



Bias-free double judgment accuracy during spatial attention cueing: Performance enhancement from voluntary and involuntary attention [☆]



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ABSTRACT

Recent research has demonstrated that involuntary attention improves target identification accuracy for letters using non-predictive peripheral cues, helping to resolve some of the controversy over performance enhancement from involuntary attention. While various cueing studies have demonstrated that their reported cueing effects were not due to response bias to the cue, very few investigations have quantified the extent of any response bias or developed methods of removing bias from observed results in a double judgment accuracy task. We have devised a method to quantify and remove response bias to cued locations in a double judgment accuracy cueing task, revealing the true, unbiased performance enhancement from involuntary and voluntary attention. In a 7-alternative forced choice cueing task using backward masked stimuli to temporally constrain stimulus processing, non-predictive cueing increased target detection and discrimination at cued locations relative to uncued locations even after cue location bias had been corrected.

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1. Introduction

Many cueing investigations have reported that involuntary and voluntary covert attention can enhance target detection and/or discriminability. In these tasks, a cue captures attention to a spatial region or feature in the visual field, leading to improved target identification when the cue precedes a target stimulus within the same spatial region and/or has the same target feature (Lin et al., 2011). While some studies have examined cueing effects across a temporal range spanning the activation of both involuntary and voluntary attention (Cheal & Lyon, 1991; Hein, Rolke, & Ulrich, 2006; Koenig-Robert & VanRullen, 2011; Ling & Carrasco, 2006; Müller & Rabbitt, 1989; Nakayama & Mackablen, 1989) the present investigation provides additional insight into voluntary and involuntary attention performance enhancement by quantifying response bias in a double judgment accuracy task. In some studies, cue location bias has been shown to increase accuracy judgment performance with valid cues and decrease performance with invalid cues, thereby producing misleading cueing effects (Prinzmetal, Long, & Leonhardt, 2008; Prinzmetal, McCool, & Park, 2005), although other studies finding cueing effects have demonstrated

that cue bias can be avoided using control experiments, comparative judgments, or by making identification judgments exclusively (Carrasco, 2011; Carrasco, Fuller, & Ling, 2008; Pack, Carney, & Klein, 2013).

To address the concerns over response bias from target location uncertainty confounding cueing effects, we developed a bias removal process by which the extent of a response bias can not only be measured, but also corrected in the observed results to reveal the unbiased accuracy judgment performance. In this study, observers make a location judgment which is susceptible to cue location response bias, and an identification judgment that is not equally susceptible to cue location response bias. While it can be said that a spatial cue can still influence the integration of sensory information, thereby potentially creating individual subject bias or unequal weighting assigned to each stimulus location which may affect identification accuracy, the bias removal procedure implemented in this study examines the influence of the spatial location of the cue on the observer's tendency to report that the target is at the cued location when the target location is unknown. The bias correction quantifies the extent of this response bias which mainly influences location judgment accuracy. This is not to say that the identification judgments are completely unbiased or that the cue location does not influence identification judgments. Throughout this article, the identification judgments will be referred to as "unbiased," but we only mean that the interaction of the spatial cue adds no additional noise to the identification judgment

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accuracy than what is already present (perhaps in the form of response bias to a specific number). We assume that responding with the cued location when the target location is unknown does not affect the accuracy values for identification judgments in the same manner that location judgments can be affected by a subject's tendency to respond with the cued location excessively when the target location is unknown. In the 7 alternative forced choice (7AFC) divided attention experiment reported here, the bias removal method provides insight into underlying cognitive processes relevant to these tasks, such as response bias, independent processing of location and identification judgments, and inter-subject differences in these variables.

There is considerable evidence that enhancements in visual processing result from directing voluntary attention to a localized region of the visual field, as manifested by faster response times and improved accuracy judgments. However there remains substantial controversy over whether or not improvements in visual processing occur with involuntary attention, particularly when cues are non-predictive of the target location and the observer is making accuracy judgments. Some researchers have reported that non-predictive cueing does not improve response accuracy with letter discrimination (Prinzmetal, McCool, & Park, 2005; Prinzmetal, Park, & Garrett, 2005) or orientation discrimination of low contrast stimuli (Kerzel, Zarian, & Souto, 2009). Cueing effects have been attributed to cue bias related to location uncertainty (Prinzmetal, Long, & Leonhardt, 2008; Schneider & Komlos, 2008; Valsecchi, Vescovi, & Turatto, 2010), or sampling error (Kerzel, Gauch, & Buetti, 2010; Kerzel, Zarian, & Souto, 2009). To the contrary however, various other investigations have reported cueing effects independent of response bias (Carrasco, Fuller, & Ling, 2008; Giordano, McElree, & Carrasco, 2009; Pack, Carney, & Klein, 2013). The aim of the present investigation was to determine if the capture of involuntary and voluntary attention from non-predictive cues results in improved accuracy performance and to quantify and remove response bias to the cued location.

The influence of non-predictive cues on attention capture and response performance has been debated for both reaction time and accuracy judgment experiments, but remains more controversial for accuracy judgment tasks. Perceptual enhancement measured as faster reaction times has been demonstrated to occur when cues are predictive, non-predictive, and even anti-predictive (Esterman et al., 2008; Posner, Cohen, & Rafal, 1982; Rafal & Henik, 1994; Sereno & Holzman, 1996; Warner, Juola, & Koshino, 1990). It is interesting to note that in some of these studies, even with a cue that is anti-predictive, an involuntary cueing effect only occurs when the length of time between the cue and target onset is very short suggesting that involuntary attention has a brief, transient time window of activation.

