment. Since data collection was self-paced, there is some slight variation in the amount of data collected per subject, but the average number of trials completed by each subject was 3500 trials per experiment. In experiment 1 an average of 440 trials were completed at the lowest and highest contrast levels, and 880 trials were conducted at each intervening contrast covering the middle of the psychometric function. The subjects were initially familiarized with the task by completing 3 runs with moderately high contrast targets, having low task difficulty. The data from these training runs are not included in the final analysis. The contrast levels were fixed within each run.

Subjects were informed of the presence of the cue as a precursor to the target stimulus, but not about the reliability of the cue. In some previous published research, subjects were specifically instructed to ignore the cue since it did not reliably predict the forthcoming target location (Jonides, 1981; Kerzel, Zarian, Souto, 2009). While there is some evidence that observers cannot completely ignore a salient peripheral cue (Jonides, 1981; Muller & Rabbitt, 1989; Warner, Juola, Koshino, 1990), specifically instructing a subject to ignore the cue may activate top-down control systems that will likely decrease the saliency of reflexive attention capture and weaken any cueing effects. To avoid any potential confounds from decision processes related to the subjects' intentions when attending to the cue, we withheld specific instructions about the cue other than informing the subjects that it would be presented before the target.

2.3. Results

Accuracy was measured as the percentage of trials that the observer correctly identified the target letter. In Figure 2 accuracy is plotted as a function of stimulus contrast for each subject. Psychometric functions were fitted to each subject's valid and invalid cue data using the Weibull function. The parameters of this function are the upper asymptote (a) fixed at 97%, the floating exponent or slope (β), and the threshold definition (k) of 75% or $d'=1$, where $p(c)$ is the percent correct at a given contrast level (c) for the psychometric function from 50% chance guessing up to 100% correct: $p(c) = a-(a-.5) * .5 \uparrow([(c/k)] \uparrow \beta)$

Standard error of each datum was calculated using Binomial statistics where p is the probability of a correct response, and n is the number of trials at each contrast: $\sqrt{\frac{p(1-p)}{n}}$

The upper asymptote parameter was fixed at 97% accuracy, while the exponent parameter (slope) was allowed to vary. Analysis of the proportion correct indicates that in general valid cue trials produced lower accuracy performance than invalid cue trials, though not all data points are statistically significant. The goodness of fit (chi square, χ^2) is shown in the figure for each subject. Parameter values for the Weibull function fit are shown in Figure 3 for each experiment. Given that the degrees of freedom (df) = $N_{data} - N_{parameters} = 6$, the expected value of $\chi^2 = \text{df} \pm \sqrt{2\,df} = 6 \pm 3.5$. The t-values shown in Table 1 were calculated as t = (threshold or exponent ratio−1)/SE.

In figure 3, the fit parameter values for each individual subject are plotted with each subject ID on the horizontal axis against the specified parameter on the vertical axis. The upper left subplot shows the valid cue threshold parameter values for individual subjects from Experiments 1–3. Threshold contrast ratios from Experiment 4 were much higher since contrast levels were higher so they are not shown in the plot. The upper right subplot shows the valid cue exponent parameter values for individual subjects from all four experiments. The middle left subplot shows the invalid cue threshold parameter values for individual subjects from Experiments 1–3. The middle right subplot shows the invalid cue exponent parameter values for each experiment and individual subject. The bottom pair of panels is a summary of the four experiments with the lower left and right panels showing the means across the six observers for the threshold (left) and exponent (right) parameters. The horizontal axis corresponds to the invalid cues and each horizontal error bar is one standard error (SE) of the mean. The vertical axis and error bars are for the valid cue. The diagonal line centered on each datum is the 95% confidence interval (CI) that corresponds to a paired comparison t-test. For 5 degrees of freedom (six subjects and one mean for the difference of the within subject valid and invalid parameter), the CI would correspond to ±3.63*SE if there were no correlation of the valid and invalid judgments across observers. Our finding that CI ≈ SE indicates that the random differences between observers are 3–4 times as large as the random differences between thresholds or exponents.

The diagonal line corresponds to the null hypothesis of there being no cueing effect. A threshold value above the diagonal line of unity indicates a higher threshold with valid cue trials than invalid cue trials, indicating a reverse cueing effect. A value below the diagonal line indicates a positive cueing effect. The lower right subplot compares the mean exponent ratio of valid and invalid cue data. An exponent value above the diagonal line indicates a shallower slope with invalid cue data, while an exponent value below the diagonal line indicates a shallower slope with valid cue data. As discussed above, Experiment 1 shows a significantly negative cuing effect whereby the cue masks the visibility of the target. The finding that the valid exponent is larger than the invalid exponent (a steeper valid psychometric function) means that the cue is relatively more effective in masking the lower contrast stimuli. This is also indicated by the results of Experiment 3. The results of experiment 2 also indicate a steeper slope with valid cue data, but there were positive cueing effects and the cue was no longer causing forward masking. Experiment 4 was unique in producing a shallower slope of the psychometric function for valid cued data.

Given the insight provided by the plot showing both SE and CI it may be useful to describe how the diagonal line was plotted. Suppose the location of the datum is at [x y] and the length of the CI is given by L=CI(2)−CI(1), then the plotted CI in the bottom panels of Fig. 3 goes from [x−L/4, y+L/4] to [x+L/4, y−L/4]. The factor 3.63 comes from two sources. A factor of sqrt(2) is because the paired comparison t-test takes the difference of valid and invalid. A factor of 2.53 comes from the t-test for 5 degrees of freedom (6 data and one parameter, the mean of the six data points).

As shown in Table 1, the group averaged threshold ratio was 0.92 +/− 0.01, indicating that the threshold of the cued target was significantly increased $t(5) = -9.21$, $p<0.001$. We attribute this increase to masking by the cue. The group averaged exponent ratio was 0.76 +/− 0.03, indicating that the psychometric function for the cued stimulus with the increased threshold had a significantly increased slope $t(5) = -8.37$, $p<0.0004$. The group average goodness of fit (χ^2) of the Weibull function was 6.2. The general finding in all the four experiments was that the stimulus condition (cued or uncued) with the higher threshold had the steeper slope. Our hypothesis was that whatever factor contributes to the threshold elevation, such as stimulus uncertainty or masking by the cue, will affect low contrast targets more than high contrast targets. The stimuli with lower strength will be more degraded by factors such as stimulus uncertainty or masking by the cue.

