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Olivers, C.N.L.

***published in***

Journal of Experimental Psychology: Human Perception and Performance  
2004

***DOI (link to publisher)***

[10.1037/0096-1523.30.3.613](https://doi.org/10.1037/0096-1523.30.3.613)

***document version***

Publisher's PDF, also known as Version of record

[Link to publication in VU Research Portal](#)

***citation for published version (APA)***

Olivers, C. N. L. (2004). Blink and shrink: The effect of the attentional blink on spatial processing. *Journal of Experimental Psychology: Human Perception and Performance*, 30(3), 613-631. <https://doi.org/10.1037/0096-1523.30.3.613>

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# Blink and Shrink: The Effect of the Attentional Blink on Spatial Processing

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The detection or discrimination of the second of 2 targets in a rapid serial visual presentation (RSVP) task is often temporarily impaired—a phenomenon termed the *attentional blink*. This study demonstrated that the attentional blink also affects localization performance. Spatial cues pointed out the possible target positions in a subsequent visual search display. When cues were presented inside an attentional blink (as induced by an RSVP task), the observers' capacity to use them was reduced. This effect was not due to attention being highly focused, to general task switching costs, or to complete unawareness of the cues. Instead, the blink induced a systematic localization bias toward the fovea, reflecting what appears to be spatial compression.

Vision is set within space and time. Visual objects occupy limited spatial regions as well as limited time periods as they continuously move in and out of people's visual fields (as birds and cars usually do), as they gradually emerge from behind other, occluding objects when people themselves move around, or as they abruptly come into existence (such as blinking traffic lights). Vision is also highly selective. People are unaware of, or cannot remember having seen, the details of most objects in a visual scene even if they are directly looking at them (Mack & Rock, 1998; O'Regan, Deubel, Clark, & Rensink, 2000; Simons & Levin, 1997). Instead, certain visual events are prioritized whereas others are ignored. The study of visual selective attention looks at the determinants and level of this selection process.

The bulk of the research has focused on the spatial component of visual selection. In visual search, for instance, observers search for visual objects relevant to their task (targets), located in a visual field filled with a variable number of irrelevant objects (distractors). Efficient selection of the target may be quite difficult, for instance, when the target shares its features with the surrounding distractors or when attention is drawn to the wrong location by a more salient object. Under other circumstances, selection can be quite effortless, for example, when the target carries a salient feature distinguishing it from the distractors or when observers are cued toward its location (Duncan & Humphreys, 1989; Pylyshyn et al., 1994; Theeuwes, 1991; Theeuwes, Kramer, & Atchley, 1999; Treisman & Gelade, 1980; Wright, 1994).

More recently, researchers have started to explore the temporal dynamics of visual selection. In the rapid serial visual presentation (RSVP) task, observers again look for a target among a number of distractors. Contrary to the visual search task, where target and

distractors are simultaneously present but occupy different locations, here the target and distractors typically appear at the same location but at different moments in time. The usual pattern of results indicates that attentional processing of information following the presentation of the target is impaired for about 200 to 500 ms (see, e.g., Broadbent & Broadbent, 1987; Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992). For instance, Raymond et al. (1992) asked observers to identify a white letter (the first target) and then to determine the presence of a black X (the second target), both of which were embedded in a stream of other black letters. They found that detection accuracy for the second target was severely impaired when presented immediately after the first and gradually improved with increasing stimulus onset asynchrony (SOA). In explaining this result, Raymond et al. coined the term *attentional blink*: It is as if attention is temporarily unavailable when processing relevant visual information.

Which visual properties are and which are not affected by the attentional blink? On the one hand, the attentional blink appears to affect relatively low-level perception such as that of color (N. E. Ross & Jolicœur, 1999), orientation (Joseph, Chun, & Nakayama, 1997), basic shape (Shapiro, Arnell, & Drake, 1991), and motion (Krope, Husain, & Treue, 1998). On the other hand, several studies suggest that participants can pick up on the semantic identity of a blinked item, even though they cannot report on it. For instance, Shapiro, Driver, Ward, and Sorensen (1997) found that items that were presented during the blink and could not be reported still primed semantically related items presented later in time (see also Luck, Vogel, & Shapiro, 1996; Maki, Frigen, & Paulson, 1997; Martens, Wolters, & Van Raamsdonk, 2002). In addition, Shapiro, Caldwell, and Sorensen (1997) reported that, although an attentional blink occurs for people's names, the participant's own name is often not missed, indicating that awareness of the blinked item depends on semantic salience rather than on lower level visual salience. Other evidence comes from cross-modal studies showing that visual perception can suffer from an attentional blink induced by an auditory target and vice versa (Arnell & Jolicœur, 1999; but see Duncan, Martens, & Ward, 1997). Together, these results strongly suggest that the attentional blink operates at a relatively late stage of processing. An event-related potential study by Vogel, Luck, and Shapiro (1998) further supports this idea. They found

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Thanks to Glyn Humphreys at Birmingham University and the Cognitive Psychology Lab at the Vrije Universiteit Amsterdam for their much appreciated input. I am also grateful to Marvin Chun, Roberto Dell'Acqua, and Tram Neill. This work benefited partly from a Veni grant from NWO Netherlands and partly from a U.K. Medical Research Council grant.

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that, under attentional blink conditions, the electrophysiological activity associated with sensory processing (P1 and N1) and word meaning (N400) was left intact, whereas the activity usually associated with the updating of information in working memory (P3) was reduced. It appears then that processing a target lays a temporary claim on either access to or processing within visual working memory, preventing further information from reaching a level of awareness and response. Of course, because of the nature of the task, the conscious report of lower level visual properties such as color, shape, and motion is then affected, too.

### Does the Attentional Blink Affect Spatial Processing?

An important question is how the spatial and temporal dynamics of visual selection interact. The present study investigated if and how the temporal occupation of attention, as found in attentional blink studies, affects spatial processing. Does the temporary unavailability of attention induced by a target at one location prevent perception of the locations of other objects?

The literature provides little guidance on the role of the attentional blink on spatial coding. Some studies have manipulated the spatial locations of the items in an RSVP stream and demonstrated that the attentional blink extends across space. For instance, Visser, Zuvic, Bischof, and Di Lollo (1999; see also Breitmeyer, Ehrenstein, Pritchard, Hiscock, & Crisan, 1999; Seiffert & Di Lollo, 1997; Shih, 2000) found that the identification of a second target is also impaired when it is presented to the left or right of the first target. They argued that attention cannot be switched to a new location while the system is processing the first target. A similar result was obtained by Duncan et al. (1997). They presented participants with four RSVP streams arranged in a diamond, so that two streams were arranged to the left and the right of fixation (horizontal streams) and the other two streams above and below fixation (vertical streams). In one condition, participants had to detect the first target from the horizontal streams and the second target from the vertical streams. Like Visser et al. (1999), Duncan et al. found that second target detection was impaired at shorter SOAs. Furthermore, Joseph et al. (1997) showed that an RSVP target-detection task at fixation subsequently interferes with visual search for an orientation-defined target in more eccentric locations, again showing that the attentional blink spreads beyond the location of the first target. Interestingly, Kristjánsson and Nakayama (2002) reported evidence that the carryover of the attentional blink to other locations is not homogeneous: In their task, second targets were better identified when presented further away from the first target.

However, in all these studies, the to-be-detected second target property (e.g., identity or orientation) was essentially nonspatial. Therefore, these studies did not provide a direct test for the role of the attentional blink in spatial coding per se. Observers may have had little trouble perceiving the second target's location. Instead, the attentional blink may have disrupted an attentional switch to the correctly perceived location, or it may just have affected the identification of the target after successful localization.

A slightly different version of RSVP experiments has looked at how RSVP target processing is affected by distractors presented at separate locations surrounding the central RSVP stream (Folk, Leber, & Egeth, 2002; Jiang & Chun, 2001). In Jiang and Chun's (2001) study, flanking distractors interfered with, or facilitated identification of, the second RSVP target (depending on the

distractor–target compatibility) when the lag between first and second target was short but not when the lag was long. Jiang and Chun concluded that the attentional blink affects spatial selectivity because spatial separation of the second RSVP target from the flankers seems impaired. However, this conclusion may not be without its problems. In Jiang and Chun's task, the flanking distractors were not masked, unlike the second target, which was masked by its temporal neighbors in the RSVP stream. Thus, it is possible that under attentional blink conditions, the flankers may have gained priority over the RSVP target because they were more salient or better perceived, not because they were difficult to separate spatially. Such effects were not measurable outside the blink (i.e., at long lag conditions) because there, performance was at ceiling (Jiang & Chun, 2001, p. 670). To my knowledge, the only direct test of location coding under attentional blink conditions is Experiment 1 of Visser and Enns (2001). Visser and Enns were interested in the role of attention in the temporal integration of visual patterns. They presented observers with an RSVP task in which the second target was a  $5 \times 5$  dot matrix of which one dot was missing. The participant's task was to localize the missing dot. To study the effect on temporal integration, the dot matrices were built up in two frames, each containing one half of the number of dots (minus one for the half with the missing dot), with various blank interstimulus intervals (ISIs) in between. As expected, missing dot localization improved with shorter ISIs, as the two pattern halves became perceptually integrated. However, the improvement was much weaker under attentional blink conditions (i.e., when the dot pattern was presented in close temporal proximity to the first target). Even at an ISI of 0 ms, when there was no need for temporal integration, missing dot localization was worse under attentional blink conditions. Quite possibly, then, the attentional blink affects spatial coding directly. Nevertheless, Visser and Enns could not exclude other explanations of the drop in localization performance, such as a decrease in perceptual resolution and the pattern perception depending on this resolution (i.e., as resolution decreases, the missing dot location may actually look filled). Also, participants had to look for the absence of a dot, which may be a more inefficient and attention-demanding task than determining the location of an object presence (cf. search asymmetries; Treisman & Souther, 1985).

### The Present Study

The present experiments were designed to test whether the attentional blink affects the visual system's capacity to process spatial locations. Figure 1 illustrates the basic paradigm. Participants were presented with an RSVP target detection task intended to induce an attentional blink. The RSVP stream was then followed by a number of spatial cues. The spatial cues provided the participants with some degree of information on the future location of another target in a subsequent visual search task, which was presented outside the blink period. If participants could successfully perceive and retain the locations indicated by the cues, then this should have benefited subsequent search reaction times (RTs). The observers' capacity to use the spatial cues in search was then estimated from the RTs on the basis of a relatively simple serial search model proposed by Yantis and Johnson (1990; see below). The crucial question then was how this spatial capacity varied depending on whether the cues were presented inside or outside the blink. If the blink indeed affects spatial processing, one should