It has been argued that non-predictive cues do not always improve perception, whereas predictive cues do (Kerzel, Gauch, & Buetti, 2010; Kerzel, Zarian, & Souto, 2009; Prinzmetal, McCool, & Park, 2005; Prinzmetal, Park, & Garrett, 2005) although there are some experimental conditions that may produce cueing effects with involuntary attention such as when set size is large or when a mask is used. Some of the disagreement in the literature about the existence of improved task performance with involuntary attention and non-predictive cues is at least partly related to differences in defining involuntary and voluntary attention. At least 250 ms is required to initiate a target directed saccade (Carpenter, 1988; Mayfrank, Kimmig, & Fischer, 1987) and many studies have reported a rapid rise and decay of involuntary attention around 120 ms (Carrasco, Fuller, & Ling, 2008; Carrasco, Ling, & Read, 2004; Cheal & Lyon, 1991), which is followed by the gradual rise of voluntary attention around 300 ms (Nakayama & Mackeben, 1989; Weichselgartner & Sperling, 1987). As reviewed in Section 4, we differentiate voluntary and involuntary attention

on the basis of temporal parameters with transient involuntary attention remaining active until around 200–250 ms after the cue onset, followed by the activation of sustained voluntary attention.

The present experiment was conducted to address the controversy over cueing effects for accuracy measures using non-predictive cues and to determine if target identification and localization accuracy are enhanced by the allocation of both attention systems. A seven-alternative forced choice task was utilized to maximize the novelty of stimuli throughout the visual field and to create a high level of uncertainty of the target location and identification. The large set size has an advantage over the more common 2AFC task utilized in most cueing studies in that it is more engaging since stimulus identities and locations are more unique and the task is less redundant and predictable since there are more locations to attend to across the visual field and more target identities to discriminate. Having a large number of alternatives also enables researchers to quantify the response bias to the cued location and remove the bias by redistributing the biased trials to the abundant alternative stimulus locations as will be described in Section 2.

2. Methods: letter discrimination and localization of masked stimuli

The present investigation assessed the magnitude of improved accuracy judgment performance with non-predictive cues. While much prior research on this topic has been conducted using 2AFC tasks, in order to maximize attention capture the set size was increased to seven to improve the novelty of presented stimuli, and also to determine if cueing effects are as strong as those reported in 2AFC tasks. It was hypothesized that cueing effects would be robust over the time course of voluntary and involuntary attention, manifested as higher accuracy with valid cues compared to invalid cues.

2.1. Participants

Ten subjects (5 male and 5 female) were recruited from the local 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 in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans. Nine of the subjects were naïve observers, and one was the primary author. Subject ages ranged from 20 to 32. All participants signed an informed consent and were financially compensated for their time. All subjects had normal or corrected to normal vision.

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-in. 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/m². Subjects were positioned in an EyeLink II eye tracker with a chin and forehead rest and their eyes positioned 50 cm from the display, resulting in 2.1 × 2.1 min square pixels. Subjects were instructed to avoid making eye movements during a trial. Since target directed saccades require at least 250 ms to initiate (Carpenter, 1988; Mayfrank, Kimmig, & Fischer, 1987), and our pilot study data indicated very few saccades being made, saccades were not monitored and the eye-tracker was utilized exclusively as a chin and forehead rest.

The experiment was conducted in moderate brightness, standard indoor lighting conditions using 40 W fluorescent lighting.

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 (Fig. 1) on a grey background. The duration of the fixation circle was randomly selected from 0.5 to 2.0 s for each trial to prevent the subject from being able to predict the cue onset. The fixation target was removed before the cue onset and remained absent until the start of the next trial. There were six peripheral stimulus locations positioned at 7.5° eccentricity and one central stimulus location. The cue was an approximately isoluminant green, 120° segment of an annulus. An isoluminant cue was utilized to avoid forward masking of the targets from the cue, a confound previously reported in Pack, Carney, and Klein (2013). The peripheral cue had a uniform width of $\frac{1}{2}^\circ$, whereas the central cue was smaller with a uniform width of $\frac{1}{4}^\circ$. Stimuli presented at the center location were smaller than those presented in the periphery, so the cue size was scaled accordingly. The cue was presented for 60 ms. The peripheral cue was positioned 1° beyond the edge of the forthcoming target/distractor (edge to edge) and the central cue was positioned $1/2^\circ$ outside the central stimulus so there was never any spatial overlap between the cue and the target or distractor. The target stimulus was a number ranging from two to eight in Arial font presented at one of seven locations. Letter distractors were presented at all non-target locations. Targets and distractors presented in the periphery were $1^\circ \times 1^\circ$ in size, but when presented at the central location, they were $\frac{1}{4}^\circ$ in size.

2.4. Procedure

Subjects were instructed to complete the task at their own preferred pace and to take breaks between each run as often as desired to maintain a consistent attentive state. Each run consisted of 49 trials (lasting 3–4 min total), with $1/7$ of the trials having valid cues and $6/7$ with invalid cues. Each data collection session lasted 1 h, and each subject participated in an average of 10 h. Since data collection was self-paced, there was some slight variation in the amount of data collected per subject, but the average number of trials completed by each subject was 6076 trials, or 124 runs encompassing each of the time intervals tested. The subjects were initially familiarized with the task by completing 147 trials (3 runs) with long stimulus durations and low task difficulty. The data from these training runs are not included in the final analysis. Since the

central cue and target stimuli were presented so rarely, data analysis throughout this article only consists of trials in which both a peripheral cue and a peripheral target were presented.