2.4. Discussion

As indicated in Figure 2, at the lower contrast levels, accuracy with a valid cue is lower than accuracy with an invalid cue, indicating impairment from the presence of the cue. At the higher contrast levels the cue does not produce any reverse cueing effects since accuracy with valid and invalid cues is similar. However, the net result is a significant reverse cueing effect at threshold. The difference between the extent of the reverse cueing effect for the lower and higher contrast stimuli is likely to occur because at low contrasts the targets have much lower visibility, and a high contrast cue has a larger contrast difference with the lower contrast targets than with the higher contrast targets, which leads to a larger masking impairment capable of lowering valid cue performance below that of invalid cue performance. The absence of a positive cueing effect in this experiment is attributable to a masking sensory interaction between the high contrast cue and the targets, with a stronger effect on lower contrast stimuli.

As shown in figure 3, across all 6 subjects there was a consistent contrast threshold between 8 and 9 percent, indicating fairly equal performance and task difficulty across all subjects. The mean threshold ratio (0.92 +/− 0.01) indicated a significant decrease in performance with the valid cue compared to the invalid cue. The Weibull function exponents, corresponding to the slopes of the psychometric function for valid cue trials varied between 4 and 6, and the mean exponent ratio of invalid to valid cue data was 0.76 +/− 0.03, indicating a shallower slope of the invalid cue fit compared to the valid cue fit. The significance of the exponent ratios is that a shallower slope with valid cue trials may be indicative of spatial uncertainty reduction as predicted in signal detection theory. Signal detection theory and spatial uncertainty reduction are discussed in more detail in the General Discussion section. As will be discussed, our results indicate that masking from the cue can affect the slope of the psychometric function, therefor the observed change in slope in experiment 1 is related to the masking from the cue. Overall, the subjects performed worse with a valid cue than with an invalid cue, suggesting that the presence of the high contrast cue in close proximity to the targets impaired perception of the low contrast target stimuli, confirming our hypothesis of a cue stimulus confound. While this experiment is not an exact replication of Kerzel, Gauch, & Buetti (2010), the results are in agreement. While the results indicate that the cue used is impairing perception, additional experiments were conducted to further test this hypothesis.

3.1. Experiment 2: Low contrast letter identification with an isoluminant cue

The purpose of Experiment 2 was to determine if reducing the strength of the cue results in better performance with a valid cue than an invalid cue, thereby suggesting that the absence of cueing effects for unmasked stimuli as previously reported in Kerzel, Gauch, & Buetti, 2010 is actually due to the cue disrupting perception of low contrast targets rather than being related to mask-dependent cueing effects. To test our hypothesis that the cue stimulus used in Experiment 1 was interfering with perception of the low contrast target letters, we changed the cue color and made it approximately isoluminant with the background and increased the distance between the cue and the target from 0.45° to 0.9°.

3.2. Methods

The same 6 subjects from experiment 1 were recruited to participate in experiment 2. The stimuli were identical to those used in experiment 1 except for changes in the features of the cue. The cue was an approximately isoluminant green horizontal line spanning 1.23° × 0.27°, presented 9.7° away from fixation and 0.9° (edge to edge) below the target location. Cue luminance was set to 13 cd/m^2 using a photometer so that the green cue color was approximately isoluminant with the background as measured with a photometer. Subjects were given the same task instructions as in Experiment 1 but were informed that the cue would now appear as a light green line, rather than black. Data analysis is the same as in Experiment 1.

3.3. Results

In Figure 4 accuracy is plotted as a function of stimulus contrast for each subject. Analysis of the proportion correct indicates that across all six participants, task performance was higher with a valid cue than an invalid cue. As shown in Table 1, the group averaged threshold ratio was 1.15 +/− 0.01, indicating that the threshold of the cued target was significantly decreased $t(5) = 11.93$, $p<0.0001$. The group averaged exponent ratio was non-significant at 0.93 +/− 0.07, indicating no significant change in slope $t(5) = -1.09$, $p>0.32$. The group average goodness of fit (χ^2) of the Weibull function was 9.9.

3.4. Discussion

As shown in figure 3, the contrast threshold for the valid cue condition varied between 6 and 8 percent, while the threshold ratio was above 1, indicating the invalid cue trials had a higher threshold than the valid cue trials, corresponding to a leftward shift of the psychometric function. This is also indicated by the group averages as shown in Table 1. The exponent of the valid cue fit ranged from 3 to 5 for all subjects except subject 2 who had an exponent of 6.18. Three subjects had an exponent ratio less than 1, indicating a steeper slope with valid cue trials, while two subjects had a steeper slope with invalid cue trials, but across all six subjects there was not a uniformly significant change of slope above or below 1. The averaging of the data from all 6 subjects also indicated no significant change in slope. This is not necessarily related to spatial uncertainty reduction since (as shown in Experiment 1) the valid cue can decrease the probability of identifying low contrast stimuli. The results from Experiment 2 confirm our hypothesis that the previously reported absence of cueing effects with unmasked low contrast target letters was due to masking from the high contrast cue positioned in close proximity to the target. By making the cue approximately isoluminant with the background and doubling the distance between the top of the cue and the bottom of the target stimulus, accuracy improved at cued locations compared to uncued locations.

These results question whether the results in Kerzel, Gauch, & Buetti, 2010 were actually due to mask dependency since there were statistically significant cueing effects with unmasked stimuli in this experiment. To provide additional evidence that the high contrast cue produces masking on low contrast stimuli and determine if this masking also occurs with backwardly masked stimuli, a third experiment was conducted using the original high contrast cue parameters, but with masked stimuli. Kerzel, Gauch, & Buetti (2010) did not test for cueing effects with masked stimuli using the same cue that was used with unmasked stimuli, overlooking a critical factor in their experiments. Since the results of the first two experiments indicated a strong forward masking effect from the high contrast cue, we hypothesized that the high contrast cue would create the same impairment with masked stimuli as unmasked stimuli.

4.1 Experiment 3: Low contrast letter identification with a post mask

In Kerzel, Gauch, & Buetti (2010), the experimental conditions were different between the masked and unmasked conditions, so it is unreasonable to conclude that cueing effects were mask dependent. In our third experiment we wanted to determine if cueing effects were present for masked stimuli when targets were low contrast and a full contrast cue was presented in close proximity to the target stimulus. Since the two previous experiments demonstrated that the cue contrast and proximity were confounds leading to backward cueing effects with unmasked low contrast stimuli, we wanted to test if the same interference occurs with masked stimuli. An absence of positive cueing effects would confirm our hypothesis that the cue was masking the targets, and indicate that the reported absence of cueing effects with unmasked stimuli was not in fact due to the absence of a post mask but because of masking from the cue.