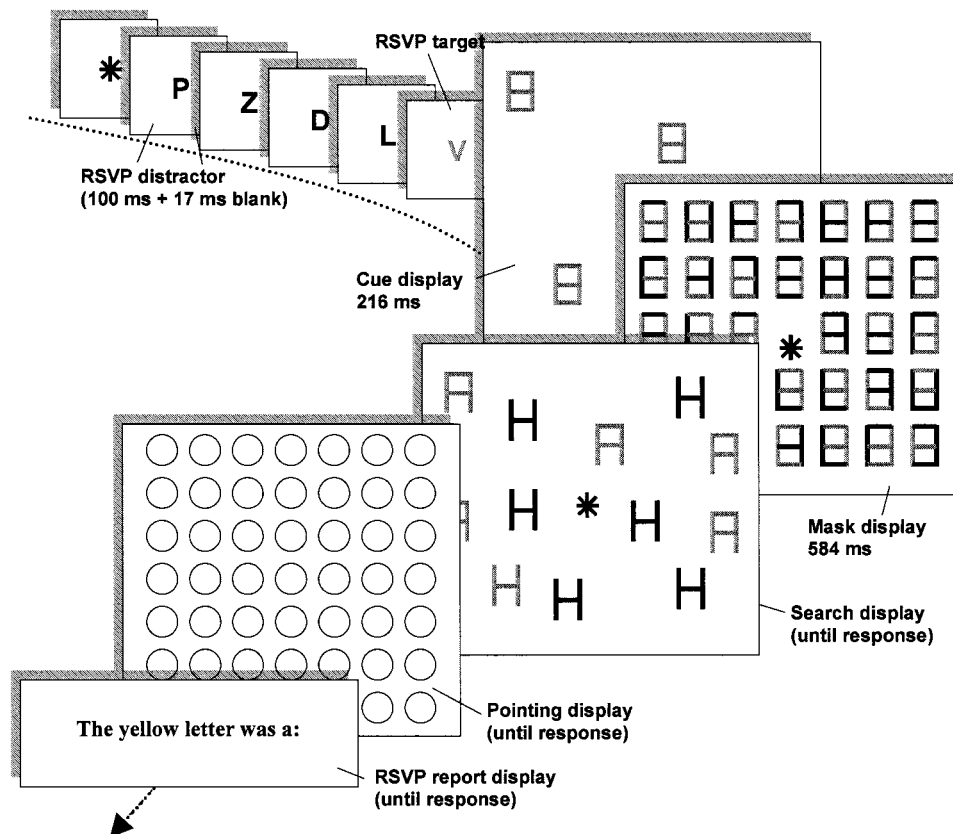


Figure 1. Outline of the basic paradigm. Participants had to identify a target letter in a rapid serial visual presentation (RSVP) stream. The RSVP stream was followed by a masked cue display containing spatial cues to the target position of a subsequent search task. The search target was a blue H among green Hs and blue As. Participants had to respond as soon as they spotted the target and then click on its location (using a mouse). Finally, participants reported on the RSVP target identity.

find a reduction in spatial capacity, resulting in frequent mislocalizations of the cues and longer search RTs as a consequence. This was tested in Experiments 1–5. Finally, Experiment 6 used a more direct measure by requiring observers to point to the locations of cues presented inside or outside the blink.

What results could one expect? Relatively little is known of the effects of attention on localization. Early indications that localization may suffer from inattention come from the partial report paradigm, in which typically arrays of several letter or digit characters are briefly flashed, followed by a position cue (e.g., an arrow or bar marker) indicating the to-be-reported item. Work by Mewhort and colleagues (Mewhort, Campbell, Marchetti, & Campbell, 1981) has shown that observers tend to make two types of errors on this task, the relative proportions of which change with the increasing interval between the character array and the cue. At short intervals (several tens of ms), observers mainly make so-called *item errors*, that is, they report items that were not present in the array. At longer intervals (between 100 and 200 ms), so-called *location errors* become relatively more frequent: Observers report an item that was present in the display but at a different position than the cued one, with positions near the cue being preferred (see also Eriksen & Rohrbaugh, 1970; Snyder, 1972; Townsend, 1973). Mewhort et al. (1981) interpreted this pattern as evidence that, with increasing stimulus–cue intervals,

spatial information from the array is lost, whereas identity information is preserved. Although attention was never explicitly manipulated in these studies, one may infer from the volatility of spatial representations relative to identity representations that because the attentional blink affects the latter, it must certainly also affect the first. However, Mewhort et al.'s results are open to different interpretations. It is unclear whether the increase in localization errors is indeed the result of spatial degradation or of strategic guessing (Butler, Mewhort, & Tramer, 1987) and cue mislocalization effects (Hagenaar & van der Heijden, 1997; Mewhort, Butler, Feldman-Stewart, & Tramer, 1988). Moreover, Chow (1986; though see Mewhort et al., 1988), as well as Logan and Bundesen (1996), has shown that the same pattern of errors may also be predicted by models that assume exactly the opposite, namely, that identity information is lost whereas spatial information is preserved.

More recent studies have shown that localization variance increases when less attention is available (Adam, Huys, van Loon, Kingma, & Paas, 2000; Adam, Ketelaars, Kingma, & Hoek, 1993; Egly & Homa, 1984; Newby & Rock, 2001; Prinzmetal, Amiri, Allen, & Edwards, 1998; Tsai & Bareket, 1999). This has led theorists to propose that attention increases spatial resolution (He, Cavanagh, & Intriligator, 1997; Tsai, Meiran, & Lamy, 1995; Tsai & Shalev, 1996; Yeshurun & Carrasco, 1998). On the basis of

these studies, one might expect similar decreases in spatial accuracy in the present study. However, it is important to mention that most of these studies manipulated attention in a spatial manner, usually by cuing attention toward one region or another (I return to some exceptions below). It may then not be surprising that when observers are cued to process one location, other locations suffer relative to this location.

The present study sought to address the more general case of whether a temporal lapse of attention as induced by the attentional blink affects spatial processing. As explained above, so far the attentional blink paradigm has used nonspatial detection and identification tasks. If, as has been proposed, the attentional blink reflects impaired access to, or consolidation within, visual working memory, then this impairment may be limited to the nonspatial part of working memory. There are indications that visual working memory may be separated into a visual part (corresponding to what an object is) and a spatial part (corresponding to where an object is; see, e.g., Logie, 1995; Smith et al., 1995; Tresch, Sinnamon, & Seamon, 1993). An important question then is whether the attentional blink generalizes from disrupting *what* processing to disrupting *where* processing, in other words, to spatial working memory. A reason why it may not generalize is the possibility that location has a special status in attentional processing: Selection of objects may occur either exclusively or preferably through their location, and thus, location information must be available preattentively (Cave & Pashler, 1995; Nissen, 1985; Theeuwes, 1989; Treisman & Gelade, 1980; Tsal & Lavie, 1988; Von Wright, 1968). Interesting in this respect is that Rock, Linnett, Grant, and Mack (1992) found no difference in localization performance between their inattention, divided attention, and full attention conditions. This led them to conclude that “all participants who perceived *something* in the inattention trial were correct about location” (Rock et al., 1992, p. 510, italics in original), which suggests that location information may indeed be available without attention. However, Rock et al. did not require their participants to be very precise (they had to select the correct quadrant of the display), and thus, the test may not have been sensitive enough (see Newby & Rock, 2001).

### Experiment 1: Spatial Capacity Is Affected

In Experiment 1, the observers' main task was to detect and localize a blue H target among blue A and green H distractors (see Figure 1). This task results in inefficient search, as has been shown elsewhere (Olivers & Humphreys, 2002). About 800 ms before the search display, a cue display appeared, followed by a mask. The cue display consisted of a variable number of blue figure eights at different locations. These cues indicated the positions of a subset of blue items in the subsequent search display. The blue H target, when present, was always one of the cued items. Thus, the cues provided valid information about the future target position, and performance should have benefited substantially if search could be limited to the cued locations only. This benefit would then depend on the number of cues present, as the positional uncertainty of the target increased with the number of cues. The assumption was that, if participants were able to make use of such cues, some form of spatial short-term memory must be involved. Presumably, this memory successfully represents the positions of the cues and makes them available for later use. Many researchers have proposed such a short-term spatial indexing or tagging system, and

moreover, there is substantial evidence that it is limited in capacity (Pylyshyn, 1989; Pylyshyn & Storm, 1988; Yantis & Johnson, 1990).

The important question was whether the capacity to process and retain spatial cues varies under different attentional blink conditions. For this purpose, the cue display was preceded by an RSVP task in which the participant was asked to detect and identify a yellow target letter among a rapid stream of gray distractor letters (however, the target letter was only reported at the end of the trial). This task should induce an attentional blink, as has been confirmed elsewhere (Olivers & Humphreys, 2002). By varying the lag between the RSVP target and the cue display between 117 ms (Lag 1) and 934 ms (Lag 8), the spatial cues were presented either inside or outside this attentional blink (note that the blink has been shown to be over by 500 ms for normal observers; see also Olivers & Humphreys, 2002). If the attentional blink limits spatial processing capacity, then one should see reduced cuing benefits on the subsequent visual search task.

The spatial processing capacity under different attentional blink conditions was estimated using a model based on that of Yantis and Johnson (1990, Model 4). For this purpose, the number of cues in the preview displays was varied. Let us call this variable  $n$  (for number of cues). Now, if participants indeed limit their search to the cued subset of items and if they possess the (unlimited) capacity to represent all spatial cues, then the average number of display items searched is affected only by the number of cues (i.e., the size of the subset). If one calls the capacity  $c$  and the average number of items searched  $k$  ( $k$  stands for number of search comparisons the model has to perform), then this can be formulated as follows:

$$\text{If } c \geq n, \text{ then } k = (n + 1)/2. \quad (1)$$

Note that the number of cues is divided by two because the search target is, on average, found after half the number of items has been searched.

If, on the other hand, spatial capacity ( $c$ ) is zero and participants cannot maintain the locations of any of the cues, then they have to resort to a normal search of all the items in the display, just as they would when there are no cues at all. The average number of searched items ( $k$ ) is then solely determined by the overall display size ( $d$ ):

$$\text{If } n = 0 \text{ or } c = 0, \text{ then } k = (d + 1)/2. \quad (2)$$

Crucially, if capacity is greater than zero but limited, search times represent a mixture of these two types: First, participants search as many cued positions as their spatial memory capacity allows them. After this, they must search the remainder of the items (i.e., the total display size minus the capacity) until the target is found, regardless of whether they are cued or not. The expected average number of search comparisons is as follows:

$$\text{If } c > 0 \text{ and } c < n, \text{ then } k = (nc + nd - cd + n)/2n. \quad (3)$$

Figure 2 illustrates how, according to the model, varying the number of cues ( $n$ , 0 to 6), as well as varying the spatial capacity ( $c$ , 0 to  $\infty$ ), leads to different predictions concerning the number of items that need to be searched on average ( $k$ ). With capacity greater than the number of cues (e.g., infinite capacity; Equation 1),  $k$  is affected only by the number of cues, regardless of the overall display size. With capacity  $c$ , or number of cues  $n$ , set to



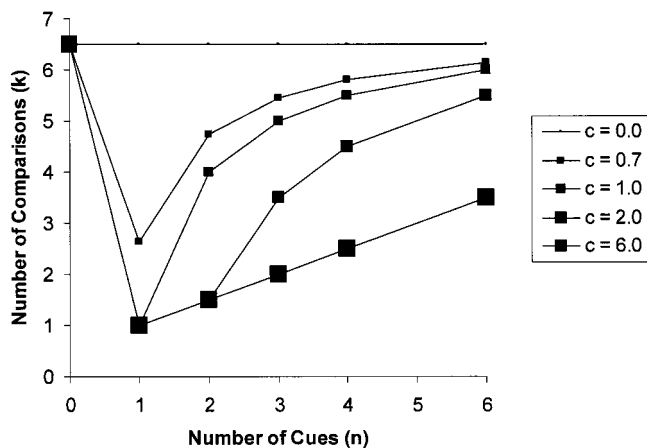


Figure 2. Predicted number of search comparisons ( $k$ ) under variable numbers of cues ( $n$ ) for different spatial capacities ( $c$ ). Calculations based on a mathematical model by Yantis and Johnson (1990).

zero (Equation 2),  $k$  is solely determined by the display size  $d$  and stays constant across the number of cues. With limited capacity (Equation 3), however, not all the cues can be processed, and  $k$  increases more rapidly as cued positions lose their priority.

For my present purpose, the important parameter in the model is the spatial capacity  $c$ . If the capacity to represent spatial cues is limited, then one would expect performance to be limited even further under attentional blink conditions. In other words, if  $c$  turns out to be modulated by the attentional blink, then one would have strong evidence that the attentional blink affects spatial processing.

### Method

**Participants.** Sixteen participants (7 male, 2 left-handed) participated for either course credits or money. The average age was 21.6 years (range 18–23 years). One participant was substituted because of too many errors on the search task (> 30%).

