



# The attentional blink in space and time

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Received 7 November 2001; received in revised form 5 June 2002

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## Abstract

We report the results of two experiments addressing spatiotemporal variations in the “attentional blink” (AB). In the first experiment, six streams of letters were presented simultaneously around a circle on a screen. The identity of the letters changed every 140 ms. The task was to identify two target digits (T1 and T2) that could appear in any of the streams with a variable time lag between the two. The results show that the AB is not constant across space and that following the allocation of attention to a certain location (the location of T1), discrimination can be better at locations quite far away from T1, than at locations closest to T1. Furthermore, performance at the farthest locations seemed to recover sooner from the AB than locations closer to where T1 appeared. Similar results were obtained in a second experiment where observers performed a cued discrimination task. The results accord well with the proposal that there is a region around the attended site (the center of attention) where attentional resolution is particularly poor, worse than at sites further away from the attended one. We propose that this reflects lateral inhibition of neurons responsive to the region around the attended site, with the goal of suppressing potentially distracting or interfering information. © 2002 Elsevier Science Ltd. All rights reserved.

*Keywords:* Attentional blink; Inhibition; Attention; Attentional suppression; Resolution

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## 1. Introduction

When a rapid stream of letters is presented in sequence in the same location, and observers are required to report what digit was presented within the stream, detection of a target presented a few 100 ms after the target digit is usually impaired. This “attentional blink” (AB) has been well documented when the second target (T2) appears in the same location as the first (T1) (Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992; Shapiro, Raymond, & Arnell, 1994). The research on the AB has thus mainly focused on how visual attention varies as a function of time.

How attention is allocated in space, has, on the other hand, often been studied with a different paradigm. Many studies have examined the effect of a precue upon the detection or discrimination of a subsequent target. A consistent finding is that spatial attention can be narrowed down to a small region indicated by the cue

(Eriksen & Collins, 1969; Posner, 1980; Nakayama & Mackeben, 1989). In fact visual attention seems surprisingly efficient at filtering out irrelevant information (Yantis & Johnston, 1990).

Another important finding is that after attention has been deployed to a particular location or object, latency for a revisit to that location is increased, a phenomenon known as “inhibition of return” (Klein, 2000; Posner & Cohen, 1984; Posner, Rafal, Choate, & Vaughan, 1985). What these studies indicate is that there are spatiotemporal interactions in the deployment of attention, since the attentional benefit of a precue does not only taper off, but also leads to *worse* performance at the cued site than an uncued one, when a few 100 ms have passed.

If attention is in some way inhibited from returning to a previously attended location, the AB could possibly be more pronounced at the location where T1 appeared than in more peripheral areas. There is thus some reason to suspect that the AB may vary as a function of space, but a conclusive answer to that is at present unavailable. Reeves and Sperling (1985), presented two targets in different locations, with a certain time lag between the two, but they did not look at differences in locations explicitly. Breitmeyer, Ehrenstein, Pritchard, Hiscock, and Crisan (1999), presented what amounts to one

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RSVP stream but each of the items in the stream could be in up to nine different locations. They concluded that if the AB was to disrupt performance considerably, the item following T1 needed to be presented at the same location as T1 to serve both as a mask and as a distractor. Visser, Zuvic, Bischof, and Di Lollo (1999), found differences in correct T2 identifications depending on whether T2 was in the same location as T1 or not, but again there was only one RSVP stream, but the items could appear in two different locations. Their conclusion was that attention cannot be switched to a new location while engaged in the processing of another stimulus. Also, Duncan, Ward, and Shapiro (1994), concluded that the AB appears not to be limited to stimuli appearing at the same spatial location. It seems, however, that spatiotemporal variations in the AB have not been addressed explicitly although Jiang and Chun (2001), presented results showing that spatial and temporal selection may tap the same attentional resources.

### 1.1. The spotlight metaphor

Visual attention has often been conceived of as a “spotlight” or a “zoom lens”, that “highlights” the attended area (Broadbent, 1982; Castiello & Umiltà, 1990; Eriksen & Yeh, 1985; Jonides, 1983; LaBerge, 1983; Podgorny & Shepard, 1983; Posner, 1980). Thus Jonides (1983), stated: “...we may view the mind’s eye as analogous to the body’s eye: It has a field of concentrated processing like the fovea...”. This implies that attentional resolution would then fall off gradually further out from the center of attention (the so-called “gradient” model of attention; Downing, 1988; LaBerge, 1983; Mangun & Hillyard, 1988, 1990). Others, however, have pointed out that attentional selection can be object-based (Duncan, 1984; Lavie & Driver, 1996) or that it can operate on perceptual groups (Driver & Baylis, 1989; Bichot, Cave, & Pashler, 1999).

Implicit in the spotlight account in its simplest form is that areas outside the attended one should be “unattended” to the same degree, since the spotlight of attention cannot be split between two locations as some have claimed (Castiello & Umiltà, 1990; Eriksen & Yeh, 1985; Podgorny & Shepard, 1983). Visual discrimination should then be equally good (or bad) at all locations outside the attended one, given that visual acuity is constant. Castiello and Umiltà (1992), found evidence contradicting this however. They claimed that observers could split focal attention between two sites when the items to be attended were in different hemifields (see also Müller & Hübner, 2002). Furthermore, Driver and Baylis (1989), showed that common motion was a better predictor of which items were selected than spatial proximity. They concluded that attention operates on perceptual groups rather than spatial locations.