4.2 Methods

The same 6 subjects from experiments 1 and 2 were recruited to participate in experiment 3. The stimuli and task were identical with the first experiment except that the low contrast target was followed immediately by a 100ms mask consisting of an X and O target stimulus superimposed and presented on both sides of fixation. In each trial, the contrast of the mask was the same as that of the targets. In the previous two experiments, there was a 100ms duration of blank screen following the offset of the target during which iconic memory was undergoing decay. In the masked experiment, the mask is presented for the duration of the 100ms, maintaining the same time interval between the target offset and question prompt. The difference was that with the mask, the iconic memory decay was interrupted instead of gradually decaying.

4.3 Results

In Figure 5 accuracy is plotted as a function of stimulus contrast for each subject. The Weibull function was fit to the valid cue and invalid cue data. As shown in Table 1, the group average threshold ratio was 0.96 +/− 0.01, indicating that the threshold of the cued target was significantly increased $t(5) = -3.34$, $p<0.0207$. The group averaged exponent ratio was significant at 0.84 +/− 0.04, indicating an increased slope for the valid cue trials $t(5) = -4.39$, $p<0.007$. The group average goodness of fit (χ^2) of the Weibull function was 13.6.

4.4 Discussion

As shown in figure 3 by the dashed lines with circle data points, thresholds for valid cue data were higher in Experiment 3 than in Experiments 1 and 2, ranging from 8.6 to 10. Threshold ratios were less than 1, but not all individually statistically significant. Averaging the data across all 6 subjects indicated a statistically significant increase in the threshold of the cued target (Table 1). The individual Weibull fit exponents ranged from 3.5 to 5 while the exponent ratios were less than 1, though not all were statistically significant. Averaging across all 6 subjects resulted in a statistically significant reduction of the exponent ratio, producing a shallowing of the slope of the invalid cue data fit.

A comparison of the effect of masking from the cue from Experiments 1 and 3 indicates that a valid cue provides very weak masking when combined with a post mask. The ratio of masking for valid cues for Experiments 3 and 1 was 1.09 +/− 0.02, showing only a 9% increase in masking from the post-mask. With invalid cues, the ratio was 1.14 +/− 0.03, showing a 14% increase in masking from the post mask. These ratios indicate that the masking effect of the cue is substantial, leading to the absence of positive cueing effects for targets with and without a post mask. Of particular interest is the observation that the post mask induces more masking with invalid cues since the uncued stimuli are not forward masked by the high contrast cue. This provides strong support for our hypothesis that the reported absence of cueing effects with the high contrast cue is not due to the absence of a post mask but because of forward masking from the cue. Contrary to the conclusions in Kerzel, Gauch, & Buetti (2010), the results are not evidence of mask dependent cueing effects.

The results of Experiment 3 show that even with masked stimuli, using these cue parameters resulted in lower accuracy performance with valid cues than invalid cues. This is further evidence that the absence of cueing effects reported in Kerzel, Gauch, and Buetti (2010) is not in fact due to an absence of a post mask, but instead because of a confound in the cue stimulus that impairs perception of both masked an unmasked low contrast target letters. They argued that cueing effects are only observed with masked stimuli at full contrast, but didn’t test low contrast, masked targets. They concluded that masked targets produce perceptual enhancement from involuntary attention and that unmasked targets do not, except at small eccentricities where crowding is less influential. Our results indicate that perception of post masked low contrast targets is disrupted with a high contrast cue, and that the cue stimulus parameters are the reason for the absence of cueing effects previously reported. Since the post mask contrast was the same as the low contrast letters, backward masking effects were very weak.

5.1 Experiment 4: Short duration letter identification without a post mask

A significant amount of previously published research has suggested that involuntary attention is maximally captured around 110ms post-cue and that it decays rapidly thereafter (Montagna, Pestilli, & Carrasco, 2009; Muller & Rabbitt, 1989; Nakayama & Mackaben, 1989; Turatto, Vescovi, & Valsecchi, 2007). Since many studies reporting cueing effects with transient involuntary attention used shorter stimulus intervals than those tested in Experiments 1–3, a fourth experiment was conducted to determine if cueing effects were still prominent with very brief stimuli more closely related to cueing experiments that other researchers have conducted. The temporal parameters of the stimuli were different from those in Kerzel, Gauch, & Buetti, 2010, so the results can't be directly compared to those previously reported, but the results do provide additional evidence in support of the conclusions of this article.

5.2 Methods

The stimuli and task were similar to Experiment 2 except that the low contrast target was only presented for 10ms instead of 100ms, and different contrast levels were examined. As evident from Bloch's Law, there is a tradeoff between the contrast and the duration of stimuli in terms of visibility. Lowering the duration of the stimulus necessitates increasing the contrast of the stimulus to maintain a consistent level of performance. The cue was presented for 60ms, followed by 40ms of blank screen (making a 100ms stimulus onset asynchrony) and then a 10ms target stimulus. Seven contrast levels were tested in this experiment: 28.1%, 31.7%, 35.3%, 37.8%, 41.2%, 43.4%, and 46.8%. Pilot studies indicated that this range of contrast levels covered task performance from chance guessing to near 100% correct letter identification.

5.3 Results

In Figure 6 accuracy is plotted as a function of stimulus contrast. The Weibull function was fit to the valid cue and invalid cue data. Analysis of the proportion correct indicates performance was higher with a valid cue than an invalid cue with the exception of stimuli presented at 46.8% contrast where performance was near 100% correct. As indicated in Table 1, the group averaged threshold ratio was 1.21 +/− 0.03, indicating that the threshold of the cued target was significantly decreased $t(5) = 7.75$, $p<0.0006$. The group averaged exponent ratio was significant at 1.36 +/− 0.05, indicating a shallowing of the slope for the valid cue trials $t(5) = 8.1$, $p<0.0005$. The group average goodness of fit (χ^2) of the Weibull function was 5.6.