**Apparatus and stimuli.** The displays were presented on a 15-in. (38.1-cm) monitor, driven by a Pentium-200 PC with VESA graphics card running at  $800 \times 600 \times 256$  resolution. The stimuli were generated by a purpose-written Turbo Pascal 7.0 program, which also recorded RTs and responses. The viewing distance was approximately 75 cm. The letters of the RSVP task were randomly drawn from the alphabet (with the restriction that two consecutive letters could not be identical) and presented in a light-gray 24-point Helvetica font (approximately  $0.5^\circ$  by  $0.5^\circ$ ). The RSVP target was yellow. The cue, mask, visual search, and pointing displays were all based on the same  $8 \times 8$  grid, subtending approximately  $8.5^\circ \times 8.5^\circ$  in visual angle. In the search displays, the grid was randomly filled with 11 blue As and green Hs, as well as 1 blue H target, all of which were rectangular (as on a digital alarm clock),  $0.6^\circ$  high  $\times$   $0.4^\circ$  wide. The green and blue were chosen to be roughly isoluminant (as determined by a flicker test on the experimenter). The cue display consisted of a variable number of blue rectangular figure-eight cues in the same positions as a subset of blue search items (and also of the same size). The mask was constructed by filling every cell in the display with similar figure eights, but consisting of line segments that were randomly colored green or blue. In the pointing display, all cells of the  $8 \times 8$  grid were filled with gray circular position markers, with a radius of about  $0.2^\circ$ .

**Design and procedure.** After a 750-ms blank screen, each trial started with a 500-ms fixation asterisk, followed by the RSVP task in which a series of between 14 and 20 letters was presented, each for 100 ms, with 17-ms blank intervals between the letters. The series also ended with an

asterisk, which served as a fixation point as well as a mask for RSVP targets presented at the end of the series (there is evidence that the attentional blink is abolished if T1 is not masked; see Breitmeyer et al., 1999; Raymond et al., 1992; Seiffert & Di Lollo, 1997). Counting backward from the end of the series, the yellow RSVP target letter appeared at either Lag 1 (117 ms from the cue display; short lag) or Lag 8 (936 ms from the cue display; long lag). The RSVP series was then followed by a 216-ms cue display containing 0, 1, 2, 3, 4, or 6 location markers. The cue display was followed by a mask, which stayed on for 584 ms and was immediately followed by the search display. The search display consisted of six green and six blue items (display size 12), and participants had to localize a blue H target within a time limit of 4,000 ms. They did this by clicking the left mouse button as soon as they detected the target. Immediately following this first click, the search display changed into a pointing display (a grid filled with circles), and the participants had to point to the target's location by clicking on the corresponding circle. If they clicked in between the correct circle and a neighboring circle, the response was also counted as correct. The first click was timed (and makes up the RT measure), the second click was not. Finally, after the participants had correctly localized the search target, they were asked to type in the RSVP target letter they had seen (a task that was not timed). They were encouraged to guess if they were not sure. If they made an error in the search part of the task, they were not asked for the RSVP target. All cued locations were occupied by a blue search item, one of which was always the target, except on 8% catch trials, on which no target was present. These catch trials were included to prevent participants from completely anticipating the search target when only one cue was present and thus there was complete positional certainty on the target's position. For the same reason, most of the catch trials (50%) were one-cue trials, with 25% two-cue trials, 12.5% three-cue trials, 12.5% four-cue trials, and 0% six-cue trials. Participants were told of the near-perfect validity of the cues. All conditions (short/long lag; number of cues: 0, 1, 2, 3, 4, 6, including catch trials) were randomly mixed and presented in three blocks of 104 trials each, preceded by a practice block. Erroneous trials were repeated by randomly inserting them in the remainder of the block. This resulted in 24 correct trials for each SOA  $\times$  Number of Cues combination. Participants first practiced RSVP target detection only, for about 10 trials. After the RSVP task, participants practiced the search task only, for about 25 trials, followed by 35 trials in which the two tasks were combined.

**Model fitting.** The number of comparisons for each combination of lag and number of cues,  $k$ , was estimated from the display size  $d$ , the number of cues  $n$ , and the capacity  $c$ . Subsequently,  $k$  was linearly transformed into a model RT estimate by the following equation:

$$RT_{\text{model}} = I + bk. \quad (4)$$

Model RTs were then optimized by minimizing the root-mean-square error (RMSE, the root of the averaged squared differences) between the model and the data. The model had two fixed parameters: The display size parameter,  $d$ , was fixed at 12 items, and  $n$  followed the number of cues (zero to six). In addition, four free parameters required estimation. The RT constant,  $I$ , was allowed to vary freely with a minimum of 200 (ms). The slope of the RT function,  $b$ , was also estimated from the data, with the restriction that it would be greater than 0 ms/item.  $I$  and  $b$  were assumed to be equal for both lag conditions (short and long), as was justified by the data. Finally, and of most interest, the spatial capacity parameters were estimated for each lag separately,  $c_{\text{short lag}}$  and  $c_{\text{long lag}}$ , which were allowed to vary freely between zero and six (note that six corresponds to infinite capacity in the present displays because it equals the maximum number of cues). Fitting was done within Microsoft Excel Solver and was initiated from several different combinations of starting values. In case several rounds converged to more than one minimum, the outcome that resulted in the smallest RMSE and highest  $R^2$  was selected. The model was fitted to each individual's data, as well as to the overall mean RTs across participants. The average individual fits differed little from the overall fit, and I mainly report on the latter.

Results

*RTs.* Figure 3 shows the RT data for each lag and number of cues. Erroneous trials (i.e., due to search target mislocalizations or RSVP target misidentifications) were excluded from the RT analysis. A recursive clipping procedure with modified criterion (Van Selst & Jolicœur, 1994) resulted in another 2.4% of the data points being removed. An analysis of variance (ANOVA) with lag (short, long) and number of cues (0, 1, 2, 3, 4, 6) as factors revealed a significant main effect of lag,  $F(1, 15) = 27.7$ ,  $MSE = 3,520$ ,  $p < .001$ . RTs were faster when cues were presented at long lag relative to the RSVP target. Number of cues also had a significant effect,  $F(1.5, 22.2) = 29.1$ ,  $MSE = 11,358$ ,  $p < .001$ . RTs were slowest with no cues at all and fastest with only one cue. RTs gradually increased with more cues. Furthermore, there was a significant Lag  $\times$  Number of Cues interaction,  $F(3.4, 50.7) = 4.3$ ,  $MSE = 2,498$ ,  $p < .01$ . The drop in RT from zero to one cue was steeper for the long lag condition, and the subsequent rise in RTs with increasing number of cues was less sharp. More details of this interaction emerge from the model fit below. Subsequently, I performed planned  $t$  tests (Fisher’s least significant difference [LSD]) to assess the effect of lag for each number of cues. With no cues, there was no difference in search rate,  $t(15) = 0.36$ ,  $p = .725$ . With one, two, and four cues, participants were significantly faster in the long lag condition,  $t(15) = 3.2$ ,  $p < .01$ ;  $t(15) = 7.9$ ,  $p < .001$ ; and  $t(15) = 2.22$ ,  $p < .05$ , respectively. With three cues, the difference was not significant, but there was a strong trend in the same direction,  $t(15) = 2.0$ ,  $p = .066$ . Finally, with six cues, the difference, although still in the same direction, also fell short of significance,  $t(15) = 1.5$ ,  $p = .158$ .

*Errors.* Table 1 contains the error percentages for each lag and number of cues in the search task. The search error rates were fairly constant across conditions, although there was a significant effect of number of cues,  $F(3.0, 45.2) = 2.9$ ,  $p < .05$ . As with RTs, the number of errors tended to first drop and then rise again with the number of cues. The average false alarm rate on catch trials was 33%, with no noticeable differences across lag or number of cues. The RSVP target miss rate was 12.3%. Experiment 5, below, included a more detailed analysis of RSVP target errors.

*Model fit.* Figure 3 shows how well the model fits the data. This is reflected in a high  $R^2$  (0.992) and a low RMSE (17.1 ms). The estimated RT intercept ( $I$ ) was 450 ms, and the estimated RT slope ( $b$ ) was 54 ms/item. Most important, the spatial capacity

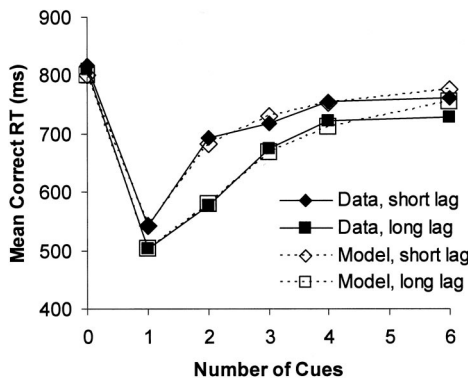


Figure 3. Average reaction time (RT) data and model fit for Experiment 1.

Table 1  
Error Rates for Experiments 1–5

Experiment	Lag	Number of cues					
		0	1	2	3	4	6
1	Short (117 ms)	2.6	1.9	1.9	4.0	4.7	4.0
	Long (936 ms)	2.3	3.0	1.0	2.3	2.5	3.6
2	Short (117 ms)	1.1	1.0	0.3	0.0	2.1	1.8
	Long (936 ms)	0.6	0.5	1.9	1.2	0.9	0.9
3	Short (117 ms)	0.8	0.0	0.4		1.4	
	Long (936 ms)	1.7	2.7	1.6		0.0	
	Absent (task switch)	1.2	0.4	0.4		0.8	
4	Short (117 ms)	0.3	0.3	0.9			
	Long (936 ms)	0.2	0.2	0.8			
5	Short (117 ms)	0.4	0.8	0.8	0.3	0.8	0.0
	Long (936 ms)	0.3	1.6	0.0	0.3	1.3	1.7

estimates varied for short lag and long lag conditions, with  $c_{\text{short lag}} = 0.87$ , and  $c_{\text{long lag}} = 1.64$ . Looking at the average individual fits instead of the overall group fit, a  $t$  test revealed a significant reduction in spatial capacity at short lags ( $c_{\text{short lag}} = 0.85$ ) relative to long lags ( $c_{\text{long lag}} = 1.64$ ),  $t(15) = 4.11$ ,  $p = .001$ .

Discussion

The results suggest a decrease in spatial processing capacity under attentional blink conditions. Participants were less able to make use of valid spatial cues when these cues were presented inside the blink compared with outside the blink. This resulted in increased RTs in conditions when cues were present. Note that there was no difference in RTs between the short and long lag conditions when there were no cues present (just a blank display followed by the mask). This result is important because (a) it shows that the attentional blink was over by the time the search display appeared, and thus, the blink did not affect the search directly but solely the processing of the cues; and (b) it justifies keeping the RT intercept ( $I$ ) and slope ( $b$ ) estimates the same for both the short and long lag conditions when fitting the model (see *Method* section above).

Yantis and Johnson’s (1990) model appears to provide a good fit for the data. The spatial capacity estimates derived from this model suggest that the number of spatial cues being processed was halved under attentionally demanding conditions. Outside the blink, observers could make use of, on average, between one and two cues, whereas inside the blink, observers could make use of barely one cue. This strongly suggests that the attentional blink reduces the spatial capacity of the visual system. The fact that Yantis and Johnson’s model fits the data so well is encouraging. This model has been tested extensively and successfully by Yantis and Johnson themselves (see also Yantis & Jones, 1991), providing the best fit for their data. The fact that it fits the data equally well here offers some validity for its application. Note that the model offers a rather straightforward account of visual search, containing a strong serial component. Visual attention seems to first select those locations that have been marked by a cue (as here) or a rapid onset (as in Yantis and Johnson, 1990) before it returns to the remainder of the items. I return to this model in the General Discussion, below.