Part of the impetus for the present research were experiments in our laboratory that seemed contradictory to the spotlight account of attention. Our studies indicated that when attention is drawn towards one location by a cue, the effect on the discrimination of a target in another location is not constant as a function of space, but rather that in some cases discrimination can be better far away from the cue than closer to it (Kristjánsson, unpublished experiments). A similar conclusion was reached by Bahcall and Kowler (1999). Furthermore, our results indicated that this spatial effect could vary as a function of the time lag between the presentation of the cue and the target, showing that the deployment of spatial attention could vary with time. The experiments described here were designed to address this issue more explicitly, i.e. whether “temporal” attention can vary as a function of space or similarly, whether “spatial” attention can vary as a function of time. To achieve this goal we needed a task where the position of the critical stimulus that needed to be acted upon could vary as a function of both time and space. We used a hybrid of the AB paradigm and a cueing paradigm where six streams of letters were presented around a circle on a screen (see Fig. 1). The letter identity changed every 140 ms. A digit target (T1) was presented in one of the streams, presumably drawing attention, since it was slightly brighter than the distractors. A second target (T2) was presented in one of

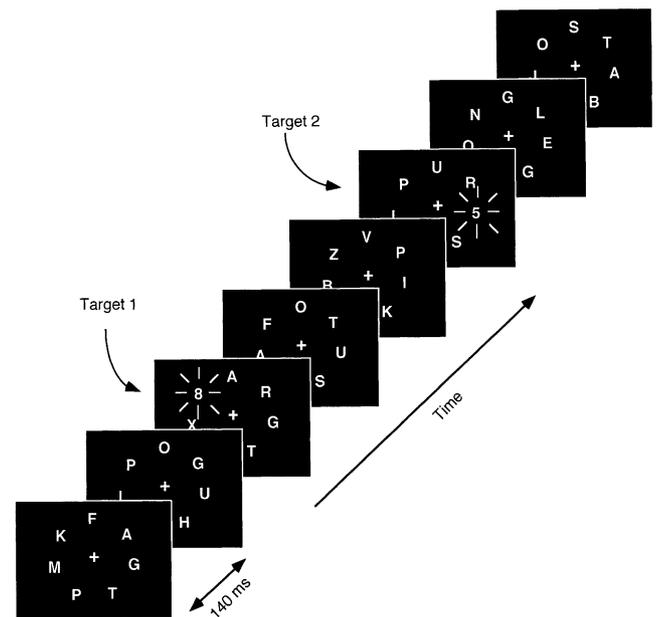


Fig. 1. The design of experiment 1 (see methods). The two targets (T1 and T2) were digits presented at any of the seven possible locations. The lag between the two targets ranged from one to six frames (140–840 ms). All the other stimulus items were uppercase letters. The two target digits were slightly brighter (see Methods) than the distractor letters. Observers were to answer what two digits were presented, but only after the whole sequence of frames was over.

the seven locations at a variable time following T1. If there are variations in attentional capacity as a function of space, performance of the second task (identifying the second digit), might not be uniform across the different locations at a given moment in time. Furthermore, such an experiment could also reveal temporal variations in attentional resolution as a function of space. Toet and Levi (1992) found that the zone of interference between two visual stimuli can be quite large, especially at high eccentricities. In fact, its size increases faster than the rate at which visual resolution falls as a function of eccentricity (see also Intriligator & Cavanagh, 2001). This opens up the possibility of extensive effects of attending to one location on the processing of stimuli at another location.

Another issue that our study could potentially address is whether attention acts by “enhancing” processing of the relevant stimulus or by “suppressing” the processing of irrelevant stimuli, stimuli that might interfere with the processing of the target, in this case the nearby items. While one need not exclude the other, the emphasis laid on each type of process has varied (Braun, Koch, Lee, & Itti, 2001; Tootell et al., 1998; Yeshurun & Carrasco, 1998; Eckstein, Shimozaki, & Abbey, 2002; see Milliken & Tipper, 1998 for a discussion of this issue). If attentional performance is better at locations far away from T1 than at locations close to it (as our pilot studies had indicated) this would argue for suppression of responses to locations surrounding T1, for it is hard to see why locations far away from T1 would receive enhanced processing as well as the location of T1. It can be mentioned in this context that it is possible that so-called gradient models of attention (Downing, 1988; LaBerge, 1983; Mangun & Hillyard, 1988, 1990), reflect inhibition. We have more to say on this issue in Section 4.

## 2. Experiment 1

### 2.1. Methods

The basic design of the experiment is depicted in Fig. 1. We presented seven simultaneous streams of letters in which two target digits (T1 and T2) were embedded. The task was to report the identity of the two digits. The two target digits were slightly brighter than the distractor letters. The task was designed to vary in difficulty both as a function of time (the temporal lag between T1 and T2) and space (the distance between the two targets), and should thus be well suited to address the question of spatiotemporal variations in attentional deployment. Another benefit of the experimental design is that differences in performance are likely to be attentional rather than due to differences in low-level perceptual masking (see Seiffert & DiLollo, 1997), since the same number of items is presented at the same time in each

location, so low-level masking should be relatively constant at each of the seven locations. There were, however, brightness differences between the targets and the distractors,<sup>1</sup> so in one condition of the experiment participants were asked to identify both the first and second target, while in the control condition, identification of the second target only, was required. Performance differences between these two conditions should then be due to attending to the first target *with* the explicit purpose of identifying it.