Subjects were informed that a cue would precede the target stimulus, but they were not given any information about the reliability of the cue. In some previous published cueing experiments, subjects were informed about the cue validity (Jonides, 1981; Montagna, Pestilli, & Carrasco, 2009; Pestilli & Carrasco, 2005) or specifically instructed to ignore the cue since it was non-predictive of the forthcoming target location (Kerzel, Zarian, & Souto, 2009). Some research however has shown that observers cannot completely ignore a salient peripheral cue (Jonides, 1981; Müller & Rabbitt, 1989; Warner, Juola, & Koshino, 1990). Providing subjects with explicit instructions to ignore the cue could activate voluntary top-down control systems that may interfere with reflexive attention capture and alter cueing effects. To avoid any confounds related to the subjects' intentions regarding attending to the cue, subjects were not given any specific instructions about the cue or bias except that the cue would be presented before the target. Beginning with the onset of the cue, there was a variable inter-stimulus-interval (ISI) consisting of a blank screen, after which the target and distractors were presented at all seven stimulus locations.

Full contrast peripheral targets and distractors were presented at 7.5° eccentricity from the center of the screen for 40 ms. After the target offset, there was an ISI consisting of a blank screen (20 ms), followed by a 50 ms mask stimulus consisting of random letters presented at each of the seven stimulus locations. The total amount of time available to direct attention to the stimuli is the length of time between the cue onset and mask onset (COMO). This interval includes the duration of the iconic image and determines when voluntary attention is utilized by the observer. After the mask offset, there was 400 ms of blank screen, after which the question "Where was the target number?" was presented at the center of the screen until the subject responded by pressing a number on the keypad between one and seven. After responding with a location, "What was the target number?" was displayed until the subjects responded by pressing a number between two and eight to indicate the target feature identity. After reporting the location and feature identity of the target letter there was 1 s of visual feedback provided in the form of the previously presented target display containing the distractors. A button press initiated the next trial, starting with the display of the fixation point.

Distractor letters were randomly selected from the English alphabet in each trial. Each target number appeared an equal number of times at each of the seven locations. The order of the target numbers was randomly selected but followed an organized

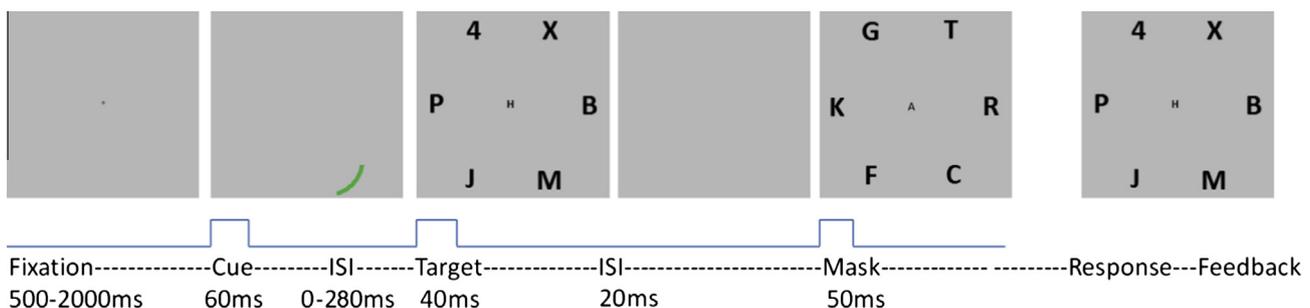


Fig. 1. The sequence of stimuli in a single trial. An invalid cue trial is shown. After a fixation period, the cue was presented for 60 ms, followed by a variable ISI before the target stimulus appeared. The target stimulus was presented with distractor letters for 40 ms. After the target offset, there was a 20 ms ISI followed by a 50 ms mask stimulus consisting of random letters. The observer's task was to report the location and feature identity of the target number, and visual feedback was provided in the form of the previously presented display containing the target and distractors. The cue was non-predictive of the forthcoming target location. Observers reported their response by pressing any number 1–7 to indicate target location, and any number 2–8 to indicate the target feature identity.

structure. There were 7 trials with valid cues at each of the target locations, and 42 trials with invalid cues at each of the target locations, totaling 49 trials for a single run. Of those 49 trials, 36 consisted of a target and cue appearing in the periphery, with 30 of those trials invalidly cued and 6 validly cued. The central cue and target conditions were utilized to encourage the subjects to maintain fixation at the center of the screen throughout each trial. The cue was always non-predictive of the forthcoming target location whether in the peripheral or central visual field. Multiple interleaved ISIs (randomly selected) spanning the time course of involuntary and voluntary attention were tested for each subject.

2.5. Bias correction method

The procedure for quantifying and correcting for cue location bias begins by categorizing the observed responses (Obs) into contingencies. The double judgment accuracy task allows for independent analysis of feature identity and location judgments, providing insight into these response contingencies. This analysis is conducted at each time interval tested (COMO), yielding individual bias values per time interval. The contingency categories are labeled by whether the cue is valid or invalid (“V” or “I”) and whether the location response was the same as the target (“L”) or at a location not containing the cue or the target (“O”), and whether the feature/identification response was correct (“F”) or incorrect (“O”). With an invalid cue, there is an additional response category for location judgments in which the observer picks the cued location (“C”) even though the cue does not contain the target. There are four possible response contingency categories with a valid cue:

1. Correct location and feature identity (VLF).
2. Incorrect location but correct feature identity (VOF).
3. Correct location, but incorrect feature identity (VLO).
4. Incorrect location and feature identity (VOO).

For invalid cue data, there are six possible response contingency categories:

1. Correct location and feature identity (ILF).
2. Picked the cued location, thus an incorrect location response but correct feature identity (ICF).
3. Some location other than the cue or the target, but correct feature identity (IOF).
4. Correct location, but incorrect feature identity (ILO).
5. Cued location (incorrect), and incorrect feature identity (ICO).
6. Incorrect location (not the cued location) and incorrect feature identity (IOO).