So far, I have suggested that the temporal unavailability of attention disrupts spatial processing. However, several alternative

explanations of the data exist. First, the disruption of spatial processing may have been brought about by a difference in the distribution of spatial attention between the long lag and short lag conditions. Identifying the target in the central RSVP stream presumably requires attention to be highly focused on the center of the screen, whereas processing of the spatial cues requires attention to be distributed across different regions of the display. When the lag between the RSVP target and the cues is long, there may be sufficient time for attention to expand from a focused state to a distributed state, whereas when the lag is short, attention is still focused when the cues arrive. Observers might not even notice the onset of the cues when they are in such a focused state (Yantis & Jonides, 1990). Thus, under this scenario, attention may not be temporarily unavailable for spatial processing—instead, it is available but not in the right shape. I refer to this as the zoom lens explanation of the results (Eriksen & St. James, 1986), and Experiment 2 tested for this possibility.

A second alternative is that the lapse in performance is due to general task switching demands (as participants need to switch from the RSVP detection task to the cued visual search task), rather than to an attentional blink induced by the perceptual processing of an RSVP target. This was explored in Experiment 3.

A third alternative is that on a substantial proportion of trials, observers are simply unaware of the spatial cues, especially under short lag conditions. In the extreme case, the attentional blink may be so strong that cues are not processed at all. It is then not surprising that spatial localization fails too: After all, if observers are unaware of the stimulus, there is then not much to localize. Because the spatial capacity estimates in Experiment 1 were based on average RTs across trials, there is the danger that this average merely reflects a mixture of trials on which the cues are fully perceived (and correctly localized) and trials on which the cues are not perceived at all (and trivially not localized either). Thus, according to this account, the blink affects perception but not necessarily localization. Experiment 4 (and, to a lesser extent, also Experiment 6) controlled for this possibility.

A fourth alternative is that the attentional blink affects processes during the search task rather than those involved during the spatial encoding of the cues preceding the search displays. Experiment 1 already provided one control for this in that there was no difference in search rates between the short and long lag conditions when there were no cues. Experiment 5 provided additional tests.

### Experiment 2: Eliminating a Zoom Lens Account

To test the zoom lens account, I changed the RSVP stimuli. The relatively small letters in the center of the screen were replaced by big, square-shaped letters and digits, which encompassed the entire subsequent cue, mask, and search displays (i.e., the outline of the characters followed exactly the outline of the virtual square inside which the cues and search items were plotted). To identify the target character, the attentional zoom lens would thus have to be in a wide, distributed state in all conditions—at least sufficiently wide to cover the cue display. If the reduction in spatial capacity found in Experiment 1 were due to the focused state of attention, then this reduction should now have disappeared. If the reduction in spatial capacity were due to an attentional blink (i.e., due to the unavailability of attention), one should have found it again here.

### Method

**Participants.** Eleven participants (five male, all right-handed) participated for either course credits or money. The average age was 21.1 years (range 17–26 years).

**Stimuli, apparatus, design, and procedure.** The experimental setup was the same as in Experiment 1, except for the following. The RSVP stream now consisted of seven-segment box-shaped letters and digits that were as tall and wide as the virtual matrix in which the subsequent cue, mask, and search items were drawn (i.e.,  $8.5^\circ \times 8.5^\circ$ ). The characters were randomly drawn from the set {2, 3, 4, 5, 6, 7, 8, 9, A, C, E, F, H, J, L, P, U}. These characters were chosen because they can be constructed out of the seven segments making up the box and its horizontal midline. The RSVP target was now always a digit (between 0 and 9, with the exception of 1, which was excluded because it does not cover the dimensions of the box). Instead of a fixation asterisk, the RSVP series started with a square-shaped 0 for 500 ms. The series were also followed by a square-shaped 0, which served as a mask for the RSVP target and provided a frame around the cue, mask, and search displays. The cue display was again presented for 216 ms. The postcue mask time was now 800 ms, increasing the time between the RSVP target and the search display to at least 1,000 ms. This provided extra certainty that the attentional blink would be over by the time search started. The number of catch trials was increased to 13%. Of these, 43% were on single-cue trials, 29% on two-cue trials, 14% on three-cue trials, and 7% each on four- and six-cue trials.

### Results

**RTs.** The analysis followed Experiment 1. Figure 4 shows the RT data for each lag and number of cues. The clipping procedure resulted in 2.0% of the data points being removed. There was a significant main effect of lag,  $F(1, 10) = 28.6$ ,  $MSE = 1,689.9$ ,  $p < .001$ . RTs were overall faster when cues were presented after a long lag. Number of cues also had a significant effect,  $F(2.6, 25.9) = 106.1$ ,  $MSE = 4,966$ ,  $p < .001$ . RTs were slowest with no cues at all and fastest with only one cue. RTs gradually increased with more cues. The Lag  $\times$  Number of Cues interaction was not significant,  $F = 1.8$ ,  $p = .14$ . Nevertheless, for compatibility with Experiment 1, I performed planned  $t$  tests (Fisher's LSD) to assess the effect of lag for each number of cues. With no cues, there was no difference in search rate,  $t(10) = 0.42$ ,  $p = .686$ . With one, two, three, and four cues, participants were (close to) significantly faster in the long lag condition,  $t(10) = 2.4$ ,  $p < .05$ ;  $t(10) = 6.3$ ,  $p < .001$ ;  $t(10) = 2.2$ ,  $p = .057$ ; and  $t(10) = 4.9$ ,  $p = .001$ ,

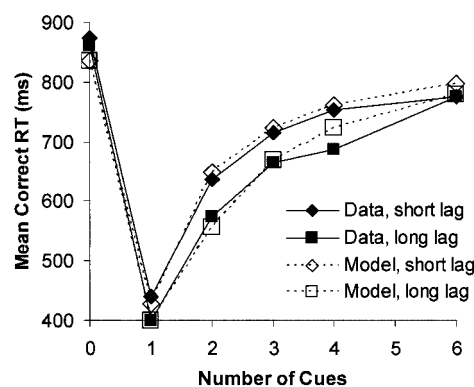


Figure 4. Average reaction time (RT) data and model fit for Experiment 2.



respectively. With six cues, there was no difference between the short and long lag conditions,  $t(10) = 0.05$ ,  $p = .96$ .

**Errors.** Table 1 contains the search error percentages for each lag and number of cues. Overall, the error rate was very low, at around 1%, and there were no significant main effects or interactions (all  $ps > .15$ ). The RSVP target miss rate was 6.8%. A more detailed analysis of RSVP target errors follows Experiment 4 below. The average false alarm rate on catch trials was 13.2%. In contrast to Experiment 1, there were now more false alarms on single-cue trials (22%) compared with multiple-cue trials (with 5% false alarms for two-cue trials, 6% for three-cue trials, 12% for four-cue trials, and 6% for six-cue trials).

**Model fit.** The model fit (see Figure 4) resulted in an  $R^2 = 0.990$  and an RMSE = 28.6 ms. The estimated RT intercept ( $I$ ) was 321 ms, and the estimated RT slope ( $b$ ) was 79 ms/item. Most important, the spatial capacity estimates again varied for short and long lag conditions, with  $c_{\text{short lag}} = 0.94$ , and  $c_{\text{long lag}} = 1.40$ . Looking at the average individual fits instead of the overall group fit, a  $t$  test revealed a significant difference in spatial capacity at short lags ( $c_{\text{short lag}} = 1.0$ ) versus long lags ( $c_{\text{long lag}} = 1.43$ ),  $t(10) = 10.6$ ,  $p < .0001$ .

### Discussion

The results of Experiment 2 were highly comparable to those of Experiment 1. RTs were overall slower in the short lag condition than in the long lag condition, when cues were present. When no cues were present, search rates were no different, suggesting again that the attentional blink was over by the time the search task started. Instead, the attentional blink reduced the capacity to process the spatial cues, as indicated by capacity estimates very similar to those found in Experiment 1. It is important to note that the results of Experiment 2 are difficult to explain under a zoom lens account. The RSVP characters were as wide as the entire cue display, and thus, the attentional zoom lens should already have been in a distributed state by the time the cues appeared. Instead of a slow spatial redistribution of attention, there appears to be a genuine temporary lapse of processing, in line with previous attentional blink findings (e.g., Raymond et al., 1992).

### Experiment 3: Eliminating a Task Switching Account

The results may also be accounted for by more general task switching demands, rather than by the demands imposed through actually processing the RSVP target. On this view, spatial processing is disrupted because observers need to switch from monitoring the RSVP stream to detecting the cues for the visual search task. Assuming that this task switch takes time, spatial detection is at a disadvantage at a short lag from the RSVP target. Several studies have shown the involvement of a task switching component in the RSVP paradigm and how it may be dissociated from the attentional blink (Allport, Styles, & Hsieh, 1994; Enns, Visser, Kawahara, & Di Lollo, 2001; Kawahara, 2002; Pashler & Johnston, 1998; Potter, Chun, Banks, & Muckenhoupt, 1998). To control for general task switching effects, Experiment 3 included a condition in which the RSVP target was absent on one third of the trials (randomly mixed with the short and long lag conditions, in which an RSVP target was present). Presumably, on these trials, observers would keep on monitoring the RSVP stream right until the end. Only at the appearance of the spatial cues would they know it was

an RSVP target-absent trial and switch to the cued search task. If the temporal lapse in spatial processing were due merely to the requirement to switch tasks, then this condition should have yielded a deficit in spatial capacity at least equal to that for the short lag condition. One might even expect task switching effects to be stronger in the RSVP target-absent condition because observers would only know when to switch once the cues were already there, whereas in the short lag condition, the signal to switch would be roughly 117 ms sooner, when the RSVP target appeared. If, on the other hand, the deficit were caused by processing the RSVP target up to a level available for response, as is the standard attentional blink explanation, then one should find an effect only in the short lag condition and not in the task switching and long lag conditions.<sup>1</sup>

### Method

**Participants.** Ten participants (six male, two left-handed) participated for either course credits or money. The average age was 22.5 years (range 17–28 years).

**Stimuli, apparatus, design, and procedure.** The experimental setup was the same as Experiment 2, except for the following. First, in Experiments 1 and 2, the cues shared the color of the search target (blue). Hence, part of the attentional blink effect may have been related to color cuing (although this would not explain the effect of the number of cues present). Here, the cues were gray and thus unrelated (in color) to the target. Any remaining effects should thus have been purely spatial. Second, in addition to the short lag (SOA = 117 ms) and long lag (SOA = 936 ms) conditions, there was now also a condition without an attentional blink. In this task switching condition, all RSVP items remained gray (in other words, there was no target). In this condition, participants were not requested to enter a digit at the end of the trial. To keep the overall number of trials at a reasonable level, the number of spatial cue conditions was reduced to 0, 1, 2, or 4 cues. There were 24 trials per condition per number of cues. There were 13% catch trials, of which 60% were single-cue trials and 40% two-cue trials. All trial types were randomly mixed. A final change involved the handling of catch trials and trials on which participants made a search error. Unlike in Experiments 1 and 2, participants were now required to enter the RSVP target on these trials (except in the task switching condition).

### Results

**RTs.** The analysis followed Experiments 1 and 2. Figure 5 shows the RT data for each condition (short lag, long lag, and target absent) and number of cues. The clipping procedure resulted in 1.8% of the data points being removed. There was a significant main effect of condition,  $F(2, 18) = 7.7$ ,  $MSE = 5,620.5$ ,  $p < .01$ . RTs were overall slowest when cues were presented at short lags, with hardly any difference between the long lag and target-absent

<sup>1</sup> One may argue that the RSVP target-absent condition is not a fair control for task switching because, in the other conditions, the task is to detect and identify a target, which may be more difficult to switch from. This may be true, but by accepting this argument, the distinction between the attentional blink and task switching becomes blurred because both then claim it is the processing of the target that is crucial. It all depends on the definition of the task. If one defines the only relevant task as detecting and identifying a target, then the attentional blink will always involve a task switching component. Here, I was more interested in whether the attentional blink could be distinguished from the general task of having to monitor an RSVP stream for a target.