5.4 Discussion

Across all 6 subjects, contrast thresholds ranged from 30 to 36 percent for the valid cue condition, and threshold ratios were consistently greater than 1. Averaging of the data across all subjects as shown in Table 1 indicated that threshold ratios were significantly increased, meaning that valid cue trials had a lower threshold than invalid cue trials. Exponents ranged from 2.8 to 7, and the mean exponent ratio was significantly higher than unity (1.0), indicating a shallowing of the slope for the cued data. The threshold values from Experiment 4 are larger given the higher contrast levels, so they are not shown in the first plot of Figure

3 but the values for subjects 1:6 are (respectively) 31.5, 35.7, 31.8, 33.1, 30.0, and 34.4 percent. The results show a large increase in response accuracy from involuntary attention with valid cues over invalid cues, for stimuli with a shorter duration (10ms) and therefore a shorter length of total processing time in this task (110ms vs 170ms). The positive cueing effect further confirms our hypothesis that the previously reported absence of cueing effects with unmasked low contrast target letters was due to disruption from the high contrast cue positioned in close proximity to the target rather than backward mask dependency.

6. General Discussion

In these experiments, we tested if the reason Kerzel, Gauch, & Buetti (2010) did not find cueing effects for unmasked low contrast letter stimuli in the periphery was exclusively because of a confound in their cue stimulus and not from the absence of a post mask. In their experiments with peripheral stimuli, observers performed worse with valid cues than invalid cues, indicating that the cue interfered with perception of the low contrast target letters. They found that cueing effects re-emerged when stimuli were presented within the parafovea, but only at small eccentricities within this region. While they did not observe cueing effects in the peripheral visual field for unmasked low contrast letters, our results indicate a large cueing effect in the peripheral visual field. By increasing the distance between the cue and the target, and by lowering the contrast of the cue to match the background luminance, we observed a large increase in accuracy judgment performance with valid cues compared to invalid cues.

In our first experiment using a full contrast cue and unmasked target stimuli, target identification accuracy was lower with a valid cue compared to an invalid cue. It was hypothesized that the high contrast of the cue relative to the low contrast of the target was impairing perceptual sensitivity at the cued location and that by lowering the contrast of the cue, positive cueing effects would emerge. As in Kerzel, Gauch, & Buetti (2010), we hypothesized that the cue may be masking (they attributed it to crowding, but the conclusion is the same) the target stimulus, and we therefore doubled the distance between the two stimuli and lowered the cue contrast. The results of Experiment 2 show that target identification accuracy was higher with a valid cue than an invalid cue when the cue contrast was lowered and moved further away from the target. In Experiment 3, we used the full contrast cue stimulus with masked stimuli and observed that accuracy with valid cues was lower than invalid cues, providing evidence that the high contrast cue produced forward masking on both post-masked and non-post-masked stimuli. These results challenge the conclusion of Kerzel, Gauch, & Buetti, 2010 that their cueing effects were mask dependent since we observed a reverse cueing effect with backward masked stimuli using the high contrast cue. In Experiment 4, stimulus duration was reduced from 100ms to 10ms, and correspondingly, contrast levels were increased. We found larger cueing effects in this short stimulus condition than in Experiment 2 as indicated by a larger threshold ratio. Together, the results indicate that there was an improvement in target identification accuracy for low contrast letters and that these cueing effects are not dependent on the presence of a post mask.

Mechanisms of Involuntary Attention

While some researchers have reported perceptual signal enhancement with involuntary attention using non-predictive cues and unmasked stimuli, there is evidence that observer uncertainty over the location of the target stimulus can improve target detection (Pelli, 1985; Tanner, 1961) and can instigate response bias leading to what appears to be improved target detection at cued locations (Prinzmetal, Long, & Leonhardt, 2008; Prinzmetal, McCool, & Park, 2005). In our experiments and those of others, accuracy judgments were not susceptible to response bias to the cue since the observer reported the stimulus identity and not its location. One question that remains from the presently conducted experiments is whether or not the observed cueing effects were a result of a perceptual process such as signal enhancement or a mechanism of uncertainty reduction broadly defined. Gould, Wolfgang, & Smith (2007) "use the term 'uncertainty reduction' to refer to a mechanism that improves the efficiency of an observer's decision making," for example, improved transfer of visual information into VSTM as postulated in the mask dependent cueing hypothesis (Liu, Wolfgang, and Smith, 2009).

According to signal detection theory, uncertainty reduction makes the slope of the psychometric function shallower (Pelli, 1985). As some researchers have done, one could use the data from Experiment 2 as evidence against uncertainty reduction since the results showed a strong cueing effect without a reduction of the psychometric function slope. Since uncertainty reduction is often associated with slope reduction one might think that our Experiment 2 provides evidence against uncertainty reduction. There are two flaws in that argument. We showed in Experiment 1 that the cue can have a forward masking effect and that the masking effect can strongly increase the slope. It is possible that in Experiment 2 the cue reduced uncertainty thereby reducing the threshold and reducing the slope, but the slope reduction wasn't sufficient to overcome a residual masking effect that increases slope. Our second argument is based on the Gould, Wolfgang, & Smith (2007) approach of broadly defining uncertainty reduction as improving efficiency of the decision stage. There are a variety of mechanisms, whereby increased efficiency shifts the psychometric function without changing slope. Klein & Levi (2009) and Dosher & Lu (1999) showed how changes in multiplicative noise can shift psychometric functions without changing their slope. For this reason, we do not interpret changes in slope as either an indication or refutation of spatial uncertainty.

In order to investigate signal enhancement, any effects of spatial uncertainty reduction must be controlled (Shaw, 1984). Controlling for spatial uncertainty is a difficult task and researchers have developed a number of arguments for and against accounts of spatial uncertainty reduction leading to cueing effects, which requires brief review. One common argument presented in the current literature against spatial uncertainty reduction accounting for reported cueing effects is that if localization accuracy is high, then spatial uncertainty must be low and uncertainty reduction would not account for any observed cueing effects (Cameron, Tai, Carrasco, 2002). When task performance is low, such as when stimuli are difficult to identify or localize, there may be more spatial uncertainty (Pelli, 1985) and the magnitude of any task improvement could be highest at low performance levels, though not necessarily exclusively leading to a change in slope of the psychometric function. As stated, there are other factors that can change the slope of the psychometric function besides uncertainty reduction. However, similar results would be expected from a signal enhancement mechanism since attention would increase the signal strength of attended stimuli, producing a larger signal to noise ratio for low contrast stimuli (Cameron, Tai, Carrasco, 2002; Carrasco, Penpeci-Talgar, Eckstein, 2000; Lu & Dosher, 1998). While this argument has been presented in multiple published articles, it does not conclusively support either a mechanism of signal enhancement or spatial uncertainty reduction in the experiments we have conducted. Either mechanism could produce the observed results, but without constraining spatial uncertainty, we do not conclusively adopt one hypothesis over another.