#### 2.1.1. Observers

The seven observers were members of the Vision Sciences Laboratory at Harvard University and were unaware of the purpose of the experiment. All were experienced psychophysical observers, and ranged in age from 28 to 36 years. All observers underwent substantial training (on average ~700 trials) on the task until their overall accuracy for detecting T2 given that T1 was detected was consistently around 70%.

#### 2.1.2. Stimuli

The capital letters used as distractors were light gray (40 cd/m<sup>2</sup>), while the target digits (T1 and T2) were slightly brighter (46.5 cd/m<sup>2</sup>). The stimuli were presented on a black background (0.5 cd/m<sup>2</sup>) and were all presented in the ‘Helvetica’ font (uppercase only). Stimuli were presented on a 75 Hz screen controlled by a G3 Macintosh computer. The radius of the circle the targets appeared on was 6.1°, and the height of the letters and digits was 1.1°. Viewing distance was 60 cm. The VisionShell programming library was used for stimulus presentation (for info go to <http://www.kagi.com/visionshell>).

#### 2.1.3. Procedure

Seven streams of letters were presented at a rate of 7.1 Hz (each letter in each stream presented for 140 ms and then immediately replaced by the next one). On each trial 30 letters were presented in each location with T1 (one of the digits 2–9) embedded within one stream and T2 (one of the digits 2–9) within another one. Thus 30 frames (see Fig. 1) were presented on each trial. Which stream the targets appeared in was determined randomly on each trial. The positions on the imaginary circle that the streams of letters appeared on was determined randomly from trial to trial, but the seven streams of letters were always equidistant from each other. The digits were only presented in temporal positions between 13 and 25 (of 30). The lag between T1 and T2 ranged from one to six frames which means that the minimum lag between T1 and T2 was 140 ms and the maximum lag

<sup>1</sup> This was necessary to ensure that observers were able to detect T1 and T2.

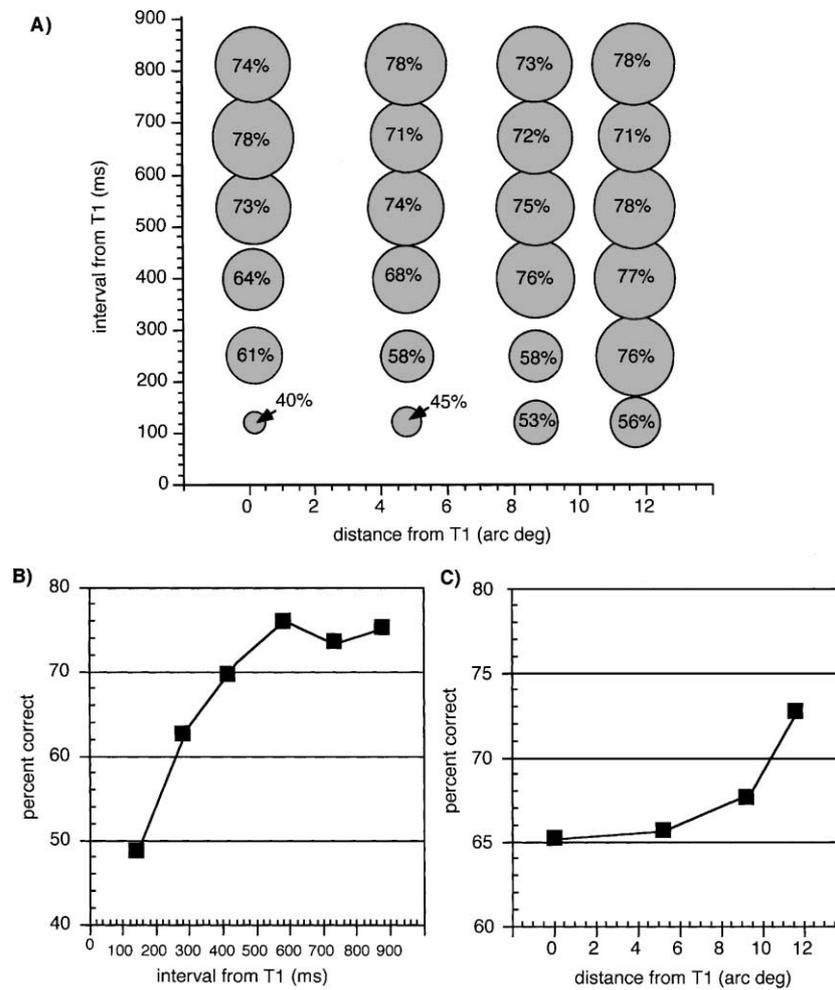


Fig. 2. The results of experiment 1. The “bubble” plot in panel A shows the percentage of trials that T2 was correctly identified provided that T1 was also correctly identified, as a function of the temporal lag (ordinate) and the spatial distance (abscissa) between T1 and T2. The size of the bubbles corresponds to the percentage correct. Panel B shows the percentage of trials on which T2 was correctly identified as a function of time, “collapsed” over space, or averaged over all the different spatial positions. Panel C shows the percentage of trials on which T2 was correctly identified as a function of space, averaged over the different temporal lags between T1 and T2.

was 840 ms. The targets could appear in any of the six streams (the spatial distance between T1 and T2 could thus range from  $0^\circ$  to  $11.8^\circ$ ), so the observers needed to attend to all of the streams in order to maximize the chances of detecting both T1 and T2. They maintained fixation on a central cross throughout each trial. They were able to do this without difficulty after some practice. At the end of each trial observers were asked to indicate by pressing the appropriate keys what two digits were presented on each trial. They were encouraged to guess if they were unsure, but were allowed to give an answer of ‘0’ if they had no idea what the digits were. Observers responded only after all 30 frames on each trial had been presented. Each observer participated in 1600 experimental trials, following the practice trials. On 800 of the trials observers were instructed to try to identify both T1 and T2, but on the other 800 trials they were instructed to identify T2 only, to assess baseline performance without identification of T1. This

was done to assess the effects of the brightness difference between the two targets and the distractors, when T1 needed not to be identified. Differences between these two conditions should then reflect the effects of identifying the first target on the identification of T2.