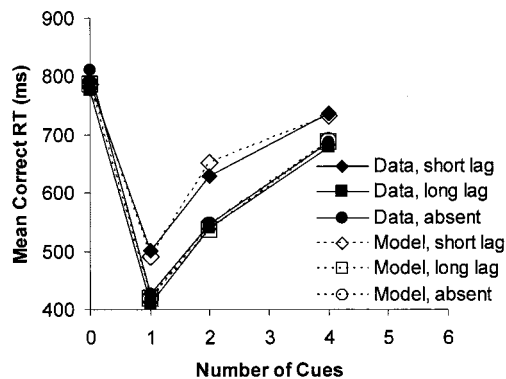


Figure 5. Average reaction time (RT) data and model fit for Experiment 3. The data points for the long lag and task switching conditions are difficult to distinguish because they lie virtually on top of each other.

(task switching) conditions. Number of cues also had a significant effect,  $F(1.5, 13.8) = 205.0$ ,  $MSE = 3,344.4$ ,  $p < .001$ . RTs were slowest with no cues at all and fastest with only one cue. RTs gradually increased with more cues. The interaction between blink condition and number of cues approached significance,  $F(3.2, 28.8) = 2.45$ ,  $MSE = 2,471.2$ ,  $p = .08$ , because the difference between blink conditions was small when there were no cues and larger when there were one, two, or four cues.

**Errors.** Table 1 contains the search error percentages. Overall, the error rate was low, at around 0.9%, and there were no significant main effects or interactions (all  $ps > .13$ ). The average false alarm rate on catch trials was 10.2%, with slightly more false alarms on single-cue trials (11.1%) than on two-cue trials (8.9%). The RSVP target miss rate was 5.8%. Experiment 4 included a more detailed analysis of RSVP target errors.

**Model fit.** The model fit (see Figure 5) resulted in an  $R^2 = 0.997$  and an RMSE = 19.9 ms. The estimated RT intercept ( $I$ ) was 352 ms, and the estimated RT slope ( $b$ ) was 67 ms/item. The spatial capacity estimates again varied for short lag and long lag conditions, with  $c_{\text{short lag}} = 0.80$ , and  $c_{\text{long lag}} = 1.49$ . Most important, the capacity estimate for the task switching condition was very similar to the long lag condition,  $c_{\text{task switching}} = 1.45$ . Conducting  $t$  tests on the average individual fits revealed a significant difference in spatial capacity between the short lag and long lag conditions ( $c_{\text{short lag}} = 0.94$ ;  $c_{\text{long lag}} = 1.70$ ),  $t(9) = 2.85$ ,  $p = .02$ , and the short lag and task switching conditions ( $c_{\text{short lag}} = 0.94$ ;  $c_{\text{task switching}} = 1.61$ ),  $t(9) = 2.54$ ,  $p < .05$ , but not between the long lag and task switching conditions,  $t < 1$ ,  $p > .40$ .

## Discussion

Again spatial capacity was considerably reduced (by about half) for cues presented inside the blink relative to outside the blink. Absolute spatial capacity values were comparable to those of Experiments 1 and 2, with maximum capacity outside the blink averaging around 1.5 cued positions. Most important is the performance in the task switching condition, which was almost identical to the long lag condition. There was no evidence that general task switching demands affected spatial processing in the way that actually processing the RSVP target did. I conclude that the temporary lapse in spatial processing is due to the attentional blink and not due to task switching.

## Experiment 4: Eliminating an Unawareness Account

The results indicate that observers' awareness of the spatial locations of cues is reduced when still processing a target character. One possibility is that this is because observers are simply not aware of (a number of) cues at all. This would be problematic to the current claim that the attentional blink affects spatial processing. After all, if observers simply do not perceive a cue, then it is not surprising that they do not know its location either (unless one attributes some sort of blindsight to them; see, e.g., Weiskrantz, Warrington, Sanders, & Marshall, 1974). In the extreme, it is possible that, despite the arguments for a late (memory) locus of the attentional blink, on some trials the cues are not processed at all—even at a perceptual level. In other words, the cues may simply not exist to the visual system, and hence, there is no localization. To claim that the attentional blink affects spatial processing, one thus needs to show that localization is specifically disrupted despite the fact that the cues are being processed at some level. For this purpose, Experiment 4 was the same as the preceding experiments but included an independent measure of awareness of the spatial cues. In addition to using the cues to localize the target in the visual search task, participants were now also required to count the cues. The assumption is that when observers correctly count the number of cues, they are aware of them, and the cues are therefore being processed at some level. Contingent upon this awareness (i.e., contingent upon a correct count), one can then assess spatial performance. If the difference in spatial performance under short and long lag conditions in the previous experiments were simply due to a proportion of trials on which observers were not aware of the cues at all, one should see the spatial capacity differences disappear. If observers, despite being aware of the cues, still mislocalize them, one can conclude that the attentional blink affects spatial processing.

## Method

**Participants.** Ten participants (nine male, one left-handed) participated for money. The average age was 21.5 years (range 18–23 years).

**Stimuli, apparatus, design, and procedure.** The experimental setup was the same as in Experiment 3, except for the following: There was now no task switching condition. Also, the number of spatial cues was reduced to zero, one, or two. The most important change was the introduction of a counting task. In addition to the RSVP target detection and visual search tasks, participants were required to count the number of cues present. They were explicitly told that the number could vary between zero, one, and two, with equal proportions of each. It was stressed that the absence of any cues was a distinct possibility. At the end of each trial, the participants typed in the number of cues they had seen, at their own pace, after they had typed in the RSVP target. In Experiments 2 and 3, the RSVP target was always a digit. In Experiment 4, this might have led to confusion on the participant's behalf in that reporting the RSVP digit might have interfered with reporting the number of cues. The RSVP targets were therefore selected from a set of letters (A, C, E, F, H, J, L, P, and U) rather than digits. Because Experiment 1 also used letters instead of digits, I did not expect any major effects from this change. The factors lag (short lag, SOA = 117 ms; long lag, SOA = 936 ms) and number of cues (zero, one, two) were randomly mixed within three blocks of 72 trials each, resulting in 36 trials per combination. Twelve catch trials (14%) were added to each block. The RSVP, counting, and visual search tasks were first practiced separately, followed by a combined practice session. There was a break between blocks, and the experiment lasted approximately 75 min.

Results

*Counting performance.* Table 2 shows the percentage error rates on the counting task for the different lags and number of cues. There was a trend toward more counting errors under short lag conditions than under long lag conditions, 9.0% versus 5.6%,  $F(1, 9) = 3.92$ ,  $MSE = 0.004$ ,  $p = .079$ . There were no effects of, or interactions with, number of cues ( $F_s < 1$ ).

*RTs.* The analysis followed Experiments 1, 2, and 3, with the important difference that only those trials were included on which the number of cues was correctly reported. This was to ensure that participants were at least aware of the cues and that the attentional blink effect on spatial processing would therefore not be overestimated. Figure 6 shows the RT data for each lag (short, SOA = 117 ms; long, SOA = 936 ms) and number of cues (zero, one, and two). RTs were overall slowest when cues were presented after a short lag,  $F(1, 9) = 22.9$ ,  $MSE = 2,714.5$ ,  $p = .001$ . Number of cues also had a significant effect,  $F(1.4, 12.8) = 180.1$ ,  $MSE = 7,762.8$ ,  $p < .001$ . As before, RTs were slowest with no cues at all and fastest with only one cue. They increased again with two cues. The interaction between blink condition and number of cues was not significant,  $p = .34$ .

*Search and RSVP errors.* Table 1 contains the search error percentages for each lag and number of cues. Overall, the error rate was low, at around 0.4%. There was a slight but significant increase with the number of cues,  $F(1.6, 14.7) = 4.7$ ,  $MSE = 0.000044$ ,  $p < .05$ . There were no further effects ( $ps > .20$ ). The average false alarm rate on catch trials was 18.1%. There were more false alarms on single-cue trials (35.1%) than on zero- or two-cue trials (6.5%, 12.6%, respectively),  $F(1.9, 16.9) = 12.6$ ,  $MSE = 0.037$ ,  $p < .001$ , indicating that there was some anticipation of search target appearance. The RSVP target miss rate was 2.9%. Experiment 5 included a more detailed analysis of RSVP target errors.

*Model fit.* The model fit (see Figure 6) resulted in an  $R^2 = 0.998$  and an RMSE = 21.0 ms. The estimated RT intercept ( $I$ ) was 381 ms, and the estimated RT slope ( $b$ ) was 94.8 ms/item. It is important to note that the spatial capacity estimates again varied for different lags,  $c_{\text{short lag}} = 1.22$ , and  $c_{\text{long lag}} = 1.6$ . Conducting  $t$  tests on the average individual fits revealed a significant difference in spatial capacity between the short lag and long lag conditions ( $c_{\text{short lag}} = 1.17$ ;  $c_{\text{long lag}} = 1.55$ ),  $t(9) = 7.88$ ,  $p < .001$ .

Discussion

Experiment 4 included a counting task to provide a measure of awareness of the spatial cues under attentional blink conditions. The results showed a modest reduction in counting performance at short lags relative to long lags (by 3.4%), suggesting that observers were indeed somewhat less aware of the cues when these were

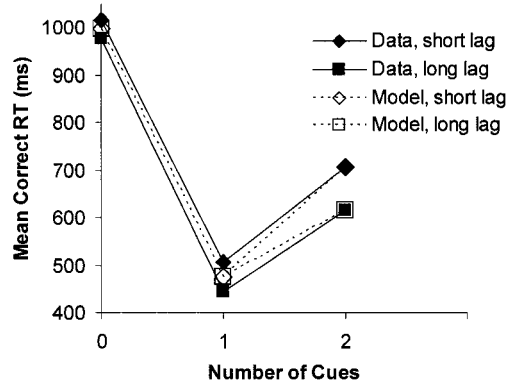


Figure 6. Average reaction time (RT) data and model fit for Experiment 4.

presented inside the attentional blink period. This implies that in the previous experiments, the estimated effect of the attentional blink on spatial processing may indeed have been slightly contaminated by trials on which the cues were not perceived (and thus, trivially, were not spatially processed). Experiment 4 therefore estimated again the spatial capacity for short and long lag conditions but now for only those trials on which the number of cues was correctly perceived. The results still revealed a reduction in spatial capacity under short lag conditions, from 1.6 to 1.2 cues. Thus, spatial processing was affected despite the fact that the participants were aware of the cues. Put the other way around, the participants perceived the cues under attentional blink conditions but could not adequately use them to localize the target in the visual search task. I conclude that spatial processing is disrupted by the attentional blink.<sup>2</sup>

Why are performances on the counting and localization tasks dissociated? An obvious difference is that, for localization to be useful in the search task, the cues need to be explicitly remembered in visuospatial working memory for an extended period of time (i.e., across the mask and search period). They may thus be subject to decay. In contrast, in the counting task, the answer can immediately after presentation of the cues be transferred to some sort of verbal working memory containing just one item (i.e., the number of cues perceived). Participants may have been aware of the presence of a stimulus but not of its exact location as measured by a subsequent search task. Alternatively, they may have been

<sup>2</sup> One may argue that rather than individuating and counting the number of cues, participants may just have determined the overall luminance of the display (as this was confounded with the number of cues). I would contend that this is unlikely. The cues were immediately preceded by a large letter consisting of a varying number of elements and thus varying levels of luminance. Furthermore, the cues were immediately followed by a luminant mask completely filling the display. At best, then, overall luminance would be an unreliable guide. Also, Experiment 6 showed that observers are generally able to individuate the cues because, even under attentional blink conditions, localization was roughly correct (but coarse). Even if the participants did rely on luminance in Experiment 4, this still supports the argument that observers were aware of something of the stimulus, thus providing an estimate of the extent of the attentional blink. The argument would then be that even though observers could see (presumably) a blob of a certain luminance, the attentional blink prevented them from localizing the correct source(s) of that blob.

Table 2  
Error Percentages for the Counting Task of Experiment 4

Lag	Number of cues		
	0	1	2
Short (117 ms)	10.4	8.4	8.1
Long (936 ms)	7.8	5.6	3.3

briefly aware of its location but forgotten it by the time the search display appeared. Whichever way, Experiments 1–4 show that either this perception or this retention of a spatial location suffers under attentional blink conditions and that this suffering is not simply due to complete unawareness of the stimulus. Experiment 6 provided further evidence for this, using a different task. Before that, Experiment 5 looked at the role of masking.