If this argument were adopted in the present experiments, it would appear as follows. In Experiments 2 and 4 where positive cueing effects were observed, the contrast response function shifted towards lower contrasts for both suprathreshold stimuli (for which there would be little spatial uncertainty since the targets are highly visible) and subthreshold stimuli (where spatial uncertainty reduction could account for some of the performance improvement), suggesting that spatial uncertainty alone wouldn't account for the cueing effect observed across all the levels of task difficulty. However, spatial uncertainty could increase with lower contrast stimuli, in which case the magnitude of task improvement from spatial uncertainty reduction would be much higher at these low contrasts and could potentially account for a larger proportion, if not all, of the cueing effect. As evident, the results are not taken to be evidence either in support or against spatial uncertainty reduction or signal enhancement.

Another argument presented in the literature against spatial uncertainty reduction accounting for the observed cueing effects is that since stimuli were not spatially localized there was spatial uncertainty in all of our experiments, yet in the two experiments with a high contrast cue, there were no significant cueing effects. This argument was presented in Kerzel, Gauch, & Buetti (2010) to dismiss a spatial uncertainty reduction explanation for stimuli that were not spatially localized. If spatial uncertainty reduction were in fact the mechanism responsible for the cueing effect, we would have expected a cueing effect for all experiments where spatial uncertainty was present. While we could adopt the same conclusion that since we didn't see any positive cueing effect in Experiments 1 and 3 while spatial uncertainty was present, spatial uncertainty is not a sufficient explanation for the observed cueing effects in Experiments 2 and 4, we find this conclusion to be flawed. While spatial uncertainty was present in all 4 experiments, the absence of cueing effects in experiments 1 and 3 is due to forward masking and spatial uncertainty reduction is likely insufficient to overcome the masking effect of the high contrast cue. As such, it cannot be argued that spatial uncertainty was not sufficient to produce cueing effects in the experiments with the isoluminant cue.

The results of the present experiments do not provide direct evidence for a specific mechanism of improved target identification accuracy from involuntary attention. It is difficult to ascertain which mechanism(s) best account for our results or even to determine whether the improvement in accuracy judgment performance is due to perceptual or decisional processes. The mechanism of improved transfer of stimulus information into VSTM as proposed by Smith and colleagues could account for the observed cueing effects we obtained. Using a mask eliminates the iconic image, limiting the time available for searching for the target stimulus within memory (Phillips, 1974; Sperling, 1960). When this occurs, the valid cue is effective since it directs attention to the correct location before the signal is lost. Without a mask, more time may potentially be available to search more potential target locations, so a valid cue does not offer a performance advantage since processing time is less constrained. However, the precise duration of the image in iconic memory is unknown, and brief, low contrast stimuli may have such a rapid decay that available search time is not significantly extended. In this way, very brief or low visibility stimuli could act similarly to a mask since search time is highly constrained. The brief stimuli explanation of rapid iconic decay could thereby explain our results and provide support for a mechanism of faster information transfer to VSTM. Additionally, as indicated by the results of Experiments 1 and 3, the high contrast cue produces masking of the targets and this forward masking effect could limit the time available to search for the target within memory in the same manner that backward masking does as proposed in the mask-dependent cueing hypothesis. Various signal enhancement mechanisms could also account for the observed cueing effects, but it is difficult to ascertain these mechanisms without spatially localizing the target stimuli as concluded in Gould, Wolfgang, & Smith (2007). Since the results do not conclusively provide evidence of any specific mechanism of improved target identification, we leave this question open to future investigations.

Further Contributions of this investigation

Only a few studies have investigated the influence of attention on target identification across the full psychometric function when targets are presented in isolation (Cameron, Tai, Carrasco, 2002; Carrasco, Penpeci-Talgar, & Eckstein, 2000). In all of the presently conducted experiments, multiple target contrast levels were tested in order to produce a psychometric function and demonstrate that cueing effects are not isolated to near-threshold levels or specific performance difficulty levels. Some studies have claimed that cueing effects only occur near detection threshold (Kerzel, Zarian, Gauch, Buetti, 2010; Schneider, 2006). It has also been suggested that involuntary attention cueing effects are absent when the task is very difficult and performance is low (Kerzel, Zarian, Souto, 2009). The present experiments measure perceptual enhancement across a large range of contrast levels, encompassing stimulus intensities that are both well above and well below threshold detection levels. In agreement with Ling & Carrasco (2006), the cueing effect is present well above and below threshold detection levels.

In some of the previous reported literature arguing against accuracy performance enhancement from involuntary attention and non-predictive cues, data was collected only at single contrasts (often using staircase procedures to obtain a specific level of performance such as 71% correct) or at a specified level of difficulty and performance(Kerzel, Gauch & Buetti, 2010; Kerzel, Zarian, Souto, 2009). In the present experiments, the same amount of data was collected at each contrast level (on average 220 valid and 220 invalid trials), but 5 or 7 contrast levels were tested, producing significantly more data per subject. Whether or not experienced subjects such as in our experiments produce significantly different results than less trained subjects as in Kerzel, Gauch, & Buetti (2010) is a topic in need of investigation. Perhaps subjects who have longer exposure to cueing tasks assign different weights to the cue, potentially leading to differences in observed cueing effects. This topic requires further investigation.

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Highlights

- Cueing effects with involuntary attention are not dependent on backward masking
- Accuracy performance enhancement was not due to response bias
- 4 Experiments were conducted across the full psychometric function of contrasts
- Non-predictive cues elicit improve accuracy for involuntary attention in 110–170ms
- A cue can mask, changing the psychometric function and weakening the post-mask