The extent to which the observer was biased to the cued location can be quantified from the invalid cue trials as the number of trials in which an observer responded with the cued location (C) in excess of the number of trials the observer reported the other uncued, non-target containing locations (O). A higher level of cue location bias is manifested as higher ICF and ICO values. There are two cue location bias parameters for whether or not the target feature identity was known (F) or unknown (O). For simplicity, we have presented the contingency data as percentages of the total data per valid and invalid conditions. That is, VLF + VOF + VLO + VOO = 100% and ILF + ICF + IOF + ILO + ICO + IOO = 100%. A walk-through of this bias correction method is provided to aid the reader. The contingency percentages of an imaginary data set that were chosen to be very close to the data of observer 1 for COMO = 190 ms and were as follows:

VLF	VOF	VLO	VOO	ILF	ICF	IOF	ILO	ICO	IOO
84%	4%	8%	4%	41%	20%	8%	4%	15%	12%

Although the cued location was uninformative in the present study, the cue may have attracted attention so that the cued location would be chosen if the correct location was not seen. For the invalid trials the bias correction is made by comparing the number of responses to the cued location to the responses to locations other than the target and the cue. In the above example let us begin by focusing on the case where the feature identity was correctly identified. This fraction consisted of two parts. One part was a contribution due to the cue bias after not detecting the location and the other part was due to guessing. We begin our analysis by focusing on the case where the feature identity is known for the invalid cue trials. The feature is correctly identified (sometimes by a lucky guess) $ILF + ICF + IOF = 69\%$ of the time. The goal of our analysis will be to separate the term ILF into three parts: true detection of location and feature identity (39%, see Eq. (2a)), a guessing amount of 2% (see Eq. (1)), and the cue bias amount that should have been added to the guessing (3%, see Eq. (2b)). By adding the cue bias the corrected value of ILF becomes $ILF^* = ILF + 3\% = 44\%$.

The first step of the cue bias correction is to determine the contribution to each choice due to guessing,

$$IOF1 = IOF / (N - 2) = 8\% / 4 = 2\% \tag{1}$$

The IOF1 notation indicates that every single one of the six locations get a 2% contribution from guessing. Once we know this guessing amount we can do the guessing correction for the fraction of target location and cue location judgments:

$$ILFg = ILF - IOF1 = 41\% - 2\% = 39\% \tag{2a}$$

$$IbF = ICFg = ICF - IOF1 = 20\% - 2\% = 18\% \tag{2b}$$

$$IOFg = IOF + 2 * IOF1 = 8\% + 2 * 2\% = 12\% \tag{2c}$$

For simplicity of notation we call the guessing-corrected probability of choosing the cued location “IbF” as seen in Eq. (2b). Eq. (2a) indicates the subject detected the correct location 39% of the time with 2% of the correct judgments being due to guessing. Of the remaining 30% of the trials 18% went to the cue and 12% were distributed to the 6 locations by random guessing. This 12% number could also have been calculated as $6 * IOF1$. The removal of the cue bias is done simply by dividing the 18% that went to the cue by 6 so that an extra 3% should be distributed to each of the possibilities.

Thus the corrected value of the probability of landing on the target is given by:

$$ILF^* = ILF + ICFg / N = 41\% + 3\% = 44\% \tag{3}$$

We now need to do a similar calculation for the valid trials. We will make the assumption that since the observer does not know whether a trial is valid or invalid, the ratio, *R*, of going to the cued location relative to guessing is the same for valid and invalid. That is, when the target location was not detected, a fixed fraction of the missed targets would go to the cue and the remainder would be distributed across the *N* alternatives by guessing. The assumption for connecting the valid to invalid ratio is simply:

$$VRF = IRF \tag{4}$$

where IRF and VRF are defined by:

$$IRF = IbF / IOFg = 18\% / 12\% = 1.5 \tag{5a}$$

$$VRF = VbF / VOFg = IRF = 1.5 \tag{5b}$$

So now we can shift to the valid case and carry out calculations similar to the invalid case:

$$VOF1 = VOF / (N - 1) = 4\% / (6 - 1) = 0.8\% \tag{6}$$

where VOF1 is the amount of guessing that contributes to each of the six locations and the total amount of guessing is:

$$\text{and } \text{VOFg} = \text{VOF1} * N = 0.8 * 6 = 4.8\% \quad (7)$$

Thus by combining Eqs. (5b) and (6) we get the contribution of the cue for the valid trials to be:

$$\text{VCFg} = \text{VRF} * \text{VOFg} = 1.5 * 4.8\% = 7.2\% \quad (8)$$

We are finally able to make all the bias corrections by simply spreading out the bias term (VCFg) that inappropriately went to the cued location. The bias corrected terms are:

$$\begin{aligned} \text{ILF}^* &= \text{ILF} + \text{IbF} * 1/N = 41\% + 18\% * 1/6 = 44\% \\ \text{IOF}^* &= \text{IOF} + \text{ICF} - \text{IbF} * 1/N = 20\% + 8\% - 18\% * 1/6 = 25\% \\ \text{VLF}^* &= \text{VLF} - \text{VbF} + \text{VbF} * 1/N = 84\% - 7.2\% + 7.2\% * 1/6 = 78\% \\ \text{VOF}^* &= \text{VOF} + \text{VbF} * 5/N = 4\% + 7.2\% * 5/6 = 10\% \end{aligned} \quad (9)$$

Note that when the bias correction is taken into account the categories ICF and IOF can be combined for the corrected IOFc. The exact same process can be done for the case where the feature identity was not correctly detected by replacing the letter F with O in all the above equations. There is a totally independent bias correction for those terms. The bias corrected contingency values for all 10 terms become the following 8 terms:

$$\begin{array}{cccccccc} \text{VLF}^* & \text{VOF}^* & \text{VLO}^* & \text{VOO}^* & \text{ILF}^* & \text{IOF}^* & \text{ILO}^* & \text{IOO}^* \\ \hline 78\% & 10\% & 5.3\% & 6.7\% & 44\% & 25\% & 6\% & 25\% \end{array}$$

With bias parameters of: VbF = 7.2% and IbF = 18%.