### Experiment 5: Removing the Postcue Mask

In Experiments 1–4, the cue displays were followed by a masking pattern (filling the search array with green and blue box figure eights). Several studies have shown that masking of the to-be-detected information is crucial to creating an attentional blink (Brehaut, Enns, & Di Lollo, 1999; Giesbrecht & Di Lollo, 1998). The attentional blink is greatly reduced or even disappears completely when the to-be-detected information is not masked. This has led theorists to propose that the attentional blink occurs because, in visual working memory, the to-be-detected information is being replaced, or being hindered in its consolidation, by the mask (Brehaut et al., 1999; Giesbrecht & Di Lollo, 1998; Maki, Couture, Frigen, & Lien, 1997). In fact, the masking studies, together with the priming studies (Luck et al., 1996; Maki, Frigen, & Paulson, 1997; Martens et al., 2002; Shapiro, Driver et al., 1997; see introductory section above) and neurophysiological studies (Vogel et al., 1998), provide some of the strongest evidence that the locus of the blink lies at a relatively high level of selection, reflecting either reduced entrance to or reduced processing within visual working memory.

Experiment 5 sought to explore whether in the present paradigm too the results depended on masking, by removing the mask after the cue display. If so, this would serve as a further diagnostic that it is indeed the attentional blink that affects visual spatial working memory here. In this respect, the removal of the mask would provide an additional check on whether the RSVP task did not affect the search task directly rather than through disrupting the processing of the spatial cues. Experiments 1–4 already suggested no such direct influence in that there was only an effect of attentional blink when cues were present (there was no effect in the zero-cues condition). However, one could think of more complex scenarios in which the blink did not affect the actual encoding of the cues but did affect the subsequent use (e.g., retrieval) of the cues during the search task. Experiment 5 controlled for this possibility.

### Method

**Participants.** Ten participants (four male, all right-handed) participated for either course credits or money. The average age was 21.1 years (range 17–26 years).

**Stimuli, apparatus, design, and procedure.** The experimental setup was the same as in Experiment 2, except that in Experiment 5, the mask was replaced with a blank.

### Results

**RTs.** Figure 7 shows the RT data for each lag and number of cues. The clipping procedure resulted in 2.5% of the data points being removed. As in the previous experiments, number of cues had a significant effect,  $F(1.6, 14.4) = 103.2$ ,  $MSE = 4,340$ ,  $p < .001$ . RTs were slowest with no cues at all and fastest with only

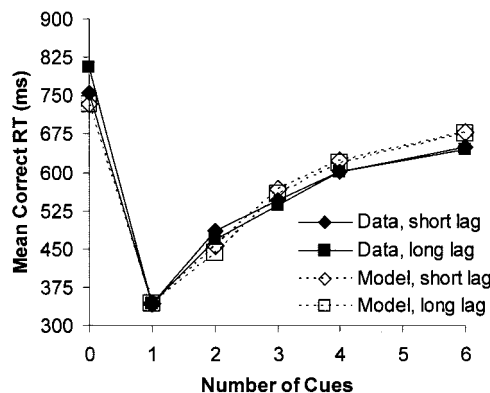


Figure 7. Average reaction time (RT) data and model fit for Experiment 5.

one cue. RTs then gradually increased with more cues. It is important to note that lag now had no significant effect,  $F < 1$ ,  $p = .68$ . RTs were equally fast when cues were presented at short or long lag. To contrast this with Experiment 2, the data were entered in a mixed ANOVA with experiment (2 and 5) as a between-participants factor. In line with the data pattern, there was a significant Lag  $\times$  Experiment interaction,  $F(1, 19) = 14.7$ ,  $MSE = 1,874$ ,  $p = .001$ . The Lag  $\times$  Number of Cues interaction was not significant,  $F = 1.1$ ,  $p = .36$ , and neither were any of the  $t$  tests (Fisher's LSD) on lag for each number of cues (all  $t$ s  $< 1.5$ ,  $p$ s  $> .18$ ).

**Errors.** Table 1 contains the error percentages for each lag and number of cues on the search task. The overall error rate was again low, at 0.7%. There were no significant effects (all  $F$ s  $< 1.4$ , all  $p$ s  $> .22$ ). The average false alarm rate on catch trials was 15.5%, with no notable differences across lag or number of cues. The RSVP target miss rate was 10.2%.

**Detailed RSVP error analysis of Experiments 1–5.** Combining the data of Experiments 1–5 allowed for sufficient power to assess to what extent the RSVP error rate depended on the different lag and cuing conditions. The conditions these experiments had in common—lag 117 ms (short lag) and lag 936 ms (long lag), for zero, one, and two cues—were entered in an ANOVA with lag and number of cues as factors. The error percentages for zero, one, and two cues were 4.1%, 4.4%, and 4.7% in the short lag condition and 11.4%, 11.6%, and 10.8% in the long lag condition, respectively. Only the main effect of lag was significant,  $F(1, 56) = 69.1$ ,  $MSE = 57.8$ ,  $p < .001$ , as the RSVP target error rate was higher for long lags than for short lags (all other  $p$ s  $> .50$ ). The same result held when Experiment 5 (where there was no net effect of lag on RTs) was left out.

**Model fit.** The model fit (see Figure 7) resulted in an  $R^2 = 0.978$  and an RMSE = 42.3 ms. The estimated RT intercept ( $I$ ) was 272 ms, and the estimated RT slope ( $b$ ) was 71 ms/item. Most important, the spatial capacity estimates varied only a little between short lag and long lag conditions, with  $c_{\text{short lag}} = 1.56$ , and  $c_{\text{long lag}} = 1.65$ . Looking at the average individual fits instead of the overall group fit, a  $t$  test also revealed no significant difference in spatial capacity at short lag ( $c_{\text{short lag}} = 2.2$ ) versus long lag ( $c_{\text{long lag}} = 2.1$ ),  $t < 1$ ,  $p = .60$ .



## Discussion

The results are clear. In contrast to Experiments 1–4, there were now no differences in RTs and spatial capacity estimates between the attentional blink conditions. The presence of the mask is crucial in obtaining a temporal lapse in spatial processing. This corroborates earlier findings that masking is key to obtaining attentional blinks for nonspatial properties such as letter identity and suggests that visual working memory is involved (Brehaut et al., 1999; Giesbrecht & Di Lollo, 1998; Vogel & Luck, 2002). It also offers further evidence against the argument that in Experiments 1–4, the RSVP task somehow affected the search task directly. There, I found no effect of the RSVP task when zero cues were present; here, I found no effect of the RSVP task regardless of the number of cues. Combined with Experiments 1–4, the results indicate that the spatial encoding of the cues into visual working memory is affected by the blink, not their retrieval from it.

The analysis of RSVP target errors across Experiments 1–5 revealed that, on average, participants made roughly three times more errors when the lag between the target and the cue display was long than when it was short. One explanation is that at short lag, the RSVP target was followed by just one RSVP stimulus (the asterisk mask in Experiment 1 and the final square in Experiments 2–5), making it easier to identify than the target that was presented at long lag and that was followed by seven distractors. Another explanation is that the period between RSVP target presentation and its report was simply longer for long lags, allowing for more forgetting. In any case, there was no effect involving number of cues, indicating that memory of the RSVP target is not affected by having to remember more cues or by a more or less efficient search. I return to this point in the General Discussion, below.

### Experiment 6: Direct Localization

Where, in Experiments 1–5, spatial capacity was estimated from a cued visual search task, Experiment 6 provided a more direct measure of localization. Either one or two cues were presented at short or long lag from an RSVP target and were followed by a mask. This time, however, the task was simply to point out the locations of the cues. For this purpose, the cue and mask displays were followed by a pointing display, in which the participant could mark the locations of the cues with the use of the mouse. The advantage of this task is that it provides additional information on where most localization errors occurred and of what type they were.

### Method

**Participants.** Twelve participants (7 male, 1 left-handed) participated for either course credits or money. The average age was 19.8 years (range 18–25 years).

**Stimuli, apparatus, design, and procedure.** The experimental setup was again largely the same as in the previous experiments. However, instead of a search or counting task, participants were now required to point to the locations of the cues, using the mouse. The pointing display appeared immediately after the mask and consisted of a grid filled with dark-gray box figure eights identical in size and position to the mask. The participant then moved the mouse pointer to the location of one of the cues and clicked. The figure eight would then turn white to mark the selected position. Where there was only one cue, the display then disappeared automatically. Where there were two cues, the program would allow the

participant to point to another location and then end the display. The pointing task was unsped and was followed by the RSVP target question. In total, there were three blocks of 80 trials, with 50% single-cue and 50% double-cue trials, 50% short lag and 50% long lag trials. There were breaks between blocks, and the experiment started with a practice session in which the RSVP and pointing tasks were first practiced separately and then combined.

### Results

Participants made, on average, 5.5% RSVP target detection errors. I assessed localization accuracy separately for one-cue and two-cue trials as a function of cue eccentricity. The results are shown in Figure 8. Two-cue trials were divided into which cue had been localized best (best of two cues) and which had been localized worst (worst of two cues) by calculating the distances of the chosen locations to the two cues and assigning the minimum distance to the best of two cues and the remaining distance to the worst of two cues. This way, it could be assessed if observers had localized at least one cue correctly on two-cue trials. On 91% of the cases, the best of two cues was actually the one that was marked first. Apparently, participants tend to report first the location of the cue about which they are most certain (Chastain, 1982). Furthermore, localization errors that were more than 2.24° off target were treated as outliers. This way, 2.3% of the data points were removed. The 2.24° cutoff point corresponded to a deviation of a maximum of two positions on the grid and served to get rid of the worst localization errors. Extreme deviations likely reflect either spurious mouse clicks or pure guessing as a consequence of complete unawareness of the cue (cf. Experiment 4). Removing these trials controlled to some extent for this. It is important to note that the number of outliers did not vary with the number of cues present (one or two) and that the pattern of results remains the same with these trials included.

Because there were not sufficient data points for each individual cell in the 8 × 8 grid, eccentricity was measured as the distance from fixation, collapsed across the *X* and *Y* directions (i.e., 0.5, 1.5, 2.5, or 3.5 positions to the left and right, or above and below, the center of the screen; one position corresponds to approximately one degree of visual angle). This resulted in an average of 15 data points per data cell per participant. In the ANOVAs reported below, the data were further collapsed across sides (i.e., positive and negative eccentricities, that is, across left, right, above, and below, after appropriate inversions; see Figure 8d), resulting in an average of 30 data points per cell. The following factors were analyzed: cue type (one cue, best of two cues, worst of two cues), eccentricity (0.5, 1.5, 2.5, 3.5), and lag (short, long).