## 2.2. Results and discussion

Since our purpose was to study what effect the correct identification of T1 has on the detection of T2, trials on which T1 was not identified correctly were not included in the data analysis.<sup>2</sup> Fig. 2A presents the percentage of trials T2 was correctly identified, given that T1 was identified correctly. The size of the “bubbles” corre-

<sup>2</sup> T1 was correctly identified on 92.9% of the trials. There were no apparent differences in detection of T2 on these error trials as a function of time and space, but the trials were far too few to draw any strong conclusions from (only 7.1% of the total number of trials).

sponds to the percentage correct. The actual percentage correct is superimposed on the bubbles. Fig. 2B and C show the main effects of the temporal lag between T1 and T2 (thus collapsed over space) and the spatial distance between T1 and T2 (collapsed over time) respectively. The main effects of time (i.e. temporal lag between T1 and T2) and space (i.e. spatial distance between T1 and T2) were significant (repeated measures ANOVA; time:  $F_{5,30} = 14.11, p < 0.001$ ; space:  $F_{3,18} = 4.85, p < 0.01$ ) as was the  $F$ -test of the interaction between time and space ( $F_{15,90} = 1.9, p < 0.05$ ) indicating that the effects of temporal position (SOA) were not constant across space, which hints at considerable spatiotemporal interactions.

There are several interesting aspects of the results. Firstly the data in Fig. 2B show the well known AB in time after the identification of T1. Identification of T2's that lag behind T1 by 140–280 ms is severely impaired. This is consistent with the original research on the AB (Raymond et al., 1992). Secondly the results in Fig. 2C show that the closer T2 is in space to T1, observers are *less likely* to identify it. Detection of T2 11.8° away from T1 is quite good (73% correct) when averaged over the different temporal intervals, but a lot worse when presented 4.5° away from, or in the same location as T1 (65% and 66% respectively). Thirdly, there seem to be considerable spatiotemporal variations in the effect that the correct identification of T1 has on T2 (see Fig. 2A). Firstly, performance seems to recover faster the further away from the first target T2 appears. For example after 280 ms performance reaches 76% correct 11.8° away from T1, but is only 61% in the same location as T1. Performance when T2 appears in the same location as T1 does not reach 70% until T2 appears 700 ms after T1 is presented. It is important to note, however, that the significant interaction could be caused by a combination of the main effect of location and a ceiling effect, since performance seems to reach a peak at 75% correct. It is also worth noting that the effects of time are larger than the effects of space (about 30%, effect size,  $r = 0.838$  and 8%, effect size,  $r = 0.669$ , respectively). The reasons for this difference in effect size are unknown.

The results suggest that when a certain location is attended, attentional resolution (or sensitivity) is not constant across the rest of the visual field, but can be better at sites that are far away from the currently attended one than closer sites. They also suggest that recovery from the AB is faster far away from where T1 appeared, though this conclusion relies on the significance of the interaction between time and space (see above). Furthermore, when only detection of T2 is required (see Table 1) performance is uniform, showing that the effects of the identification of T1 upon identification of T2 is not due to experimental confounds like low-level masking of T2 by T1. It is true, however, that the subjects needed to *detect* T1 in the control experiment

Table 1  
Percentage of trials that T2 was correctly identified when identification of T2 only was required

Interval from T1 (ms)	Distance from T1 (arc deg)			
	0	4.5	8.75	11.8
140	82.2	78.4	79.5	76.9
280	80.8	81.7	75.4	81.3
420	76.8	77.9	81.3	80.4
560	78.3	83.2	76.4	77.5
700	77.6	74.6	79.6	83.1
840	80.1	74.5	82.5	78.5

(in Table 1), but *identification* of T1 was not required so observers could use T1 as a simple time marker, indicating that T2 would shortly appear. This probably explains why the performance is so different for the experimental and control conditions of experiment 1.

What, then, do the results tell us about the spread of attention in space and time? It seems that the results of experiment 1 accord better with the idea that locations around the attended site are suppressed rather than enhanced, since performance is quite good far away from T1. It is not obvious why there should be attentional enhancement of the location of T1 as well as of areas far away from T1, but a suppression account with a certain space constant would accord well with the results. It is worth mentioning in this context, that when viewing the streams of letters some observers reported that unattended streams seemed to 'disappear'. Thus when one stream was attended, the location of streams close to the attended one seemed to be empty; only the black background was seen. We suspect that the results in Fig. 2 reflect exactly this, i.e. that recognition of T2 is poorest at locations that seemed blank, perhaps reflecting suppression of neurons responsive to that area.