This method of bias removal can be used with smaller or larger set sizes as long as $N > 2$. For the present experiments the cue was not predictive of the target location. The above also works if the cue was partially predictive as is the case in the second experiment in the companion paper (Pack et al., 2014) where the cue predictability was 50% rather than the uninformative value of 1/6 in the present paper. For a predictive cue one would expect that the overall bias term ratio, R , would be greater than the non-predictive case. This approach could also be used with cues other than spatial cues. For instance, feature cues are subject to response bias to cued features rather than cued spatial locations and this bias removal procedure is easily modifiable for that purpose. We will return to the topic of bias removal using feature cues in a forthcoming manuscript.

3. Results

Accuracy was measured as the percentage of trials for which the observer correctly identified the target number or location. Since the central cue and target stimuli were presented so rarely and the conditions are not comparable to the peripheral locations, data analysis was only performed on trials in which both a peripheral cue and a peripheral target were presented. In Fig. 2, observer accuracy for reporting the target feature identity and location is plotted as a function of the amount of time available to allocate attention which includes the time between the cue onset and mask onset which we have called COMO (60 ms cue + variable ISI + 40 ms target + 20 ms ISI). The feature identity judgment data are presented on the solid lines and bias corrected location judgment data are on the dot-dash lines. The original biased location judgment data is shown as the dotted lines. Standard errors were calculated from the standard deviation, s , across n observers.

One standard error for between-subjects are indicated on the plot for each COMO time point. Conversion of proportion correct to d' -prime was calculated using Palamedes Toolbox and is shown on the right ordinate of Fig. 2 (for details see Prins & Kingdom, 2009).

Fig. 2 captures the basic findings which are summarized here for emphasis and considered in more detail in the discussion. Performance improves with increasing COMO time irrespective of

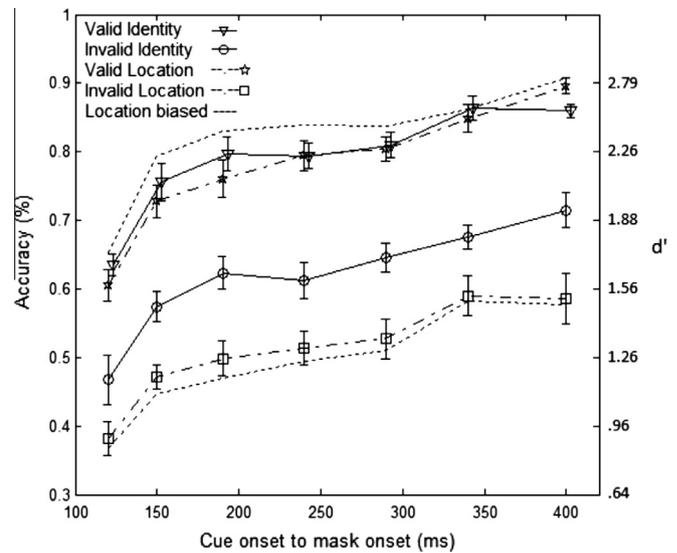


Fig. 2. Average accuracy of target identification and localization across time for valid and invalid cue data. Feature identity judgment data is shown on the solid lines, while bias corrected location data is shown by the dash-dot lines, and the original biased location judgment data is shown as the dotted lines. The error bars are \pm one standard error and the d' values are plotted along the right vertical axis for reference.

task; feature identity or location, or cue validity. As expected, valid cueing improved overall performance and the effect is robust. Response bias correction lead to nearly identically high performance levels for valid feature identity and location tasks. Invalid cueing impaired performance more on the location task than on the feature identity task. The general performance improvement over time for all conditions did not distinguish the allocation of involuntary from voluntary attention.

To validate some of these observations, we performed a three-way repeated measures ANOVA with factors, COMO, Valid/Invalid and Location/Feature Identity. The COMO factor spanned the range from 150 to 340 ms since data at 120 and 400 had fewer subjects. Only the bias corrected location data was used. As expected from Fig. 2, all of the factors were significant; for COMO $F(4,36) = 13.56$, $p < 0.0001$, for Valid/Invalid $F(1,9) = 717.58$, $p < 0.0001$ and for Location/Feature Identity $F(1,9) = 24.62$, $p = 0.001$. The COMO and Valid/Invalid interaction and the COMO and Location/Feature Identity interaction terms were not significant, neither was the three way interaction. The Valid/Invalid and Location/Feature Identity factor interaction was significant, $F(1,9) = 23.82$, $p = 0.0001$. This interaction captures the finding that the valid feature identity and location performances were nearly identical while the invalid feature identity performance was much better than invalid location performance. Plots of individual subject data are included in the Supplementary section.

The left plot in Fig. 3 shows the percentage of the total data for each contingency category. Across the time course of involuntary and voluntary attention, with both invalid and valid cues, subjects most frequently knew both the target location and feature identity together (VLF). These values increased with increasing processing time (COMO). The IbF and IbO percentage values shown in the right plot in Fig. 3 are the percentage increase in the number of trials in which the subject responded with the cued location (C) more than a different location (O) not containing the target or the cue. For example, 6 on the vertical axis means the subject responded with the cued location 6% more than an uncued location. Note that this does not mean that 6% of all of the data was biased to the cued location, but rather that the subject selected the cued location 6% more often than an uncued location.