The graphs in Figure 8 show several effects. First, the absolute deviation from the real cue location was greater when the cue was presented at short lags compared with long lags,  $F(1, 11) = 14.9$ ,  $MSE = 0.045$ ,  $p < .01$ . Second, the deviation increased with the eccentricity of the cue; eccentricity,  $F(3, 33) = 16.8$ ,  $MSE = 0.350$ ,  $p < .001$ . Third, the deviation was worse for the worst of two cues than for the best of two cues and the single cue; cue type,  $F(2, 22) = 65.5$ ,  $MSE = 0.021$ ,  $p < .001$ . Also, the eccentricity effect was stronger for the worst of two cues than for the best of two cues and the single cue; Cue Type × Eccentricity,  $F(6, 66) = 27.4$ ,  $MSE = 0.0045$ ,  $p < .001$ . Moreover, the worst of two cues suffered the most from the attentional blink; Cue Type × Lag,  $F(2, 22) = 6.3$ ,  $MSE = 0.0084$ ,  $p < .01$ . There were no differences between the single-cue and the best-of-two-cue conditions (all

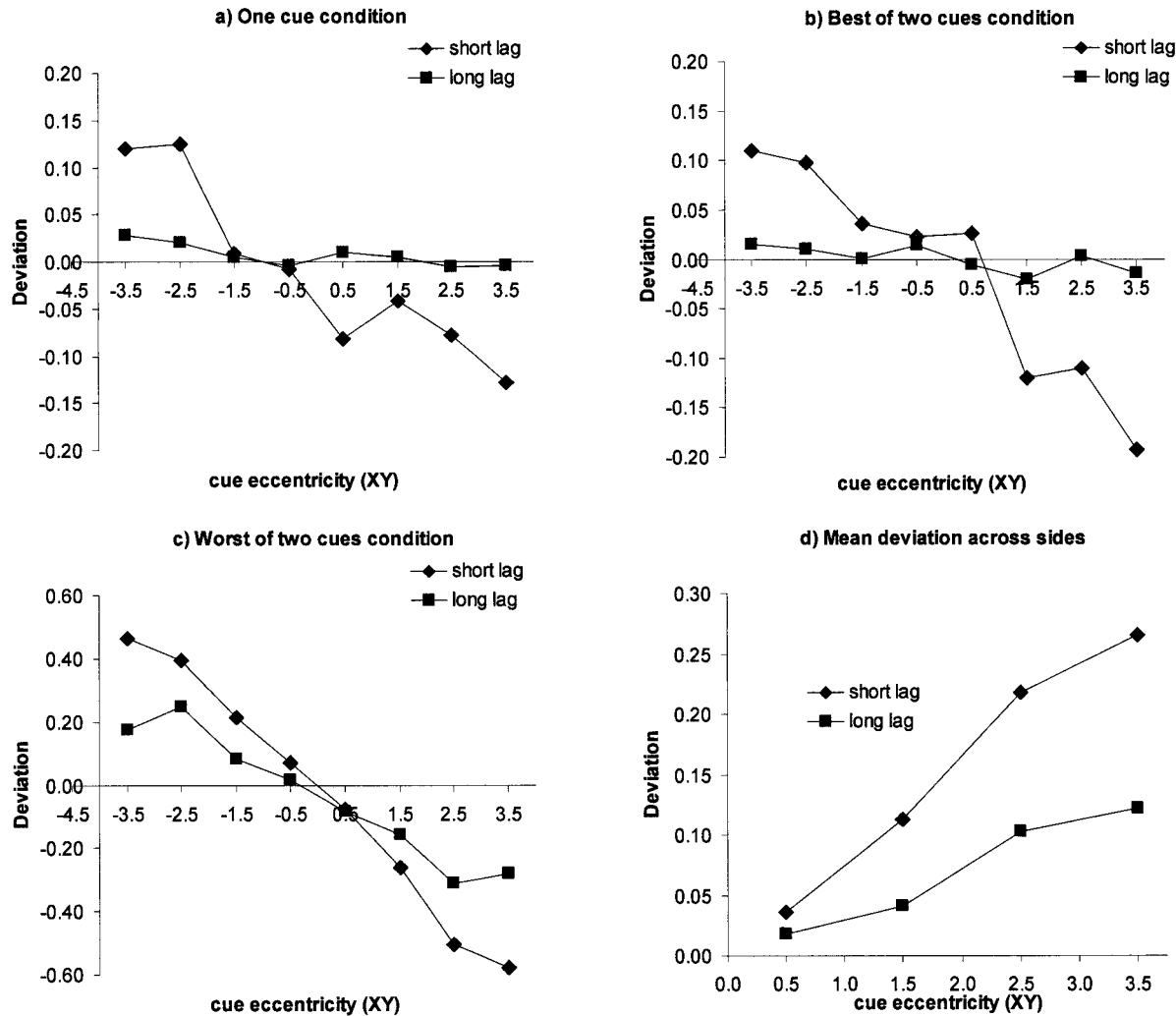


Figure 8. Average localization deviation in Experiment 6 as a function of cue eccentricity. (a) One cue present. (b) Two cues present—showing the best localized cue. (c) Two cues present—showing the worst localized cue. (d) The mean absolute deviation in all these conditions collapsed across sides (i.e., across positive and negative eccentricity). The eccentricity measure was collapsed across the *X* and *Y* directions. Eccentricity and deviation units are in screen positions, with the distance between two screen positions corresponding approximately to one degree of visual angle. Note the scale change from Panel b to Panel c.

effects involving cue type,  $ps \geq .20$ ). Fourth, it is important to note that the eccentricity effect was overall stronger at short lags relative to long lags; Lag  $\times$  Eccentricity,  $F(3, 33) = 8.1$ ,  $MSE = 0.011$ ,  $p < .001$ . Figure 8 shows that this effect was present in all conditions. Nevertheless there was a tendency for it to be stronger again for the worst of two cues; Cue Type  $\times$  Lag  $\times$  Eccentricity,  $F(6, 66) = 1.99$ ,  $MSE = 0.012$ ,  $p = .08$ . Figures 8a–8c further show that the deviation was biased toward the center of the screen (fixation), as the bias was positive when the eccentricity was negative and vice versa. Note, however, that this bias may in part have been artificially induced by the extreme eccentricities (i.e., the positions  $-3.5$  and  $3.5$ ), where it was only possible to choose an equally, or less, eccentric location. The analysis was therefore repeated with these positions removed. The same effects of lag,  $F(1, 11) = 6.5$ ,  $MSE = 0.040$ ,  $p < .05$ ; eccentricity,  $F(2, 22) = 16.3$ ,  $MSE = 0.019$ ,  $p < .001$ ; and cue type,  $F(2, 22) = 61.8$ ,

$MSE = 0.014$ ,  $p < .001$ , were found. It is important to note that the Lag  $\times$  Eccentricity interaction was significant,  $F(2, 22) = 4.83$ ,  $MSE = 0.0095$ ,  $p < .02$ , indicating again that eccentricity had a larger effect under attentional blink conditions. The only other interaction significant was Cue Type  $\times$  Eccentricity,  $F(4, 44) = 36.6$ ,  $MSE = 0.0038$ ,  $p < .001$ , as eccentricity effects were larger for the worst of two cues. Thus, the effects are not due to an artificially induced bias.

### Discussion

Again the results show a clear effect of the attentional blink on spatial processing. Localization performance was worse for cues that were presented inside the attentional blink period, even when there was only a single cue. In contrast, participants had little trouble localizing the single cue when it was presented outside the

blink. When two cues were presented inside the blink, localization of both cues was affected. When presented outside the blink, however, one of the two cues could be localized with little trouble, whereas localization of the other cue was affected. These findings correspond directly to those of Experiments 1–5, in which it was estimated that, inside the blink, less than one cue could be localized correctly, whereas outside the blink, between one and two cues could be localized correctly. Note that here localization capacity was measured directly, rather than estimated from search RTs. Thus, the present results suggest that the spatial capacity estimates found in Experiments 1–5 are genuine.

Interestingly, the localization error increased with eccentricity. Moreover, the deviations showed a consistent bias toward the center of the display, which was, presumably, also the center of fixation. Both findings confirm earlier studies reporting a foveal bias in the identification and localization of briefly presented objects (Chastain, 1982; Leibowitz, Myers, & Grant, 1955; Müsseler, van der Heijden, Mahmud, Deubel, & Ertsey, 1999; J. Ross, Morrone, & Burr, 1997; Sheth & Shimojo, 2001; van der Heijden, van der Geest, de Leeuw, Krikke, & Müsseler, 1999; Wolford & Shum, 1980). It appears as if visual space is compressed. The most important result here is that this contraction of visual space is modulated by attention: It is especially strong under attentional blink conditions. A similar finding was reported by Prinzmetal et al. (1998). In their Experiment 5, participants had to localize a dot in the periphery, either accompanied by (in the simultaneous condition) or preceded by (in the successive condition) a central letter discrimination task. Prinzmetal et al. assumed that, in the simultaneous condition, less attention would be available for the localization task. The results confirmed this idea. In both conditions, participants made errors. However, in the simultaneous condition, localization variance was greater. Furthermore, there was a slightly stronger tendency for this variance to be skewed toward fixation in the simultaneous condition compared with the successive condition, suggesting that a lack of attention aggravates the spatial contraction. However, an alternative explanation of their results is that the foveal bias stems merely from the requirement to perform a task simultaneously at fixation, rather than from a lack of attention (cf. Experiment 1 vs. Experiment 2 here). The task of localizing a central letter (as is presumably required for the identification) may affect the localization of peripheral stimuli directly. Unfortunately, the bias toward fixation disappeared in a subsequent experiment in which Prinzmetal et al. (their Experiment 6) replaced the simultaneous/successive manipulation with a different attention manipulation varying the difficulty of the central letter discrimination task—thus leaving the issue of the attentional modulation of spatial contraction unresolved. In all the experiments (bar Experiment 1), there was no task concentrated at fixation, and the spatial contraction under attentional blink conditions was the more remarkable exactly because attention was presumed to be in a wide state encompassing the entire cue display.

A final remark concerns the question whether participants were generally aware of the mislocalized cues in Experiment 6. After all, without awareness, mislocalizations become quite trivial. First, Experiment 4 already suggested participants were mostly aware of the cues. There, I found that participants counted the number of cues correctly on at least 90% of the trials but that, nevertheless, on these trials, spatial processing capacity was still affected. Here, on average, 98% of the localizations fell within  $2.24^\circ$  of the cues

(regardless of whether they were presented at short or long lags). This suggests that participants were aware of at least the rough position of the cue. The chance level of a response falling within this region under circumstances of complete unawareness is on average 25%.

## General Discussion

The present study clearly demonstrates an effect of the attentional blink on spatial processing. Experiment 1 combined the RSVP paradigm with a spatially cued visual search paradigm and showed that the estimated capacity to use the spatial cues was halved under attentional blink conditions (from between one and two cues to less than one). Experiment 2 showed that this effect was not due to attention being highly focused on the center of the display. When the RSVP characters inducing the blink were as large as the cue display itself and, thus, the attentional zoom lens was assumed to be in a distributed state, spatial capacity was reduced by approximately the same amount as in Experiment 1. Experiment 3 showed that the reduced spatial capacity was not due to general task switching demands because the condition that required participants to monitor the RSVP stream but not process a target did not result in a deficit. Experiment 4 assessed whether observers were aware of the cues at all by requiring them to count as well as localize the number of cues. Awareness of objects indeed appeared slightly reduced under attentional blink conditions, but the crucial finding was that even when observers were aware of the cue, localization was affected. Experiment 5 showed that the reduction in performance depended on masking, in line with previous attentional blink studies and contrary to an explanation in terms of search or retrieval processes. Finally, Experiment 6 used a more direct measure and asked participants to mark the locations of one or two cues. In line with the visual search experiments, the results suggested that, on average, less than one cue could be localized correctly inside the blink and between one and two cues outside the blink. Moreover, the results showed that localization errors were systematically biased toward the center of the display. This leads to the important conclusion that a temporal lapse of attention reduces spatial processing and does so in a systematic fashion.

### *Validation of Yantis and Johnson*

The present study offers additional validation of Yantis and Johnson's (1990) serial search model. The model was developed to estimate how many abrupt new onsets would be prioritized for selection in their attentional capture paradigm. It assumes that a number of abrupt new onsets are tagged for selection and that this tagging process is limited in capacity. The tagged items receive priority over older, offset-defined items and also over onsets that remain outside the capacity-limited tagging process or whose tags have decayed (Yantis & Jones, 1991). The model simply assumes that the tagged items are searched first, in a serial fashion, after which the remaining items are searched. The model appears to account well for the data of Experiments 1–5, resulting in good fits and generating capacity estimates that were validated by Experiment 6, which used a different task.