### 3. Experiment 2

In experiment 1 we tested spatiotemporal variations in attentional deployment in a paradigm most often used to study temporal variations in attentional deployment. It should be possible to address the same space–time interactions using a paradigm normally employed to study the allocation of attention in the spatial domain. We used a cued discrimination task where the cue correctly indicated the location of an upcoming target on 60% of the trials, while the target could appear in a different location than the cue indicated on 40% of the trials (Fig. 3). The cue was thus informative on the majority of the trials, but it could not be depended upon completely to perform the task as well as possible. We also varied the 'cue-lead time', the time between the presentation of the cue and the presentation of the target. Given the results of experiment 1 some predictions can be made. Firstly, if attentional resolution is higher at locations far away from the

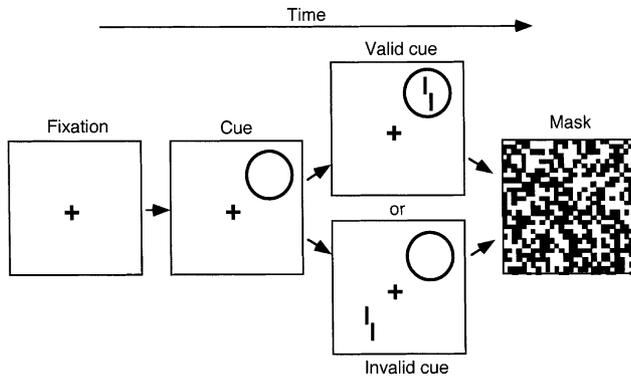


Fig. 3. The experimental design of experiment 2. A trial started with the presentation of a fixation point, followed by a spatial cue, that either correctly (60% of the trials), or incorrectly (40% of the trials) indicated the target location. The target was presented for 67 ms, followed by a mask.

attended one than closer to it, we might see better performance far away from the cue on the trials where the target does not appear in the cued location. Secondly, if recovery from the AB is faster in locations far away from the currently attended site, performance should be better at locations far away from the cued site for trials where the cue-lead time is short, but this difference should be less pronounced the longer the cue-lead time.

### 3.1. Methods

#### 3.1.1. Stimuli

We used a cued “Vernier” discrimination task, where the task of the observers was to judge whether the upper of two bars was displaced to the left or to the right relative to the lower one. The cue was a green (11.8 cd/m<sup>2</sup>) circle (diameter 3.1°). The Vernier targets were two white (51.5 cd/m<sup>2</sup>) bars (length = 1.2° each) where the upper one was displaced by 10' to the left or to the right relative to the lower one. The viewing distance was 57 cm. Stimuli were presented on a 67 Hz screen controlled by a Power Macintosh 7500 computer.

#### 3.1.2. Procedure

Following the presentation of the fixation point, a cue appeared at one of 12 possible locations on a circle with a radius of 7.5°. After a cue-lead time of 80, 180 or 280 ms the target appeared for 67 ms, followed by a mask consisting of a field of black (0.50 cd/m<sup>2</sup>) and light-gray (40.0 cd/m<sup>2</sup>) random dots, each subtending 6.6' that covered the whole screen. Observers responded by pressing the appropriate key whether the upper bar was displaced to the left or right of the lower one.

#### 3.1.3. Observers

Three observers (AK, one of the authors, IM and SM) participated in the experiment. All are experienced

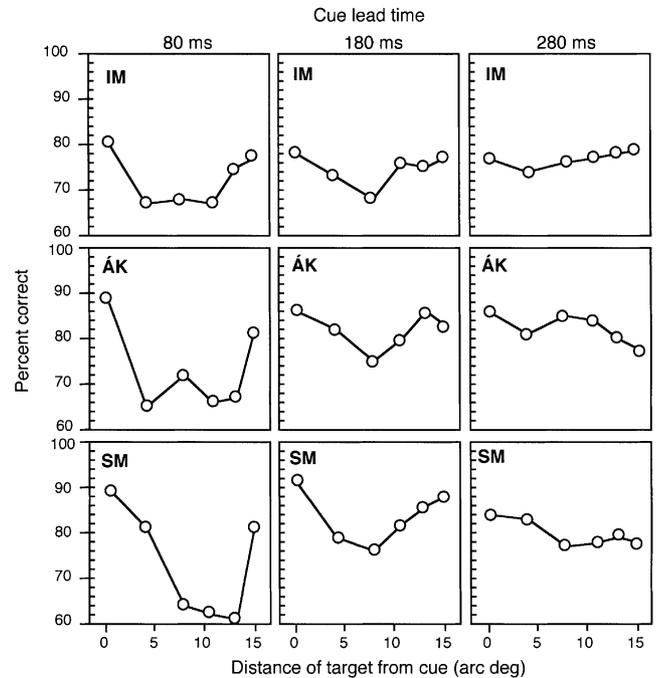


Fig. 4. The results of experiment 2, showing discrimination performance in percentages for the three observers as a function of the cue-lead time and spatial distance of the target from the cue.

psychophysical observers. IM and SM were not aware of the purpose of the experiment.

### 3.2. Results and discussion

The results (presented in Fig. 4) reveal similar spatiotemporal interactions as the results from experiment 1. Discrimination performance is overall best at the cued site, with accuracy dropping off close to it (similar to Henderson, 1991; see also Henderson, 1996). We found that the best performance outside the cued site was 15° away from the cued site, the farthest location from the cued site that we tested. This effect was most pronounced at the shortest cue-lead time, while performance seems to be more similar for the different distances from the cue, the longer the cue-lead time. This is consistent with our interpretation of the results of experiment 1, that locations far away from the cued site recover sooner from the AB than close locations. It could be argued that this result cannot be explained by low-level lateral masking due to the cue, since such masking should have been most pronounced at the site of the cue, thus interfering with target detection when the cue was valid. Note, though, that the masking effect at the cued location could be overshadowed by the attentional benefits from the cue. While this is a possible criticism of our interpretation of the results, it remains to be shown that low-level lateral masking effects over 12–14° of visual angle, as would be required for this explanation to hold.

