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Short Communication

Attentional inhibition mediates inattentional blindness

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ABSTRACT

Salient stimuli presented at unattended locations are not always perceived, a phenomenon termed inattentional blindness. We hypothesized that inattentional blindness may be mediated by attentional inhibition. It has been shown that attentional inhibition effects are maximal near an attended location. If our hypothesis is correct, inattentional blindness effects should similarly be maximal near an attended location. During central fixation, participants viewed rapidly presented colored digits at a peripheral location. An unexpected black circle (the critical stimulus) was concurrently presented. Participants were instructed to maintain central fixation and name each color/digit, requiring focused attention to that location. For each participant, the critical stimulus was presented either near to or far from the attended location (at the same eccentricity). In support of our hypothesis, inattentional blindness effects were maximal near the attended location, but only at intermediate task accuracy.

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1. Introduction

A salient stimulus presented at an unattended location is not always perceived, a phenomenon termed inattentional blindness (Mack & Rock, 1998). While the experimental conditions that give rise to inattentional blindness have been explored to some degree, the cognitive processes mediating inattentional blindness are still unknown. Inattentional blindness effects have been directly linked to classic findings in the spatial attention literature. Attentional control settings (Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994) can affect the rate of inattentional blindness, where, for example, there is greater inattentional blindness for a white stimulus if the task involves attention to black stimuli (Koivisto, Hyona, & Revonsuo, 2004; Koivisto & Revonsuo, 2008; Most, Scholl, Clifford, & Simons, 2005; Most et al., 2001).

There is also evidence that inattentional blindness effects reflect selective spatial attention corresponding to maximal facilitation of processing at an attended location (e.g., Downing, 1988; Erikson & St. James, 1986). In a typical inattentional blindness experiment, an observer fixates at the center of the display and simultaneously attends to a demanding perceptual task in the periphery. Surprisingly, participants often fail to perceive a 'critical stimulus' presented at fixation, an illustration of inattentional blindness. Mack and Rock (1998) modified this basic paradigm by presenting the critical stimulus at peripheral locations in the display. They found a lower rate of inattentional blindness when the critical stimulus was presented within the attended region versus when it was presented outside of the attended region (see Bridgeman & Lathrop, 2007, for a demonstration of robust inattentional blindness to a large critical stimulus presented outside of the attended region). In an even more detailed study, Newby and Rock (1998) presented the peripheral critical stimulus at varying distances from the locus of attention and found that the rate of inattentional blindness increased parametrically with increasing distance (see also, Most, Simons, Scholl, & Chabris, 2000). These findings are consistent with a gradient model of selective spatial

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attention, where facilitatory attention effects are maximal at the attended location and gradually fall off with increasing distance.

Mack and Rock (1998) predicted that inhibitory processes may play a role in inattentional blindness when they speculated "anything that causes attention to be inhibited at the location in which the critical stimulus appears predictably increases the likelihood of inattentional blindness" (p. 228). As such, we hypothesized that inattentional blindness may be mediated, in part, by attentional inhibition. Attentional inhibition is modeled by a facilitatory region centered at the attended location (as described above) that is surrounded by a region of inhibition (which is in turn surrounded by an area of little or no attentional modulation). This center-surround model of attention has been supported in a number of behavioral studies (Bahcall & Kowler, 1999; Bichot, Cave, & Pashler, 1999; Caputo & Guerra, 1998; Cepeda, Cave, Bichot, & Kim, 1998; Cutzu & Tsotsos, 2003; Kim & Cave, 1999; Mounts, 2000a; Müller, Mollenhauer, Rösler, & Kleinschmidt, 2005; Müller, Mühlenen, & Geyer, 2007; for a review, see Cave & Bichot, 1999) and neural studies (Boehler, Tsotsos, Schoenfeld, Heinze, & Hopf, 2009; Hopf et al., 2005; Müller & Kleinschmidt, 2004; Slotnick, Hopfinger, Klein, & Sutter, 2002; Slotnick, Schwarzbach, & Yantis, 2003). If our hypothesis that inattentional blindness is mediated by attentional inhibition is correct, the largest inattentional blindness effects for peripheral critical stimuli should be observed near to the attended location.