A noticeable difference from Yantis & Johnson's (1990) findings is that here, a maximum of between one and two items was prioritized, whereas Yantis and colleagues found prioritization of

up to four items (Yantis & Johnson, 1990; Yantis & Jones, 1991; see also Pylyshyn, 1989). There may be several explanations for this difference. First, the use of a mask in the present displays may have limited the effect of the cues. Yantis and Johnson did not use a mask. However, note that the removal of the mask in Experiment 5 did not boost the overall spatial capacity, suggesting that masking was not the major cause. Second, the overall capacity may have been reduced by the fact that participants had to remember the RSVP target letter, possibly resulting in reduced visual short-term memory capacity. However, the RSVP target-absent condition of Experiment 3 eliminated this possibility because there was no target to remember. Third, the low capacity estimate may be due to an underestimation of RTs in the single-cue condition, where the cue provided absolute certainty about the target's position (save a few catch trials) and may thus have resulted in observers anticipating the target's appearance. Note that the number of errors on catch trials was quite high. However, there were no consistent effects that more false positives were made in the single-cue condition compared with the multiple-cue conditions (with a difference in Experiments 2 and 4 but no difference in Experiments 1, 3, and 5). Furthermore, Experiment 6 circumvented the possibility of anticipation by using a different task and still resulted in very similar estimates for the spatial capacity under different attentional blink conditions. Underestimation of RTs, therefore, does not appear to be the most likely explanation.

The discrepancy is more likely due to the differences in task requirements. Previous studies used detection tasks, whereas the present task required target localization. It is possible that Yantis and Johnson's (1990) participants prioritized more items than they could localize correctly. Other differences include having to perform two tasks and having to remember the cued locations over an extended period of time here, possibly leading to stronger interference and/or decay of activity associated with the cues (Yantis & Jones, 1991).

Another aspect of the results is worth commenting on in the light of Yantis and Johnson's (1990) serial search model. Note that Experiment 6 showed that although participants had trouble localizing one or two cues precisely, they did generally end up in the right neighborhood (i.e., within  $2.24^\circ$ ). Nevertheless, the spatial capacity estimates of Experiments 1–4 suggest that there was little benefit from being in the right neighborhood unless the exact location was selected. Apparently, after selecting a wrong location, participants proceeded to search the display without giving priority to items close by. It is even feasible that they deliberately chose a different direction given that, in the multiple-cue displays, they would often be misled by one or more of the remaining cues.

#### *Perception, Attention, or Visual Working Memory?*

In the preceding discussions, I deliberately used the neutral term *spatial processing* when referring to the mechanism impaired by the attentional blink. An important question is whether it is the perception or selection of spatial information that is impaired or the retention of that same information in working memory. On the one hand, the finding of increased localization errors under attentional blink conditions corresponds to earlier reports of increased localization variance attributed to lack of attention (Egley & Homa, 1984; Newby & Rock, 2001; Prinzmetal et al., 1998; Tsai & Baret, 1999). This would point to an attentional deficit. However, note that in these studies, as in mine, observers gave their

localization responses only after the stimulus had disappeared, so it is not impossible that a memory component of some sort was involved. Within working memory, the attentional blink may prevent consolidation, increase interference, or perhaps speed up decay by suppression (see, e.g., Chun & Potter, 1995; Jolicoeur & Dell'Acqua, 1998; and Raymond et al., 1992, for different accounts). Although the present study does not speak clearly to the issue of whether attention and/or memory are involved, it is worth pointing out that the dichotomy may be more apparent than real. Recent work suggests that the two concepts may be strongly linked—perhaps so strongly that they should be regarded as one and the same (Awh & Jonides, 2001; Desimone & Duncan, 1995; Downing, 2000; Kastner & Ungerleider, 2000). Indeed, the conceptual overlap is especially apparent in attentional blink theories, where the phenomenon is termed *attentional* but the explanation is generally assumed to lie on the level of visual working memory.

One indication that memory was involved in the present study is that the blink effect disappeared when there was no mask—despite the likelihood of attention still being involved in RSVP target processing when the lag was short compared with when it was long. It has been proposed that the mask contributes to the attentional blink because it interferes with (e.g., replaces or prevents the consolidation of) the target information in visual working memory (Brehaut et al., 1999; Giesbrecht & Di Lollo, 1998). If this is the case, then this would be a likely explanation for the effects here, too.

Another indication comes from a study by Sheth and Shimojo (2001). Similar to my results, they found that observers tended to localize briefly presented objects more toward the fovea. Interestingly, however, they showed that this tendency grew stronger the longer the observers had to wait before they could respond and, thus, the longer they had to keep the object's location in memory. Sheth and Shimojo concluded that it is memory that compresses space. Again, a similar explanation is appealing here.

Also interesting in this respect is a study by Hagenaar and van der Heijden (1997), who used the partial report task explained in the introductory section above. Participants were presented with briefly (30 ms) flashed multiple-character arrays, followed by an almost equally briefly (50 ms) flashed arrow cue pointing to the to-be-reported character. Like others (Eriksen & Rohrbaugh, 1970; Mewhort et al., 1981; Snyder, 1972; Townsend, 1973), Hagenaar and van der Heijden found that observers predominantly made location errors, that is, those involving the report of a letter adjacent to the cued one. It is important to note that they also found that of the two items adjacent to the cued position, the more central one was much more likely to be reported than the more peripheral one. Furthermore, as with Sheth and Shimojo (2001), this central bias increased with increased stimulus–cue interval, suggesting a memory component to the spatial distortion of the character array. Interestingly, however, Hagenaar and van der Heijden drew quite the opposite conclusion, namely, that not the characters but the cue must have been mislocalized. They argued that had the characters been displaced toward the center and the cue correctly perceived, participants would have reported the more peripheral item. This was not the case. Future research will have to look more closely at how successive stimuli are spatially represented relative to each other.

The present results have important implications for theories of the attentional blink. If one accepts the view that the blink affects either entrance to, consolidation within, or retrieval from working



memory (as is proposed in one form or another in most theories; e.g., Chun & Potter, 1995; Jolicoeur & Dell'Acqua, 1998; Raymond, Shapiro, & Arnell, 1995; see Shapiro, Arnell, & Raymond, 1997, for a review), then one starts to see that it does so universally, regardless of what type of information needs to be held. Attentional blinks have been reported for simple object features and object identities across several modalities (Arnell & Jolicoeur, 1999; Dell'Acqua, Turatto, & Jolicoeur, 2001; Soto-Faraco et al., 2002). Moreover, many attentional blink studies have used stimulus materials that can easily be verbalized, such as letter or digit characters, words, primary colors, and canonical shapes. I have shown here that the attentional blink also affects visual spatial processing. The universality of the effect is interesting because working memory itself is seen as far from unitary. Traditionally, a verbal component has been distinguished from a visuospatial component (Baddeley & Hitch, 1974; Jonides et al., 1996). More recently, the latter type of working memory has been divided into object identity memory and spatial memory components (Logie, 1995; Smith et al., 1995; Tresch et al., 1993). The subdivision of working memory begs the question of why having to remember a letter target—that is, the usual first target in attentional blink experiments, which could presumably be stored or consolidated in some verbal fashion—would interfere with memory for object properties or spatial locations. Even if the letter identification task first requires some sort of visual object recognition memory, then one might still ask why it interferes with the consolidation of spatial information, as it did here. The analysis of RSVP target errors (at the end of Experiment 5) is instructive here. There, it was shown that the number of to-be-remembered cues (followed by a more or less effortful search as a consequence) had no effect on memory for the RSVP target whatsoever. This suggests that in the present task, participants indeed made use of independent stores to remember the RSVP target and the cues. The important implication is that the attentional blink's bottleneck does not lie on the level of actual working memory representations, nor would it be caused by interference between such representations, as has been proposed by Shapiro and colleagues (Isaak, Shapiro, & Martin, 1999; Shapiro, Raymond, & Arnell, 1994). Instead, the universality of the attentional blink points toward processing limitations at a common stage either earlier or later in the processing stream. An early candidate would be selective attention, functioning as a gatekeeper for the entrance to the multiple visual working memory systems (cf. Duncan, Ward, & Shapiro, 1994). However, the fact that observers were at least aware of the cues (Experiment 5) suggests that, at a minimum, something must have entered visual working memory. An alternative, late candidate would be a more central executive mechanism retrieving information from working memory and linking it to the required response (see, e.g., Jolicoeur, 1999). In any case, the blink appears to affect working memory processes rather than representations.

### *Tunnel Vision*

The contraction of space found in Experiment 6 is reminiscent of what in the applied and fundamental research literature has become known as *tunnel vision*: the phenomenon that the functional (or useful) field of view shrinks under conditions of cognitive and attentional load (Chan & Courtney, 1993; Holmes, Cohen, Haith, & Morrison, 1977; Ikeda & Takeuchi, 1975; Kahneman, Beatty, & Pollack, 1967; Leibowitz & Appelle, 1969; Mackworth,

1965; Miura, 1990; Plainis, Murray, & Chauhan, 2001; Rantanen & Goldberg, 1999; Sanders, 1970; Webster & Haslerud, 1964; Williams, 1982, 1988, 1995; cf. Lavie & Tsal, 1994). However, most of these studies used a detection or discrimination task for the peripheral target, and, to my knowledge, none looked at localization performance. In turn, those who have looked at systematic biases in peripheral localization did not look at the effect of central task load (see, e.g., Müsseler et al., 1999; van der Heijden et al., 1999; though see Prinzmetal et al., 1998, for a hint of an effect). Moreover, those that did include a loading task often presented it visually, concentrated at fixation, and hence, the shrinkage of the functional field of view may have been due to visual attention being spatially highly focused in the first place, rather than due to cognitive load per se (Chan & Courtney, 1993; Holmes et al., 1977; Ikeda & Takeuchi, 1975; Mack, Tang, Tuma, & Kahn, 1992; Plainis et al., 2001; Prinzmetal et al., 1998; Williams, 1982). Interesting in this respect is that J. Ross et al. (1997) reported a compression of visual space not only around the current fixation but also around future saccade destinations. Assuming that attention is focused at the saccade destination, this may mean that objects are indeed attracted to the focus of attention, whether this lies centrally or peripherally (though see Suzuki & Cavanagh, 1997).

Finally, there is one study in which participants were required to localize stimuli and attention was manipulated such that it was assumed not to be in a highly focused state. Newby and Rock (2001) asked participants to judge the arm lengths of a relatively large centrally presented cross. On a critical trial, they presented an unexpected dot inside one of the quadrants demarcated by the cross. At the end of this inattention trial, participants were asked if they (a) had seen the dot and (b) could point to its location. They repeated the procedure a few trials later, assuming that because the dot localization task was now expected, observers would be in a state of distributed attention, rather than inattention, with respect to the dot. Newby and Rock found that, on those trials in which participants were aware of the dot, localization was worse on the inattention trials than on the distributed attention trials. Contrary to what I report here, they found a slight bias outward on the inattention trials, rather than toward fixation. However, this was likely due to the fact that the dot was always presented close to the center of the cross, and hence, there was not much room for it to be perceived as shifted further toward the middle.

Thus, the present study appears to be the first to show a systematic interaction between task load and foveal biases in localization. The use of large RSVP characters (as large as the cue display), which moreover were presented before the cue display, makes certain that the bias was not due to some sort of visual interference or due to attention being highly focused on the center of the screen. Instead, attentional load appears to induce a contraction of perceptual space. Note that tunnel vision may not be the right term in this respect. The term, as well as the findings that led to it, appears to reflect a shrinkage of the functional aperture of view: Observers fail to detect or discriminate a stimulus outside this aperture. In the present study, however, this did not appear to be the case. Observers could detect the stimulus but localized it closer to the center of the display. Thus, it appears to be a compression of space, rather than a vanishing of space. Future research would have to look at further characteristics of the spatial compression, such as its shape (Rantanen & Goldberg, 1999), its

dynamics (can observers actually see it shrink?), and when it might turn into expansion (Suzuki & Cavanagh, 1997).

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Received January 30, 2003

Revision received December 4, 2003

Accepted December 22, 2003 ■

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