This overall pattern of results is similar to what we observed in experiment 1. Performance outside the attended site (where the cue appeared) is best farthest away from the cue, especially at the shortest SOA's (the cue-lead time in this case). We conclude that locations far away from the attended one recover more quickly from the “blink” that follows the deployment of attention to a location in space. Moreover, as in experiment 1 this result supports the idea that there is suppression of areas close to the cue, with some recovery at sites further away.

#### 4. General discussion

What conclusions can be drawn from the experiments that we report here? The results make it clear that when attention is drawn to a certain location, attentional resolution or sensitivity is worse at other sites than the attended one. More interestingly, though, the results also indicate that when a certain location is attended it does not necessarily mean that all other locations are “unattended” to the same degree. Discrimination of targets appearing further away from the attended site can, according to our results, be better than discrimination of targets close to the attended location. Secondly, the results uncover considerable spatiotemporal variations in how attention is deployed to locations. The results in Fig. 2 indicate that the AB may have a shorter duration at spatial locations far away from the just attended one, since performance seems to recover sooner at larger, than smaller, distances from the just attended one. Thirdly, our results show the well documented temporal variation in attention which has been called the AB.

The fact that performance is better far away from, than close to the attended site, appears to be at odds with a “spotlight” account of visual attention (Eriksen & Yeh, 1985; Jonides, 1983; Podgorny & Shepard, 1983; Posner, 1980). Instead we conclude that there is a “zone of inhibition” around the attended site, where attentional resolution is particularly poor, but that further away from the attended site, attentional resolution can be better. The results are then seemingly also at odds with the results of Posner, Snyder, and Davidson (1980) who argued that attention cannot be split between two locations at once. Our results, however, need not be taken to mean that the attentional beam is “split” between two or more locations if it is assumed that there is a zone of inhibition around the attended site. This inhibition would have a finite spatial extent allowing items far away from the center of attention to be processed. If, on the other hand, the attentional beam were “split”, there would not appear to be any compelling reason that it would be applied to the center of attention *and* the sites furthest away from it. It would certainly be a

puzzling feature, if extra resources were allocated to locations far away from the attended site as well as to the attended site itself. An account in terms of inhibition would seem to be a more parsimonious explanation for the results. An inhibition account does not require the assumption that locations far away from the center of attention receive more attentional processing than more proximal ones, as the data in this paper could be taken to suggest. Instead, the results may simply reflect that the system responsible for orienting attention “does not care” about these peripheral locations, while it suppresses activity that could interfere with its goal, which in this case is to identify T1. If there is less inhibition at peripheral sites, events there may thus simply be more likely to be detected than less peripheral ones, since they receive less attentional suppression.

In our conception, then, there is parallel build-up of information until the detection of a candidate target causes almost immediate suppression of information surrounding the candidate, *including* the location containing the target, thus accounting for the “traditional” AB effect. This suppression, or inhibition, serves the purpose of cutting down irrelevant information. This proposal puts the attentional selection at a relatively early stage, while not stating that the suppressed information is lost completely, which would be unreasonable given considerable evidence for priming of unattended, or excluded information (e.g. Tipper, 1985). This form of “cognitive masking” through lateral suppression (after Walley & Weiden, 1973) may thus allow considerable implicit processing.

Our proposal will then certainly count as an early selection account (see e.g. Jiang & Chun, 2001; Yantis & Johnston, 1990). Similarly, Bahcall and Kowler (1999) hypothesized that attentional enhancement may lead to the inhibition of nearby locations, to make the target stand out. According to this view, attention would act at the sensory level to increase the quality of perceptual information, while also cutting down irrelevant information by active suppression. This view is supported by the finding that post-synaptic potentials (as measured by event-related brain potentials), show modulation of responses to targets a considerable amount of time before a response is to be made, beginning within 100 ms of stimulus presentation (Luck et al., 1994; Luck, Girelli, McDermott, & Ford, 1997; see also Eimer, 1994; but see Vogel, Luck, & Shapiro, 1998). In fact, Luck (1998), in a review of the literature, stated that there is converging evidence from research on event-related brain potentials, neuroimaging and single unit neurophysiology that attention starts to select visual information early (in about 60 ms). While our account can certainly be considered an early selection account, we do by no means seek to exclude the possibility of “late” effects as indicated, for example, by the results of Vogel et al. (1998). We are in fact sympathetic to the view that the distinction

between early and late selection may not be a particularly useful one (cf. Braun & Koch, 2001). But the possibility remains that effects such as the AB can be caused by both sensory (“early”) and decision (“late”) processes. According to Shapiro and Luck (1999) early selection is likely to occur when the perceptual system is overloaded. Whether that was the case in the present study is open to debate, but is certainly a distinct possibility.