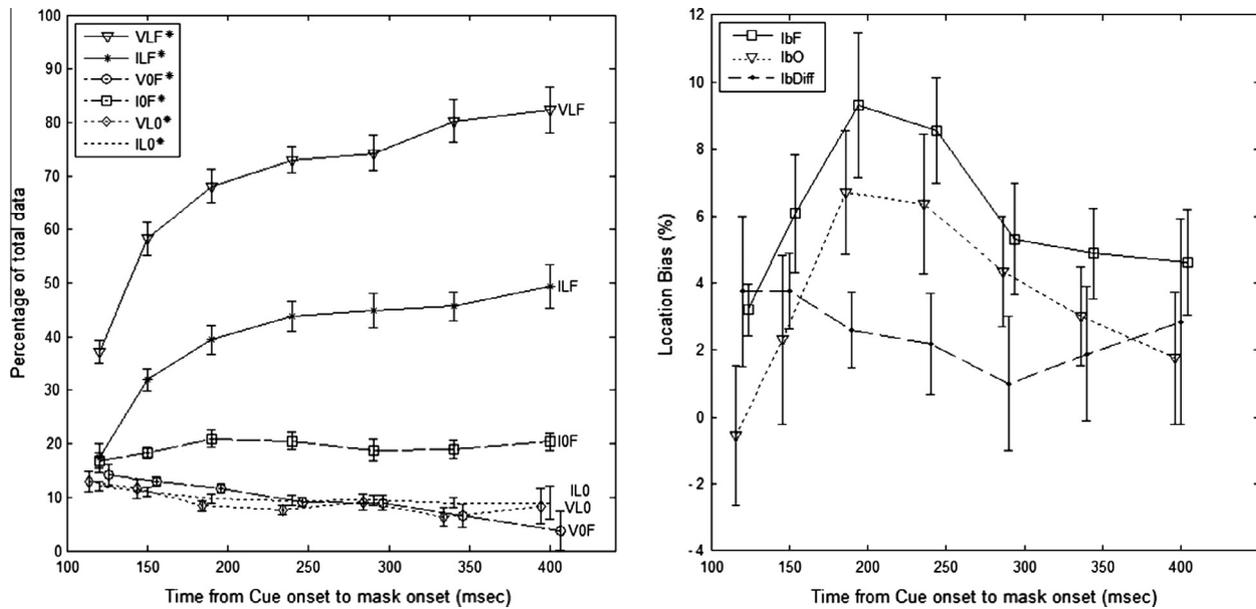


Fig. 3. The left plot shows the distribution of the total data into the bias corrected contingency categories. The VOO and IOO contingency category values have been left out of the plot since they only represent the remainder of data not contained in the other categories ($VOO = 100 - VLF - VOF - VLO$ and $IOO = 100 - ILF - IOF - ILO$). The cued location response categories (ICF and ICO) were not plotted because the data shown have been bias corrected. The right plot shows the IbO and IbF bias values which are the percentage increase in the number of trials in which the subject responded with the cued location (C) more than a different location (O) not containing the target or the cue. The difference of IbF and IbO (IbDiff) is plotted along the dashed line, showing that the difference is larger than zero. The error bars are \pm one standard error.

We performed a two-way repeated measures ANOVA with factors, COMO and IbF/IbO to assess whether the amount of bias varied over time for each bias parameter and whether IbF was larger than IbO. All of the factors were significant; for COMO $F(6,54) = 18.15$, $p = 0.001$ and for IbF/IbO $F(1,9) = 39.71$, $p < 0.001$. The COMO and IbF/IbO interaction was not significant.

4. Discussion

This experiment was conducted to assess whether or not involuntary and voluntary attention improve response accuracy for two independent accuracy judgments, localization and identification while controlling for cue location bias. This is a unique contribution to the current cueing task literature in that there are two independent accuracy judgments measured, and while one is “free” of cue location bias (identification), the other (localization) can be bias corrected using the method we devised. The contingency analysis allowed for an assessment of the relationship between accuracy of reporting the target feature identity and location, providing insight into whether involuntary attention leads to improved performance on both perceptual judgments or just one independent of the other.

The results of the three-way repeated measures ANOVA indicated that accuracy judgment performance for both valid and invalid cues increased as processing time (COMO) increased and that valid cue performance was significantly higher than invalid cue performance for both location and identification judgments. As indicated in Fig. 2 with a valid cue, location and identification accuracy were not significantly different, but with an invalid cue, target identification accuracy was higher than location accuracy. One explanation for this difference may be that at lower accuracy levels where there is more uncertainty over the target feature identity and location and task difficulty is higher, the cue may more strongly capture attention to a specific location which might impair location judgment accuracy more than identification judgment accuracy. This would lead to differences in accuracy performance between identification and localization judgments with invalid cues, as the results show.

There were two measures of cue location bias in this experiment which were calculated from the invalid cue trials. IbF was the amount of bias when the target feature identity was known and IbO was when the target feature identity was unknown. The bias was divided into these two types since perceptual processing and bias may be different depending on the level of uncertainty of the feature identity of the target stimulus. The results of the two-way repeated measures ANOVA indicate that the amount of cue location bias varied significantly across processing time (COMO) and that the IbF and IbO bias parameters followed the same trend over times tested. IbF was significantly higher than IbO across all the COMO times revealing that the tendency to have more bias when the target is known than when it is unknown is consistent across involuntary and voluntary attention. Both bias parameters rapidly increased from 120 to 190 ms, suggesting that as involuntary attention was maximally captured, observers were most susceptible to cue location bias (Fig. 3). The cue bias was highest around the time that involuntary attention was replaced by voluntary attention (190–240 ms), after which the bias amount decreased as the length of processing time available (COMO) increased. As more time was available to process the stimuli, response accuracy increased and subjects were less biased toward the cue location. Perhaps the longer processing times during voluntary attention resulted in the subjects being less influenced by the cue location and thereby less distracted by an invalid cue.