To investigate our hypothesis, we modified a paradigm used by Koivisto et al. (2004) that showed robust inattentional blindness effects. In their paradigm the unexpected stimulus was presented at fixation, while in the present study it was presented in the periphery at the same eccentricity as the attended location (as is typically done in attentional inhibition studies). Specifically, during central fixation participants were rapidly presented with to-be-attended colored digits (which they named) at a peripheral location for two trials. On the third, critical, trial an unexpected black circle, the critical stimulus, was presented along with the colored digits either at central fixation, near to the attended location, or far from the attended location (Fig. 1). It is important to note that only one critical trial occurred for each participant, as the resultant expectation of stimuli at non-target locations is known to foster subsequent perception. The spatial location of the critical stimulus near to the attended location was selected to fall within the expected region of attentional inhibition and the more distant critical stimulus was selected to fall outside the inhibitory region, based on the location of maximal attentional inhibition effects reported in previous paradigms (Bahcall & Kowler, 1999; Mounts, 2000a; Müller et al., 2005).

2. Experiment 1

2.1. Materials and methods

2.1.1. Participants

One hundred sixteen undergraduate students at Boston College with normal or corrected-to-normal visual acuity took part in the study. Each participant received either $5 or 1 study pool credit. Informed consent was obtained before the experiment commenced. The experimental protocol was approved by the Boston College Institutional Review Board.

2.1.2. Stimulus and task

Our experimental protocol was very similar to that of Koivisto et al. (2004), who observed robust inattentional blindness of unexpected stimuli at fixation. We extended their paradigm to include unexpected stimuli at peripheral locations. Each trial consisted of an initial fixation frame (1500 ms), two selective attention frames (each 350 ms), and a trailing mask frame (500 ms; Fig. 1). For each trial, the black fixation cross (subtending .5° visual angle) was presented continually at the center of a white circular aperture (10.1° visual angle in diameter) until the onset of the mask. During each selective attention frame, to-be-attended colored digits (.5° visual angle in height) were presented at an eccentricity of 3.2° visual angle from fixation, 11.0° polar angle from the horizontal meridian. Digit values (ranging from 1 through 9) and colors (orange, green, blue, yellow, gray, red, pink, purple, and black) were randomly selected for each frame. During all trials, participants were instructed to maintain central fixation and recite each number and its respective color aloud. Responses were recorded for subsequent analysis.

Each participant first completed two trials where only the rapidly presented colored digits were presented. These initial trials allowed participants to practice the task and, given that the task was relatively difficult, learn to selectively attend to the location of the digits. Then, on the third and final trial – the critical trial – a black circle (.5° visual angle in diameter) was presented along with the digits (for 700 ms); this served as the critical, unexpected stimulus. For each participant, the circle was presented at one of three locations: (1) 1.5° visual angle from the attended digit location at the same eccentricity from fixation in the 'near' condition, (2) 3° visual angle from the attended location at the same eccentricity from fixation in the 'far' condition, and (3) at fixation. As mentioned previously, the peripheral critical stimulus locations were selected based on previous work showing maximal attentional inhibition effects 1.5° visual angle from the attended location (Bahcall & Kowler, 1999; Mounts, 2000a; Müller et al., 2005).