#### 4.1. Previous accounts of attentional suppression of irrelevant information

An early theory of suppression of unwanted or ignored information is the one of Walley and Weiden (1973). They suggested that attention to one site resulted in the lateral inhibition of surrounding sites, to increase the saliency of items at the attended one. They called this “cognitive masking” of the surrounding information to distinguish this from perceptual masking. They argued that the degree to which stimuli are suppressed was a function of arousal. They said: “...what is to prevent additional inputs from impinging on the encoding mechanism, thereby disrupting the encoding of the input? If the encoding mechanism has a limited capacity for processing information, what is to prevent the overloading of this mechanism by additional input? (p. 285)” Thus they argued that suppression of irrelevant information is something of a logical necessity. Other research supporting inhibition includes the work of Krose and Julesz (1989), and Caputo and Guerra (1998).

The idea of active inhibition of unwanted information received strong support from the finding that detection times of previously ignored distractors can be longer than otherwise (“negative priming”, Tipper, 1985, 1992), lasting up to at least 1 s (Neill & Westberry, 1987). Importantly, Milliken, Tipper, and Weaver (1994) found that negative priming can operate on locations, not just the objects in each case (see also Tipper, Brehaut, & Driver, 1990). Mounts (2000a,b), showed that the detection and discrimination of a probe stimulus was worse in the vicinity of a stimulus of either unique color or orientation than further away from it. Also, Cave and Zimmerman (1997), concluded that distractor locations near the target in each case receive more inhibition than those further away (see also Cepeda, Cave, Bichot, & Kim, 1998). Tse, Sheinberg, and Logothetis (in press), found attentional enhancement in the visual field opposite a peripheral flash which may reflect inhibition. Specifically they suggested that their effect might be due to the increased latency of an attentional shift to a previously attended location relative to shifts to locations not visited in the immediate past (the “inhibition of return” effect, Posner & Cohen, 1984; see Klein, 2000 for a review). Bennett and Pratt (2001) reach a some-

what similar conclusion. A zone of inhibition around the attended site is also implicit if not explicit in many “winner-take-all” models of attentional selection (Koch & Ullman, 1985; Lee, Itti, Koch, & Braun, 1999; Tsotsos, Culhane, & Cutzu, 2001).

Cepeda et al. (1998), found that response times to probe stimuli were faster at locations that previously contained a target compared to locations of distractors. They also found that response times to probes at *blank* locations were faster than at the distractor locations. In fact, those reaction times were *faster* than at the target location. From this they argued that blank locations did not receive inhibition like distractor locations. While this is possible, an account in terms of a benefit for stimuli suddenly appearing at previously blank locations seems more plausible as an account of their data. This benefit for blank locations could result from the masking of probes at locations previously occupied by the ignored distractors. The experiment that Cepeda et al. (1998), provided to rule this out is inconclusive since probe response times at unattended blank locations were *faster* than at the target location (see Cepeda et al., 1998, Fig. 12). This, then, must be considered an unresolved issue, but it should be noted that in experiment 2 here, there were *no* distractors, yet we observed results consistent with our inhibition account, suggesting that distractors are not required for inhibition to take place.

The possibility should also be mentioned that instead of reflecting lateral suppression of unwanted information, our results reflect that neurons responsive to areas surrounding the target are “recruited” to assist in the processing of the target (Connor, Gallant, Preddie, & Van Essen, 1996; Suzuki & Cavanagh, 1997; Tolia et al., 2001). The “recruitment” hypothesis makes in many ways similar predictions as an inhibition account. While such an account is possible, it remains to be shown that recruitment resulting in “shifting receptive fields” (Connor, 2001) can have an effect on items appearing several degrees of visual angle away from the target.

While our results seem to argue for the view that attentional selection of a location or an object causes inhibition of unwanted information (a form of noise reduction), there is no reason to rule out that attending to a particular location in space, or a particular object results in enhanced processing of that center of attention. This hotly debated topic has produced results that support both sides of the argument (pro-enhancement: Henderson, 1991; Yeshurun & Carrasco, 1998; Carrasco, Penpeci-Talgar, & Eckstein, 2000; pro-noise reduction: Palmer, Ames, & Lindsey, 1993; Shiu & Pashler, 1994; Eckstein, 1998; Lu & Doshier, 1999; Eckstein et al., 2002; Solomon, 2002). There is, however, at present no compelling reason why the two should be mutually exclusive, an interaction of both types of processes is a distinct possibility (see, for example Lu & Doshier, 2000), especially given evidence for the exist-

tence of both types of effects (Yeshurun & Carrasco, 1998; Doshier & Lu, 2000; Eckstein et al., 2002).

#### 4.2. *The attentional blink*

Our proposal is that theoretical accounts of the AB should make room for spatiotemporal variations that result from lateral suppression, or inhibition. How well, then, do our conclusions fit into current theoretical accounts of the AB phenomenon?

The attentional gating model of Reeves and Sperling (1985; see also Weichselgartner & Sperling, 1987; Visser et al., 1999) implies that a “gate” at a certain location is opened allowing the target and a few subsequent items to enter visual short term memory. There is no room in such an account for spatiotemporal variations. Also, given the sluggish nature of attention (Ward, Duncan, & Shapiro, 1996) it is hard to see how attention could move from the attended site to more peripheral ones within 140 ms, as would be required to account for our results. Shapiro and Raymond (1994), proposed an “interference” model of the AB, a form of a late selection model. They based their view, among other things on the fact that the AB was still present when only detection of T1 was necessary. Our proposal places the attentional selection at an earlier site than this, while not disallowing “late” effects of something like response confusion.<sup>3</sup> The two-stage model of the AB (Chun & Potter, 1995), assumes that following the detection of a candidate target, a limited capacity process takes over, concerned with the identification of the candidate target. None of the above models are explicit about the role of location in the AB effect, and would all seem to require modification in order to account for the spatiotemporal variations that our results in this paper reveal. The view that the AB is mainly caused by a bottleneck for the consolidation of the candidate target in working memory (Chun & Potter, 1995; Shapiro & Raymond, 1994; Jolicoeur, 1999; see also Duncan, 1980), would also require modification to account for our results, since these models do not make explicit predictions concerning spatiotemporal interactions in the AB.