The left plot in Fig. 3 shows that subjects most often correctly identified both the location and feature identity of the target stimulus together since the VLF contingency category contained the highest percentage of the total data. The tendency to report both correctly within a single trial increases across time because as the task becomes easier, accuracy for both location and feature identification judgments increase. Interestingly, this trend across time is not present for the contingencies in which the subjects made a correct response for just one task but not the other (IOF, ILO, VLO, and VOF) further suggesting that as the task difficulty is lowered with increasing processing time, both feature identity and location judgment accuracy increase together.

In some cueing experiments with alphanumeric stimuli, data was collected using a staircase procedure to obtain a specific level of performance such as 71% correct or at a specified level of difficulty (Kerzel, Gauch, & Buetti, 2010; Kerzel, Zarian, & Souto, 2009). Using the method of constant stimuli has the advantage of collecting data over a range of perceptual performance encompassing low and high difficulty levels as conducted in the present experiment with varying difficulty levels corresponding to different ISIs. The results of the present experiment demonstrate that cueing effects are not isolated to specific performance difficulty levels. Some studies have reported cueing effects only near detection threshold (Kerzel et al., 2010; Schneider, 2006). It has similarly 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 experiment measured improvements in accuracy judgments across a large range of temporal parameters and difficulty levels, indicating improved accuracy throughout the time course of involuntary and voluntary attention and across a large range of accuracy levels.

One possible explanation as to why some other experiments have failed to find cueing effects with similar cueing tasks is that the subjects in the present experiment were highly trained. Subjects participated in about 10 h of data collection, completing over 6000 trials. Few other cueing experiments have collected such a high volume of data per subject. Perhaps experienced subjects such as in this experiment produce significantly different results than less trained subjects because they assign different weights to the cue, potentially leading to differences in observed cueing effects. In the present task however, cue predictability was much lower than the usual 50% validity utilized in most cueing experiments. With cue predictability only 14.3%, there is even less strategic incentive to assign more weight to the cue to guide attention. This makes the results even more surprising since the cueing effects are robust even when cue reliability is very low.

The presence of the backward mask provided a temporal constraint of processing time in this task. The mask eliminates the iconic image, constraining the time available for searching for the target stimulus within memory (Phillips, 1974; Sperling, 1960). Without a mask, more time may potentially be available to search more of the possible target locations though the precise duration of the image in iconic memory using the present stimuli is unknown. The presence of the mask provides assurance that at short ISIs there is insufficient processing time available to utilize voluntary search processes, and therefore it is reasonable to claim with relative certainty that the experiment is in fact investigating involuntary attention processes at the short ISIs. Our results did not however show a transition period between the involvement of involuntary and voluntary attention.

4.1. Characterizing involuntary and voluntary attention

The results of the present investigation do not indicate a distinct transition from involuntary attention into voluntary attention. We find a characteristic rapid increase in response accuracy beginning at 120 ms (transient involuntary attention), which remains sustained across the longer time intervals (voluntary attention). The slope between data points is highest between 120 and 150 ms, likely reflecting the rapid onset of involuntary attention enhancement effects. A large number of studies have reported a rapid rise and decay of involuntary attention around 110 ms (Carrasco, Fuller, & Ling, 2008; Carrasco, Ling, & Read, 2004; Carrasco & McElree, 2001; Giordano, McElree, & Carrasco, 2009; Liu, Pestilli, & Carrasco, 2005; Montagna, Pestilli, & Carrasco, 2009), which is followed by the gradual rise of voluntary attention (Cheal & Lyon, 1991; Nakayama & Mackablen, 1989). Here we briefly review some of the literature on this topic to provide

support for the differentiation of involuntary and voluntary attention on the basis of temporal characteristics.

In Cheal and Lyon (1991), a peripheral cue activated involuntary attention and resulted in a rapid increase in correct responses from 0 to 100 ms SOA, tapering off at a steady maximal performance level around 100 ms. An attention gating model was previously proposed, predicting that only about 100 ms are needed to engage the fast involuntary attention process, while about 300 ms are necessary for the slow voluntary attention process (Weichselgartner & Sperling, 1987). A similar cueing effect was found with peripheral cues, revealing a rapid rise in response accuracy with a short SOA, followed by an asymptote around 100 ms, and then a continuous but slow decrease in response accuracy from 200 ms onward (Nakayama & Mackablen, 1989). While these experiments (Cheal & Lyon, 1991; Nakayama & Mackablen, 1989) did not investigate performance differences with cue predictability, nor compare performance of valid, invalid, or non-cue conditions, the findings are of great interest to the current investigation as added insight is gained into the time course of involuntary and voluntary attention. This research has shaped the widely accepted experimental prediction that as involuntary attention passes its time of maximum effect, voluntary attention engages and maintains perceptual performance at a high level of accuracy. The involuntary attention system is captured reflexively to a salient stimulus and is devoid of voluntary control. The voluntary attention system begins to be activated at times long enough to give rise to voluntary orienting (covertly or overtly), and is sustained for a long time (potentially activating as early as 200 ms).

Some research has claimed that voluntary attention can be engaged as early as 50 ms, but these studies use cue-predictability as a differentiator of attention rather than temporal parameters (Prinzmetal, McCool, & Park, 2005; Warner, Juola, & Koshino, 1990). Additionally, Warner and colleagues used reaction time as a measure of performance whereas the current experiment involved accuracy judgments. Also in their experiment, no mask was used so recurrent processing of the iconic image may be a significant confound if observers can still process the visual information after stimulus offset. In the present experiment, a backward mask was used to constrain the amount of time available to attend to the visual stimuli. Using a mask eliminates recurrent iconic image processing, for which an observer can continue to access visual information from memory, thereby having extra time to cognitively search for the target stimulus even after the image is no longer present on the display or the retina (Sperling, 1960).