After these three trials, each participant filled out a questionnaire to determine whether they had been aware of the critical stimulus (Koivisto et al., 2004). The first question asked whether or not anything new had been detected that had not been described during the instructions. The second question asked the participant to choose the correct critical stimulus out of a possible five shapes (circle, triangle, square, diamond, and star). The last question asked the participant to identify

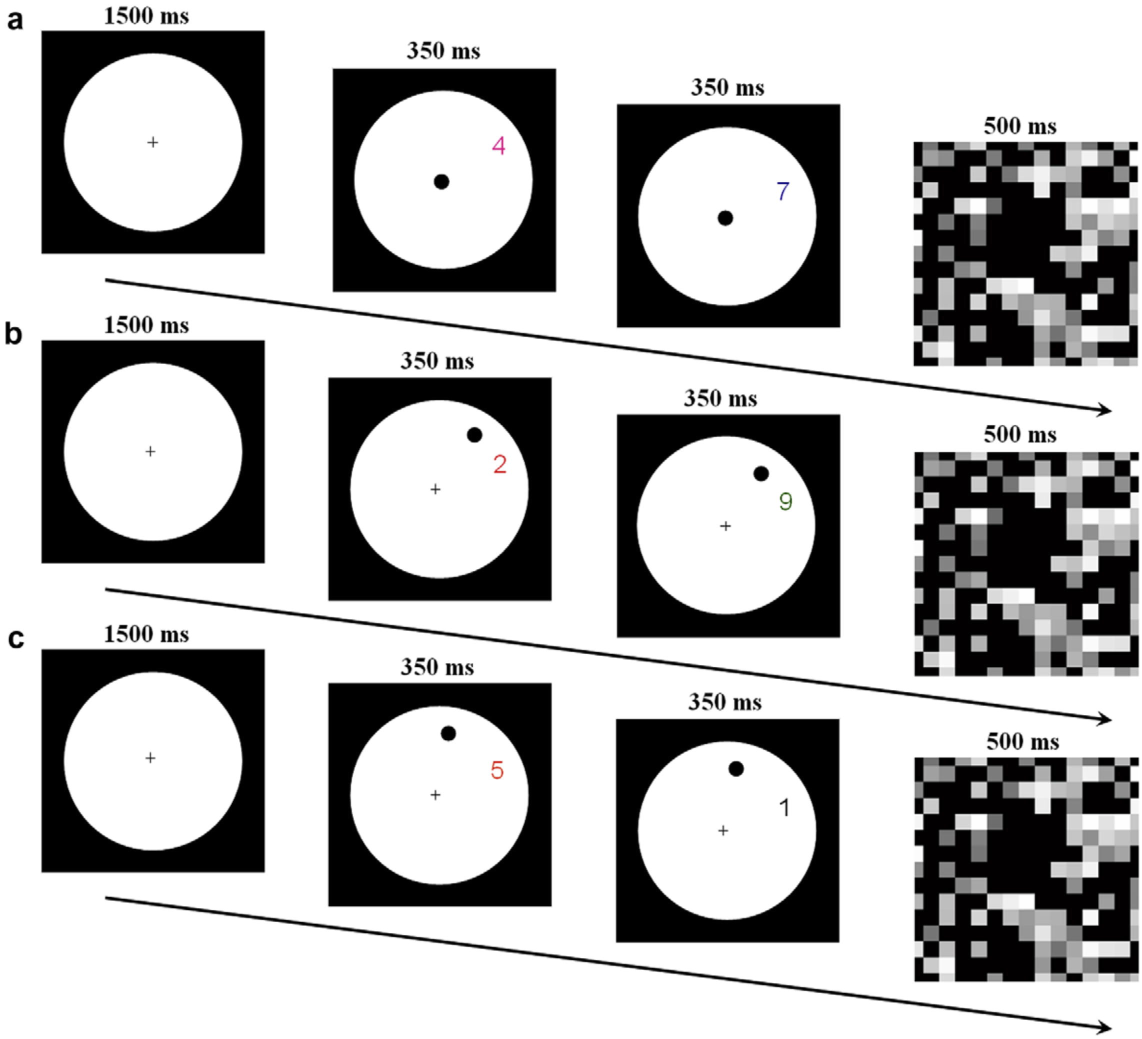

Fig. 1. Depiction of three critical trial types, each consisting of black fixation cross, to-be-attended colored digits, and critical stimulus (black circle), followed by a mask. (a) Control condition, with critical stimulus presented at fixation. (b) Near condition, with critical stimulus presented 1.5° visual angle from the attended location. (c) Far condition, critical stimulus presented 3° visual angle from the attended location.