On the face of it, it may seem that the Sperling and Weichselgartner (1995) theory of the dynamics of spatial attention would be particularly relevant to the present experiments since it is an explicit theory of how atten-

tion moves in space. Their model is, nevertheless, not directly related to our point in the present paper, since we are not addressing how “the spotlight of attention” moves in space, rather we argue that inhibition around the attended site can lead to spatiotemporal variations in attentional sensitivity, or resolution.

Our proposal for a model that would account for the results in this paper as well as the AB effect is that there is parallel build-up of information until T1 is detected (see for example, Egeth, Jonides, & Wall, 1972). Following detection there is lateral suppression of neurons responsive to areas surrounding the attended site *as well as* vigorous suppression of information from the attended site, but, of course not until after T1 appears. A similar scenario can be conceived of for detection tasks. It is important to emphasize that the spatiotemporal variations in attentional deployment that we observed in these studies do not reflect interference from response preparation or execution (see e.g. Jolicoeur, 1999), and must thus be distinguished from traditional research on the psychological refractory period (PRP, see for example, Pashler & Johnston, 1998). The reason is that the response in our task was unsped.

#### 4.3. *Neural evidence for inhibition and suppression of irrelevant information*

Much evidence for lateral suppression of neural activity within the visual areas of the cortex exists in the literature. For example, Blakemore and Tobin (1972), found evidence for lateral inhibition between orientation tuned cells in the visual cortex of the cat (see also Benevento, Creutzfeldt, & Kuhnt, 1972; Flom, Heath, & Takahashi, 1963). According to Eccles (1966), recurrent inhibition can take place through the following process: An axon collateral excites an inhibitory interneuron, which in turn inhibits the originally active cell and its neighbors (see also Creutzfeldt, Fuster, Hertz, & Strasschill, 1966). Mountcastle (1998), talks about a specific neural mechanism that may mediate lateral inhibition. Specifically, large basket cells in the visual cortex may play a decisive role in pericolumnar inhibition.

Motter (1993), showed that a certain subset of neurons in V1, V2, and V4 showed differential sensitivity when attention was directed towards versus away from the spatial location of the receptive field. Similarly, Chelazzi, Miller, Duncan, and Desimone (1993), found that around 100 ms before an eye movement to a target location, neural responses to non-targets in inferior temporal cortex were suppressed, and the neural activity was dominated by the target. This is strong evidence for suppression in attentional selection, since many studies have shown that there is a tight functional and neural link between attention and eye movements (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Doshier, & Blaser, 1995; Kustov &

<sup>3</sup> There are, in fact, several lines of evidence suggesting a “late” locus for the AB effect, for example, evidence for priming of the missed target (Luck, Vogel, & Shapiro, 1996), attentional capture of certain types of behaviorally important stimuli during the AB (Shapiro, Caldwell, & Sorensen, 1997), electrophysiological evidence for brain activity connected with the missed target (Vogel et al., 1998), evidence for across-modality interference during the AB (Arnell & Jolicoeur, 1999) as well as evidence for late signal probability effects (Crebolder, Jolicoeur, & McIlwaine, 2002).

Robinson, 1996; Mackeben & Nakayama, 1993). Furthermore, Moran and Desimone (1985) (see also Luck, Chelazzi, Hillyard, & Desimone, 1997) found that the activity of cortical cells was strongly inhibited when an ignored, irrelevant stimulus was within the receptive field. The attentional selection mechanisms seemed to be suppressing the neural response to the ignored stimulus. Britten and Heuer (1999), have also observed similar inhibition effects in MT neurons responding to moving Gabor stimuli. There is also good evidence for vigorous suppression of metabolic activity dependent on attention in visual cortex (Vanduffel, Tootell, & Orban, 2000). Furthermore, Hess, Negishi, and Creutzfeldt (1975) showed that lateral inhibition occurs after local chemical (glutamate) stimulation in the visual cortex. Research on event-related brain potentials has also provided evidence for neural suppression. For example, the results of Luck et al. (1994) showed both an enhancement of responses to attended stimuli and suppression of responses to unattended ones. They hypothesized that the inhibition and enhancement may arise from two different mechanisms (see also Eimer, 1994; Mangun & Hillyard, 1988).

## 5. Conclusions

Following the allocation of attention to a location containing a behaviorally important stimulus, observers' ability to detect targets at other locations is not uniform across the whole extent of the unattended portion of the visual field. In the cases reported here performance was often better at locations far away from the attended one than at more proximal locations. Furthermore, locations further away from the attended site seemed to recover more quickly from the AB than those closer to the attended site. We propose that these results are best accounted for by assuming vigorous lateral suppression of neuronal responses to stimuli in areas surrounding the attended one.

## Acknowledgements

ÁK was supported by a Fulbright graduate award, as well as an Eliot Grant from Harvard University. KN was supported by an AFOSR grant.

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