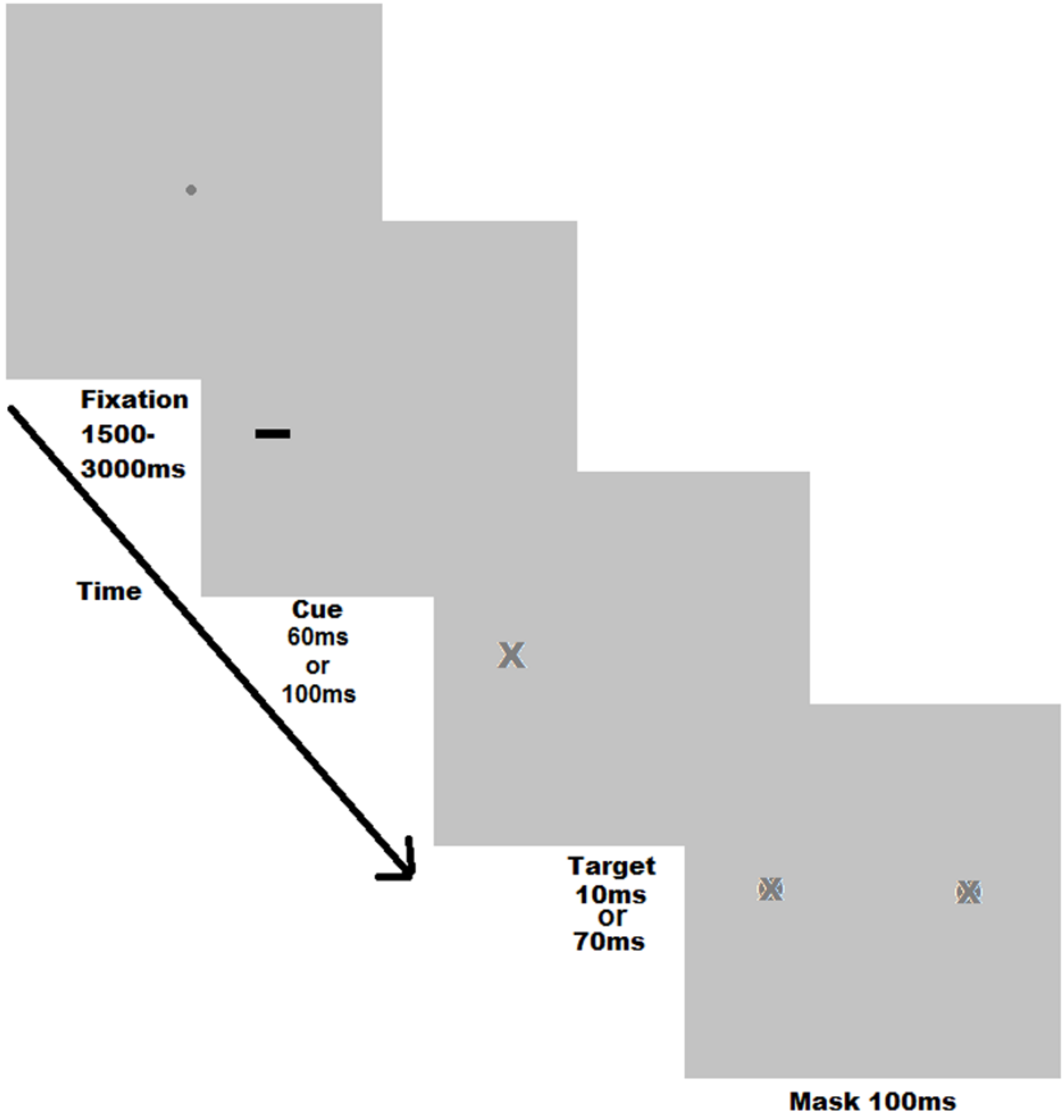

Figure 1.
The sequence of stimuli in a single trial. A valid cue trial is shown. In Experiments 1–3, after a fixation period the cue is presented for 100ms and immediately followed by a 70ms, low contrast letter target stimulus. In Experiment 4, the cue duration is 60ms, followed by a 40ms blank interval, after which a 10ms target is presented. The target stimulus is presented in isolation and unmasked in experiments 1, 2, and 4. After the target offset, the subjects reported the target identity in response to a text prompt. The observer's task was to report the identity of the low contrast letter. The peripheral cue was non-predictive of the forthcoming target location, having 50% predictability. Observers report their response by pressing either 1 or 2 (for O and X respectively). A mask was displayed only in the third experiment, but is shown here for illustrative purposes. The mask had the same contrast as the target stimulus in each trial.

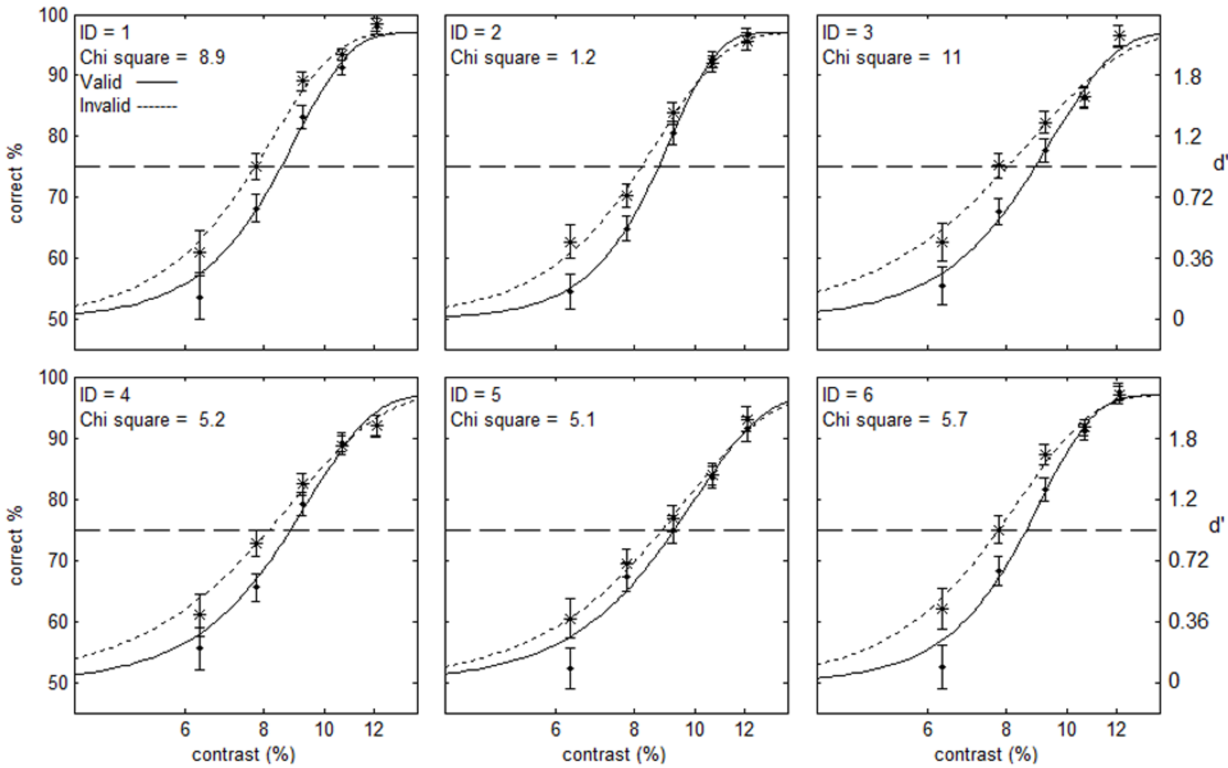

Figure 2.