In one recent publication, spatiotemporal maps of involuntary and voluntary attention were obtained with results suggesting that involuntary attention leads to improved target detection during 150–430 ms (increasing as early as 50 ms and maximizing from 200 to 350 ms), and voluntary attention activating around 400 ms and being sustained for at least another 300 ms (Koenig-Robert & VanRullen, 2011). Their task involved identifying the presence of a low contrast cross presented in a noisy background. While the present experiment did not measure beyond 380 ms, the results confirm that involuntary attention leads to a rapid increase in target identification and localization accuracy and since the cueing effect and performance levels were fairly consistent up to 380 ms, it is reasonable to conclude that voluntary attention accounts for the sustained performance levels.

4.2. Mechanisms of accuracy improvement with involuntary and voluntary attention

One question that remains is whether or not the observed cueing effects were a result of a perceptual process or a decisional

process. The observed cueing effects could result from earlier processing of attended stimuli (Hikosaka, Miyauchi, & Shimojo, 1993; Schneider & Bavelier, 2003), more efficient visual stimulus information transfer into visual short term memory (Gould, Wolfgang, & Smith, 2007), signal enhancement, or simply spatial uncertainty reduction. A reduction of uncertainty over the location of the target stimulus could have improved target detection (Pelli, 1985; Tanner, 1961). A valid pre-cue may lead to improved accuracy by reducing the observer uncertainty over where the target appeared. Spatial uncertainty increases with set size so uncertainty is very high in the present experiment and an uncertainty reduction explanation could account for the observed performance enhancement. Gould, Wolfgang, and Smith (2007) examined cueing effects in a 2AFC gabor orientation discrimination task, and found large cuing effects in the absence of localizing markers that were eliminated when localizing markers were used, consistent with an uncertainty reduction mechanism. Their experiment task was very different from the letter identification and localization task presently conducted however, so their conclusions do not readily apply to the present results. This does not dismiss an uncertainty reduction mechanism as accounting for the results, but instead means that the mere absence of localized stimuli does not necessarily mean that the results are exclusively attributable to a mechanism of uncertainty reduction.

A decision-level mechanism could also account for the increase in accuracy. The decision-level mechanism works by regulating the transfer of visual information into a system with fixed capacity that makes the decision whether the target is present (Duncan, 1980; Müller & Humphreys, 1991; Sperling, 1984). An invalid cue degrades information transfer leading to lower target identification accuracy or a slower reaction time, whereas a valid cue affects the activation of memory and decision processes to more efficiently transfer visual information into short term working memory (Gould, Wolfgang, & Smith, 2007; Luck et al., 1994). Some researchers have argued that non-predictive cues do not affect perceptual processing and instead influence decision stage processes such as selection bias to the cue (Kerzel, Gauch, & Buetti, 2010; Kerzel, Zarian, & Souto, 2009; Kerzel et al., 2010; Prinzmetal, Long, & Leonhardt, 2008; Prinzmetal, McCool, & Park, 2005; Prinzmetal, Park, & Garrett, 2005; Prinzmetal et al., 2009; Schneider & Komlos, 2008; Valsecchi, Vescovi, & Turatto, 2010). A selection bias decision process can be dismissed because of the bias removal method, but a mechanism of faster information transfer into VSTM could explain the results as a decision stage process.

Another possible mechanism of attention which could account for the results is signal enhancement. However, in order to investigate signal enhancement, any effects of spatial uncertainty reduction must be controlled (Shaw, 1984). Spatial uncertainty was not controlled for in the present experiment since the stimuli were not localized (such as with fiducial markers), so the results cannot be conclusively attributed to a mechanism of signal enhancement. The results are in agreement with studies showing cueing effects using alphanumeric stimuli which were claimed to result from mechanisms of signal enhancement (Yeshurun & Rashal, 2010) while ruling out uncertainty reduction (Luck et al., 1996), but the results do not a-theoretically provide direct support for signal enhancement.

The results of this investigation do not conclusively rule out one mechanism of performance enhancement over another with the exception of ruling out a response bias hypothesis. The observed cueing effects are not attributable to response bias since a method of quantifying and removing response bias from the observed data was implemented. Further investigations would be necessary to determine the precise mechanism of improved accuracy, perhaps after constraining spatial uncertainty reduction by localizing stimuli.

4.3. Summary conclusion

There are only a few prior cueing experiments reporting improved accuracy judgments using alphanumeric stimuli and non-predictive cues (Henderson, 1991; Henderson & Macquistan, 1993; Luck et al., 1996; Yeshurun & Rashal, 2010), with only two making use of distractor stimuli (Luck & Thomas, 1999; Müller & Rabbitt, 1989). The present investigation is unique as it is the first investigation to examine double judgment accuracy performance during both involuntary and voluntary attention, using non-predictive cues and distractor stimuli. The bias removal method has high value for conducting future cueing experiments as it allows researchers to analyze data contaminated by response bias (either feature identity or location bias), rather than dismissing results because of bias or avoiding bias-prone judgments altogether.

The present experiment tested attentional cueing for two types of accuracy judgments in a demanding divided attention task: localization and identification. Across all subjects, and over a wide range of temporal separation of the pre-cue and target, the results show that involuntary and voluntary capture of attention via a non-predictive peripheral cue improves response accuracy for identifying both where and what the target stimulus was. It also provides strong evidence that subjects either cannot or do not ignore a salient cue, even when the cue is non-predictive. This experiment demonstrated that double judgment accuracy measures can be used to gain insight into underlying psychological processes such as the relationship between correctly identifying a target stimulus feature identity and its location independently. This procedure is presently being implemented to examine other forms of attention such as feature-based attention, and the research community will certainly find many more uses of this bias removal method than what has been presently done.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.visres.2014.08.004>.

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