the spatial location of the stimulus (by marking the location within a large circle with a fixation cross similar to that shown experimentally). Participants were considered aware of the critical stimulus if they answered "yes" to the first question and responded accurately to at least one of the last two questions (i.e., the correct shape and proximate location). Two-tailed chi-square tests were used for statistical analysis, except under conditions of sparse data ($n \leqslant 5$) where Fisher exact tests were employed (Most et al., 2000).

2.1.3. Results

Replicating previous findings, robust inattentional blindness effects were seen when the critical stimulus was presented at fixation (7.7% detection, $n = 26$). Consistent with our hypothesis, the rate of inattentional blindness was greater when the peripheral critical stimulus was near to the attended location (33.3% detection) than when it was far from the attended location (42.2% detection), although this difference was not significant ($\chi^2(1) < 1$).

We reasoned that this non-significant detection rate difference for near versus far peripheral critical stimuli may have been due to variable accuracy across participants, as inattentional blindness effects have been shown to vary as a function of accuracy (Cartwright-Finch & Lavie, 2007; Fougnie & Marois, 2007; Simons & Jensen, 2009; Todd, Fougnie, & Marois, 2005). To investigate this possibility, participants in the peripheral critical stimulus conditions were separated into two accuracy groups using a median split based on digit/color naming accuracy (with a maximum accuracy of 12, computed from the 3 trials × 2 digit × 2 color responses) such that the number of participants in each group were as similar as possible. The first group had an accuracy of 86.1% ($n = 21$ for the near condition, $n = 18$ for the far condition) while the