Accuracy (percent correct) as a function of target contrast for unmasked, low contrast targets with a full contrast cue. A Weibull function was fit to each individual subject's accuracy performance from Experiment 1. The error bars are +/− one binomial standard error. The Weibull fit of performance with a valid cue is shown as the solid line, while performance with an invalid cue is shown by the dotted line. d′ values are plotted on the right vertical axis. The threshold contrast of 75% correct is plotted as the horizontal dashed line. The IDs are subject identification codes, which are the same across all 4 experiments.

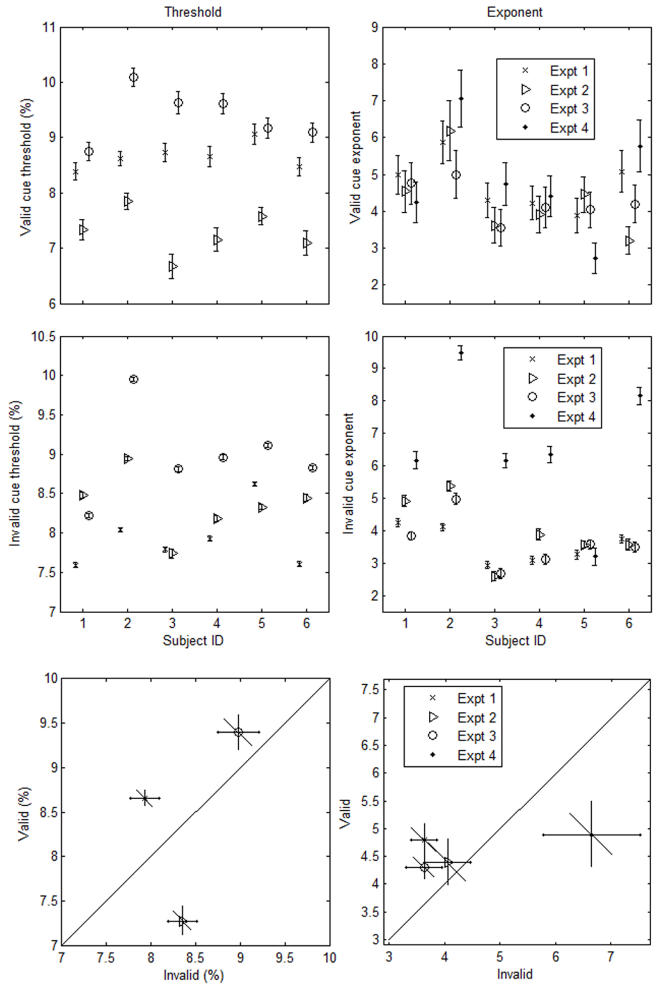

Figure 3.

Plots of the parameter values of the Weibull function fit. The upper left subplot shows the valid cue threshold parameter values for individual subjects from Experiments 1–3. The upper right subplot shows the valid cue exponent parameter values for each experiment and individual subject. The middle left subplot shows the invalid cue threshold parameter values for individual subjects from Experiments 1–3. The middle right subplot shows the invalid cue exponent parameter values for each experiment and individual subject. The lower left subplot compares the mean threshold of valid and invalid cue data. The lower right subplot compares the mean exponent ratio of valid and invalid cue data. In the top four plots, the data point alignment along the x axis is jittered to prevent overlapping error bars.

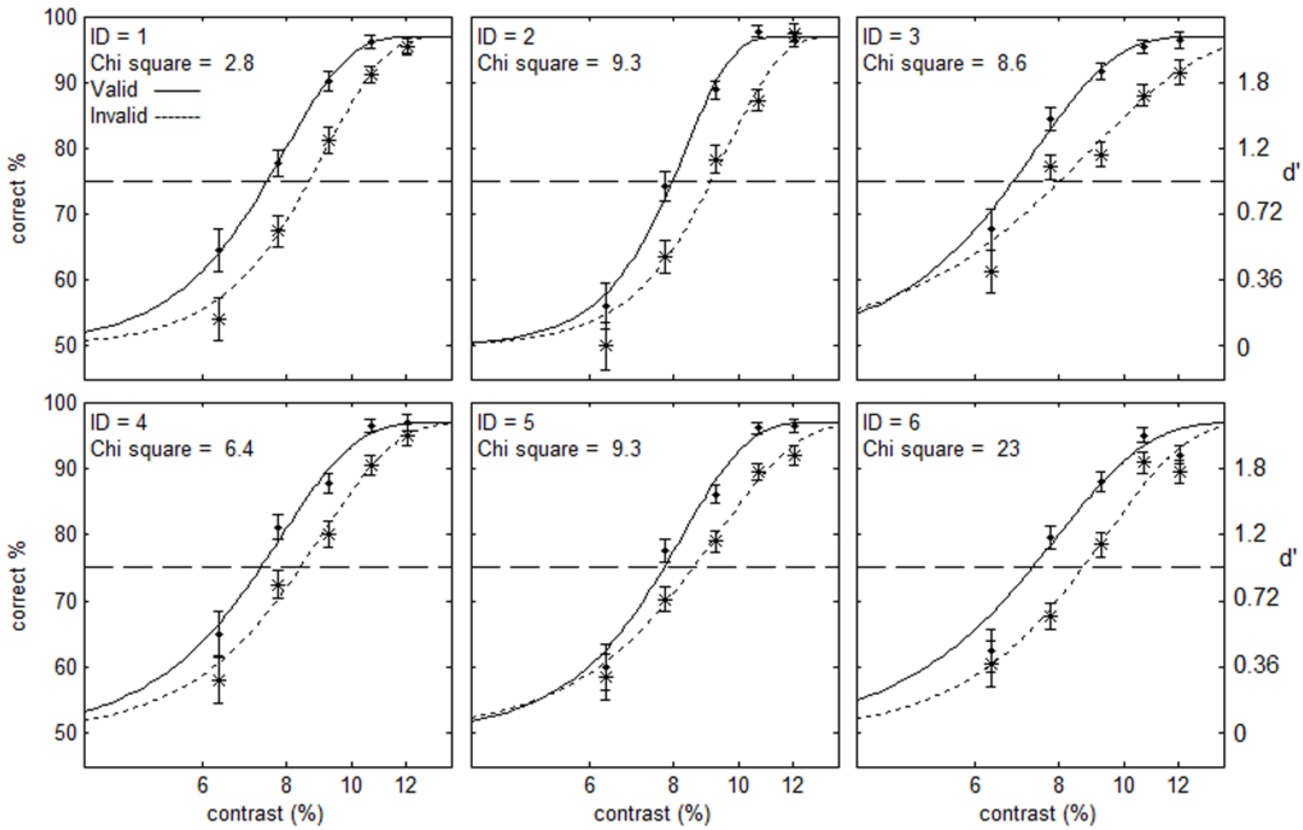

Figure 4.