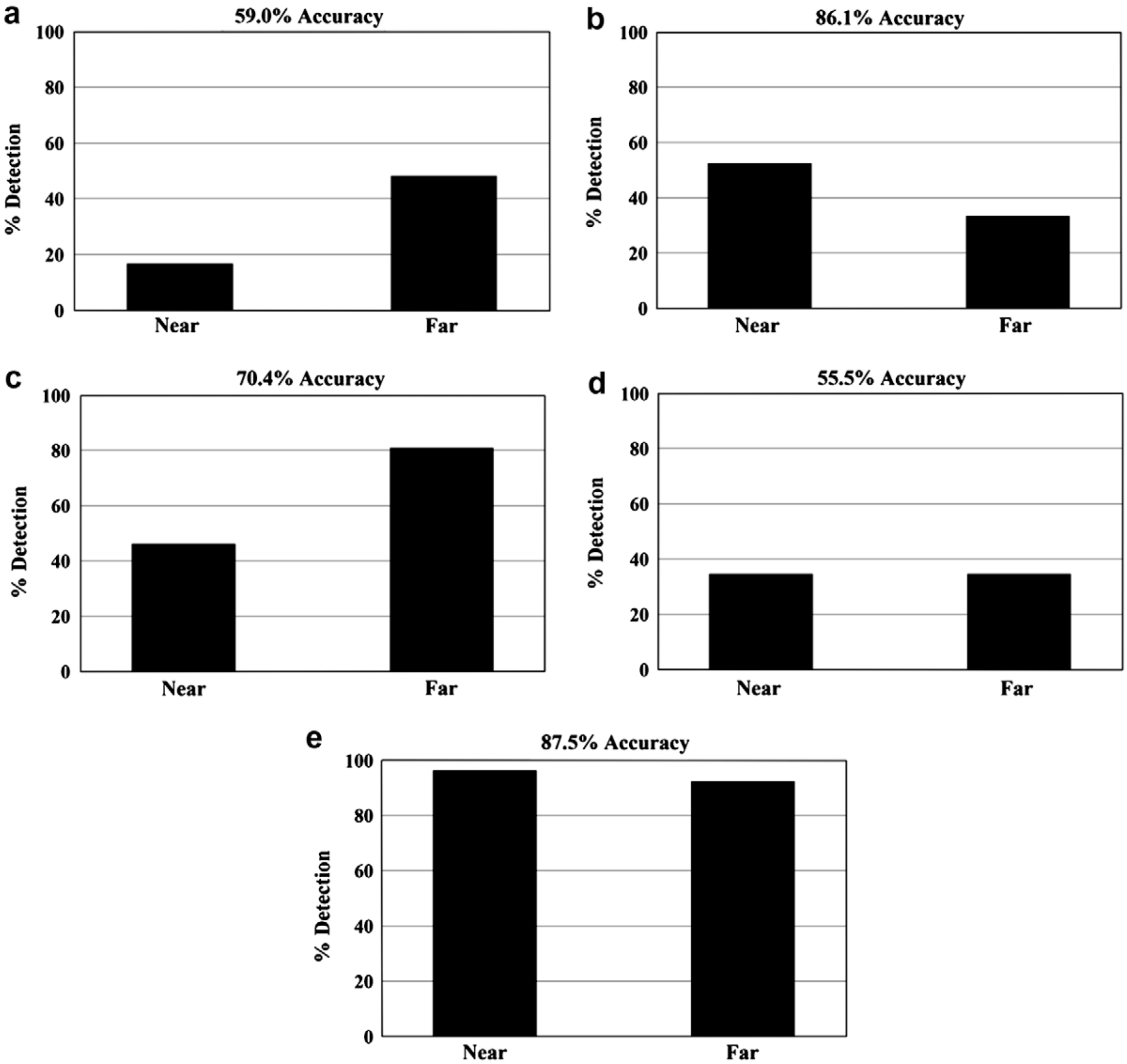

Fig. 2. (a–b) Percent detection of critical stimulus near to and far from the attended location as a function of accuracy in Experiment 1. (c–d) Percent detection of critical stimulus near to and far from the attended location, as a function of accuracy in Experiment 2. (e) Percent detection of critical stimulus near to and far from the attended location, as a function of accuracy in Experiment 3.

second group had an accuracy of 59.0% ($n = 24$ for the near condition, $n = 27$ for the far condition). As illustrated in Fig. 2a and Fig. 2b, distinct patterns of results were observed for these groups. For the 59.0% accuracy group (Fig. 2a), there was significantly greater inattentional blindness for stimuli near the attended location (16.7% detection) than for stimuli far from the attended location (48.2% detection; $p < .05$, Fisher exact test). By contrast, for the 86.1% accuracy group (Fig. 2b), percent detection of near and far critical stimuli did not significantly differ (near location 52.4% detection, far location, 33.3% detection; $\chi^2(1) = 1.43$, $p > .20$). The interaction between accuracy and location was significant ($p < .05$, Fisher exact test, computed using number of detections). The accuracy analysis was also conducted using a median split separately for each near and far group (rather than collapsing these groups first) and the identical results were observed.

3. Experiment 2

In Experiment 1, participants with differential accuracy were found to experience different patterns of inattentional blindness. However, it could be argued that our median split procedure did not separate groups by accuracy per se because this factor was not experimentally manipulated. We investigated this possibility in Experiment 2 by varying the interstimulus interval to manipulate accuracy.

3.1. Materials and methods

3.1.1. Participants

One hundred ten undergraduate students at Boston College with normal or corrected-to-normal visual acuity took part in the study (data from six participants were not included in the analysis because they did not perceive the critical stimulus during the *full attention trial*, defined below). Each participant received either $5 or 1 study pool credit. Informed consent was obtained before the experiment commenced. The experimental protocol was approved by the Boston College Institutional Review Board.

3.1.2. Stimulus and task

Unless otherwise stated, the experimental and analysis procedure was identical to Experiment 1. Each participant completed three trials with the critical stimulus (Newby & Rock, 1998), each preceded by two practice trials without the critical stimulus. The first *critical trial* was identical to that of Experiment 1, where participants had no knowledge that there might be a critical stimulus. This was followed by a *divided attention trial* where participants were not explicitly instructed to look for the critical stimulus, but the questions asked after the previous *critical trial* may have alerted them to the possibility that an additional object might appear. In a final *full attention trial* participants were instructed to actively detect whether anything new appeared on the screen which was expected to result in perception of the critical stimulus.

Two interstimulus intervals were selected based on the results of a pilot study with different participants ($n = 52$), where we varied interstimulus interval and computed the corresponding change in accuracy to match the two accuracy groups of Experiment 1. Unless otherwise specified, the procedure of the pilot study was identical to Experiment 1. To experimentally manipulate accuracy, the method of constant stimuli was used on an individual participant basis to determine the interstimulus interval that yielded the desired accuracy. Specifically, participants completed 36 trials without the critical stimulus, 3 trials at each of 12 interstimulus intervals (16, 48, 80, 120, 150, 250, 350, 450, 550, 650, 750, and 850 ms) presented in random order. Based on each participant's accuracy as a function of interstimulus interval, linear interpolation was used to compute the interstimulus interval that yielded the target accuracies of 64.9% and 87.1% (these accuracies were taken from the participants, $n = 52$, who had already completed Experiment 1 when the pilot study commenced). This yielded two specific interstimulus intervals, 248 ms and 487 ms, that were used to experimentally manipulate accuracy in Experiment 2. Specifically, each participant was randomly assigned to one of four possible accuracy groups; 487 ms/near, 487 ms/far, 248 ms/near, and 248 ms/far ($n = 26$/group).

3.1.3. Results

For *critical trials*, participants in the 487 ms group had an accuracy of 70.4% and those in the 248 ms group had an accuracy of 55.5%. For the 70.4% accuracy group (Fig. 2c), there was significantly greater inattentional blindness for stimuli near the attended location (46.1% detection) than for stimuli far from the attended location (80.8% detection; $p < .05$, Fisher exact test). By contrast, for the 55.5% accuracy group (Fig. 2d), the rate of inattentional blindness for near and far critical stimuli did not differ (near location 34.6% detection, far location, 34.6% detection; $\chi^2(1) = 1.00$, $p > .20$). The interaction between accuracy and location did not reach significance ($\chi^2(1) = 2.82$, p = .093, computed using number of detections). As expected, no significant effects were observed in the *divided attention trials* or *full attention trials*.

4. Experiment 3

The overall performance in Experiment 2 was lower than that of Experiment 1. Experiment 3 was conducted in an effort to experimentally manipulate accuracy such that it matched the higher accuracy group of Experiment 1.

4.1. Materials and methods

4.1.1. Participants

Fifty-two undergraduate students at Boston College with normal or corrected-to-normal visual acuity took part in the study. Each participant received either $5 or 1/2 study pool credit. Informed consent was obtained before the experiment commenced. The experimental protocol was approved by the Boston College Institutional Review Board.

4.1.2. Stimulus and task

Unless otherwise stated, the experimental and analysis procedure was identical to Experiment 2. An interstimulus interval of 1310 ms was selected based on the results of the pilot study described in Experiment 2 to match the 86.1% accuracy from Experiment 1 (correcting for the average deviation between predicted accuracies of the pilot study and the observed accuracies of Experiment 2).