Accuracy (percent correct) as a function of target contrast for unmasked, low contrast targets with a green cue isoluminant with the background. A Weibull function was fit to each individual subject's accuracy performance. The error bars are +/− one binomial standard error. The fit for the valid cue condition is shown as the solid line, while the invalid cue condition is shown as the dotted line. d′ values are plotted on the right vertical axis. The 75% contrast threshold is plotted as the horizontal dashed line.

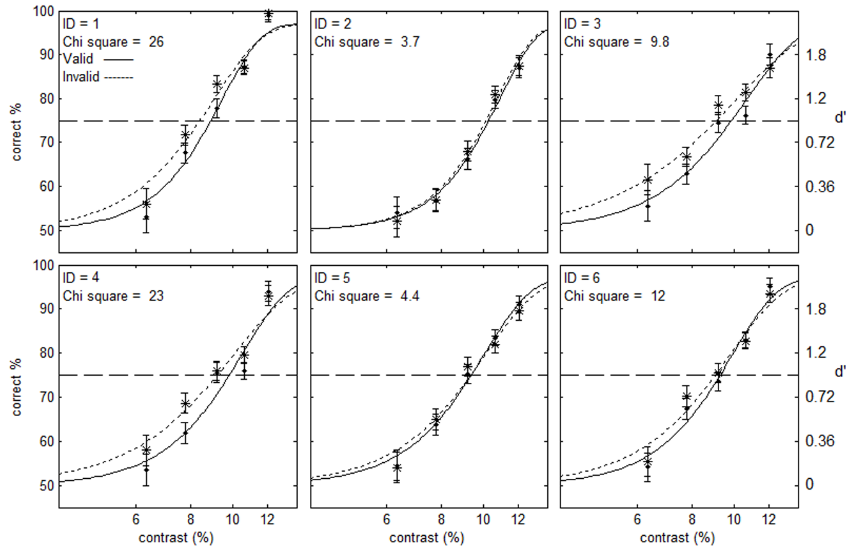

Figure 5.

Accuracy (percent correct) as a function of target contrast (percent) for masked, low contrast targets with a high contrast cue. A Weibull function was fit to each individual subject's accuracy performance. The error bars are +/− one binomial standard error. Valid cue data is illustrated by the solid line, while invalid cue data is illustrated by the dotted line. d′ values are plotted on the right vertical axis. The threshold value is plotted as the horizontal dashed line.

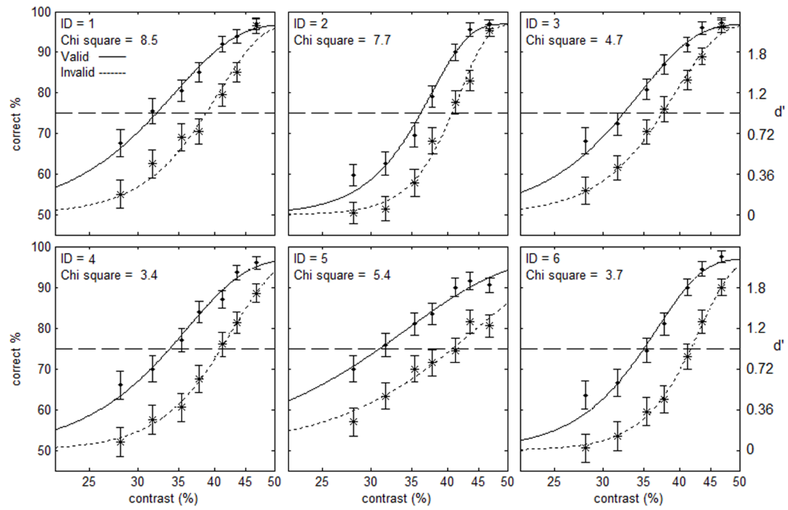

Figure 6.
Accuracy as a function of target contrast for unmasked, low contrast, 10ms targets with an isoluminant cue. Valid cue data is illustrated by the solid line fit, while invalid cue data is shown by the dotted line. d′ values are plotted on the right vertical axis. The threshold value is plotted as the horizontal dashed line. The error bars are +/− one binomial standard error.

Table 1

Analysis of group averages of exponent and threshold ratios for each experiment as well as the goodness of fit (χ^2) of the Weibull function to the averaged data. Only the exponent ratios of experiment 2 were not significantly different from 1.0.

	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Exponent Ratio	0.76 +/− 0.03	0.93 +/− 0.07	0.84 +/− 0.04	1.36 +/− 0.05
t	−8.37	−1.09	−4.39	8.1
p-value	0.0004	0.3255	0.007	0.005
Threshold Ratio	0.92 +/− 0.01	1.15 +/− 0.01	0.96 +/− 0.01	1.21 +/− 0.03
t	−9.21	11.93	−3.34	7.75
p-value	0.0003	0.0001	0.0207	0.0006
Chi Square χ^2	6.2	9.9	13.6	5.6

Table 2

Summary of results. Experiments 1 and 3 had a reversed cueing effect, a group average increase in threshold for the valid cue trials, and an increase in group average slope, while experiments 2 and 4 had positive cueing effects, a group average decrease in threshold for the valid cue trials, and experiment 4 had a group averaged shallowing of slope for valid cue trials, while experiment 2 had not significant change in slope.

Experiment	Masked	Cue Contrast	Cueing effect	Average Threshold	Average Slope
1	No	High	Negative	Cued Increased	Cued Increased
2	No	Low	Positive	Cued Decreased	Non-significant
3	Yes	High	Negative	Cued Increased	Cued Increased
4	No	Low	Positive	Cued Decreased	Cued Decreased