4.1.3. Results

For *critical trials*, participants had an accuracy of 87.5% (Fig. 2e), which was comparable to the higher accuracy group of Experiment 1 (86.1%). Similar to the higher accuracy group results of Experiment 1, percent detection of near and far critical stimuli did not significantly differ (near location 96.2% detection, far location, 92.3% detection; $p > .20$, Fisher exact test). No significant effects were observed in the *divided attention trials* or *full attention trials*.

5. Discussion

In support of the hypothesis under investigation, the differential inattentional blindness results near to versus far from the attended location mirrored those of previous attentional inhibition findings, where maximal inattentional blindness effects were observed when the peripheral critical stimulus was presented near to the attended location. However, as illustrated in Fig. 3, differential inattentional blindness effects were only revealed under conditions of intermediate accuracy (as indicated by a significant quadratic component; $\chi^2(1) = 5.40$, $p < .05$).

That inattentional blindness effects depend on accuracy can be explained in terms of the spatial extent the attentional window, which can vary depending on task demands (Downing, 1988; Erikson & St. James, 1986; Mounts, 2000b). While previous models of spatial attention have focused on the facilitatory attentional window (Downing, 1988; Erikson & St. James, 1986), the surrounding inhibitory attentional window can vary with task demands as well (Mounts, 2000b). Considered in this framework, participants in Experiment 1 and Experiment 3 who found the task relatively easy, with higher accuracy (86.1% in Experiment 1, 87.5% in Experiment 3), may have had a facilitatory attentional window such that near locations were processed to a greater degree than far locations (although these differences were not significant). Participants who found the task somewhat difficult, with intermediate accuracy (59.0% in Experiment 1 and 70.4% in Experiment 2), may have had a more focused facilitatory attentional window (i.e., at the attended location) with a narrow surrounding inhibitory window such that critical stimuli were perceived less frequently at near versus far locations. When participants found the task very difficult, as with the lowest accuracy group of Experiment 2 (55.5%), the spatial extent of the inhibitory attentional window may have encompassed both near and far locations resulting in robust inattentional blindness at near and far locations. While this interpretation is consistent with the present findings, future work will be needed to assess the degree to which the facilitatory and inhibitory attentional windows are modulated by stimulus and task factors.

As mentioned previously, Newby and Rock (1998) demonstrated that the rate of inattentional blindness increased parametrically as distance from the locus of attention increased, which is consistent with a gradient (purely facilitatory) model of selective attention (see also, Most et al., 2000). While, these results might appear inconsistent with the present findings, the presence of an inhibitory component could not be tested in that study as only one critical stimulus was presented outside the attended region. Specifically, there was no 'far' location which would have been necessary to reveal effects consistent with attentional inhibition (as with the present near versus far comparisons). As such, the present results have extended these previous findings by assessing inattentional blindness effects further outside the attended region.

It is important to consider an important methodological difference between a majority of previous attentional inhibition studies, where the attended location was flanked by task-irrelevant distractors (Bahcall & Kowler, 1999; Bichot et al., 1999; Boehler et al., 2009; Caputo & Guerra, 1998; Cutzu & Tsotsos, 2003; Hopf et al., 2005; Kim & Cave, 1999; Mounts, 2000a; Müller et al., 2005, 2007; Müller & Kleinschmidt, 2004; Slotnick et al., 2002, 2003; for a review, see Cave & Bichot, 1999), and the present study, where the attended stimulus was presented in isolation on the first two trials. It could be argued that the present inattentional blindness effects may not have been mediated by attentional inhibition, given that distractors may be necessary to tag the spatial location of attentional inhibition (i.e., the location of the critical stimulus). However, atten-

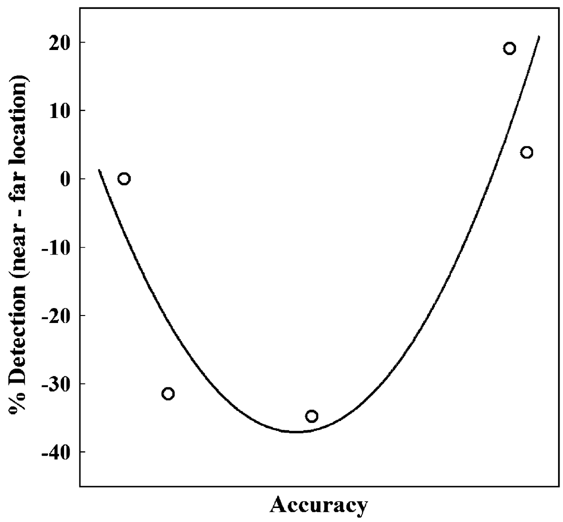

Fig. 3. Difference in percent detection of critical stimulus near to versus far from the attended location as a function of accuracy in all three experiments (open circles) and the best-fit second-order polynomial.

tional inhibition has been shown to occur at spatial locations surrounding the attended location in the absence of distractors. Cepeda et al. (1998) reported significantly slower reaction times to probes presented at non-distractor locations (1.5° of visual angle from the attended location), and attentional inhibition of spatial locations without distractors has also been observed using fMRI (Sylvester, Jack, Corbetta, & Shulman, 2008). This evidence indicates that attentional inhibition can occur at spatial locations with no distractors, thus, the current inattentional blindness results can be attributed to attentional inhibition.

Although not related to the hypothesis under investigation, we found the greatest degree of inattentional blindness when the critical stimulus was presented at fixation (7.7% detection in Experiment 1), replicating previous results that employed similar paradigms (Koivisto et al., 2004; Mack & Rock, 1998). It is important to note that when the target was presented at fixation it entailed an object changing shape (fixation cross to circle), whereas in the peripheral conditions, the critical stimulus had an abrupt onset, the latter of which is known to have relatively higher attentional salience (e.g., Yantis & Hillstrom, 1994; Yantis & Jonides, 1984). This would be expected to produce relatively higher rates of detection for more peripheral onset targets. In addition, rates of detection at fixation may have been lower as this location was the farthest away from the attended location. Recent findings have also demonstrated greater task-irrelevant suppression at central versus peripheral locations (Chen & Treisman, 2008). Even considering these factors, it is striking that detection rates at fixation were so low which supports Mack and Rock (1998) who stated "there is no conscious perception without attention" (p. 227).

It could be argued that the low rate of detection near to the attended location in Experiments 1 and 2 (for the intermediate accuracy conditions) did not reflect attentional inhibition, but rather was due to a generally lower degree of attentional engagement during the task (which would also predict low accuracy and a low rate of detection). However, a general failure to attend would predict similar rates of detection at the near and far locations. Our differential rates of detection at near and far locations (Fig. 2a and c) can be taken as evidence against an explanation based on general inattention (a similar argument can be made against other general factors, such as poor visual acuity or color blindness). It is also important to consider eye-movements as a possible explanation of these effects. Due to cortical magnification (see, Slotnick, Klein, Carney, & Sutter, 2001), if participants did make an eye-movement to the attended location, processing of stimuli at that location would be amplified the most, processing of the near target location would be amplified to a lower degree, and processing of the far target location would be amplified to an even lower degree. As such, the eye-movement account would predict the highest rate of target detection near to the attended location. Exactly the opposite was observed, where the nearest location had the lowest rate of detection (under conditions of intermediate accuracy, Fig. 2a and c) thus arguing against the possibility that the present results were due to eye-movements.

Our finding that attentional inhibition mediates inattentional blindness under conditions of intermediate accuracy has implications for present theories of spatial attention. Specifically, the present inattentional blindness evidence suggests that a complete model of spatial attention should include both facilitatory and inhibitory components (i.e., a center-surround model) and that the spatial extent and magnitude of these components are task dependant. By manipulating task factors (i.e., systematically varying accuracy) our results have provided some evidence detailing the conditions under which inhibitory effects of attention become appreciable in inattentional blindness paradigms.

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