Temporal constraints on conscious vision: On the ubiquitous nature of the attentional blink

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The attentional blink (AB) refers to the finding that observers often miss the second of two masked visual targets (T1 and T2, e.g., letters) appearing within 200–500 ms. Although the presence of a T1 mask is thought to be required for this effect, we recently found that an AB deficit can be observed even in the absence of a T1 mask if T2 is shown very briefly and followed by a pattern mask (M. R. Nieuwenstein, M. C. Potter, & J. Theeuwes, 2009). Using such a sensitive T2 task, the present study sought to determine the minimum requirements for eliciting an AB deficit. To this end, we examined if the occurrence of an AB depends on T1 exposure duration, the requirement to perform a task for T1, and awareness of T1. The results showed that an AB deficit occurs regardless of the presentation duration of T1, and regardless of whether there is a T1 task. A boundary condition for the occurrence of an AB was found in conscious awareness of T1. With a near-threshold detection task for T1, attention blinked when T1 was seen, but not when T1 was missed. Accordingly, we conclude that the minimum requirement for an AB deficit is T1 awareness.

Keywords: awareness, working memory, visual attention, temporal dynamics, attentional blink

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Introduction

Research on temporal attention examines the mind's ability to extract relevant information from stimuli that are distributed over time. A well-known phenomenon in this domain of research is the attentional blink (AB): the finding that observers often fail to perceive the second of two visual targets—appearing within 200–500 ms when both targets are masked and to be responded to (Raymond, Shapiro, & Arnell, 1992). In a recent study (Nieuwenstein, Potter, & Theeuwes, 2009), we examined if the presence of a T1 mask is truly necessary for the occurrence of an AB, an assumption that is shared by most researchers working on the AB and that is based on the finding that the AB deficit does not occur when T1 is not masked (i.e., T2 is not subject to a blink if the interval separating T1 and T2 is left blank or if T2 follows T1 at an SOA of less than 100 ms). Our reason for re-examining this matter was that the previous studies that showed no AB deficit with an unmasked T1 all used relatively easy T2 tasks, that is, tasks requiring identification or detection of a single letter or digit that was presented for 90–100 ms and followed by a mask (another character). Knowing that whether or not one observes an AB for T2 performance depends on the exposure duration of T2 (Arnell & Jolicoeur, 1999; Giesbrecht & Di Lollo, 1998; Sergent & Dehaene, 2004; Vogel & Luck, 2002), we conducted an experiment in which both the presence of a T1 mask and the exposure duration of T2 were varied. More specifically, we used a rapid serial visual presentation (RSVP) task that required identification of two letters separated either by distractors (digits) or by a blank screen, with the second letter followed immediately by a salient, high-contrast stimulus that served as the T2 mask (see Figure 1A). The crucial manipulation was that the exposure duration of T2 was varied in the condition without inter-target distractors, with T2 being presented either for 100 ms or for only

58 ms. Figure 1B shows the results for T2 performance plotted as a function of lag, the position of T2 relative to T1 (with each lag, the T1–T2 SOA increases with 100 ms). The results obtained with a 100-ms T2 duration showed a significant AB deficit only when T1 was masked, replicating the finding that has been interpreted as evidence that the AB is contingent on the presence of a T1 mask. Crucially, however, a substantial AB deficit was uncovered in the condition without inter-target distractors when the exposure duration of T2 was only 58 ms (see Figure 1B). Accordingly, we concluded that although the presence of a T1 mask increases the magnitude of the AB, it is certainly not a necessary requirement for the occurrence of an AB deficit.

In subsequent experiments, we sought to further characterize the defining condition for the occurrence of an AB by examining how the timing of successive targets affects their reportability. The starting point for these experiments was the finding that T2 was "spared" from the AB deficit when T2 appeared within less than 100 ms from T1 (i.e., the datapoint for lag 1 in Figure 1B), a finding that is typically explained in terms of a transient attentional enhancement effect elicited by T1, the idea being that if T2 follows closely after T1, it can benefit from the attentional boost intended for T1 (e.g., Bowman & Wyble, 2007; Nieuwenhuis, Gilzenrat, Holmes, & Cohen, 2005; Weichselgartner & Sperling, 1987). On the basis of this finding, we surmised that the AB deficit may be specific to conditions in which a sufficiently long temporal gap separates two successive targets, thus causing T2 to fall outside of the attentional episode elicited by the preceding target. Consistent with this hypothesis, we found that a T2 that appeared at lag 2 (i.e. at a 200 ms T1–T2 SOA) was spared from the AB deficit when an additional letter target appeared during the inter-target interval, thus creating a sequence of three successive targets that appeared at an SOA of 100 ms. In a similar fashion, another experiment showed that the AB deficit observed for a T2 that appeared at a 300-ms T1–T2 SOA was markedly attenuated when an additional target was presented 100 ms prior to T2, thus regenerating a T2 sparing effect, during the AB. Based on these findings, we concluded that the occurrence of an AB deficit is specific to conditions in which observers attempt to encode two targets that are separated by at least 100 ms, that is, when T2 is unlikely to benefit from the attentional episode elicited by T1. In this situation, accurate identification of a brief and strongly masked T2 would demand a second attentional response to enable the rapid acquisition of perceptual information (e.g., Alexander & Reinitz, 2000), but this response appears to be delayed, thus giving rise to a failure to perceive the identity of T2 (see also, Nieuwenstein, 2006; Nieuwenstein, Chun, Hooge, & Van der Lubbe, 2005; Weichselgartner & Sperling, 1987).

The present study

Compared to the AB observed with a masked T1, the AB observed with an unmasked T1 has the important

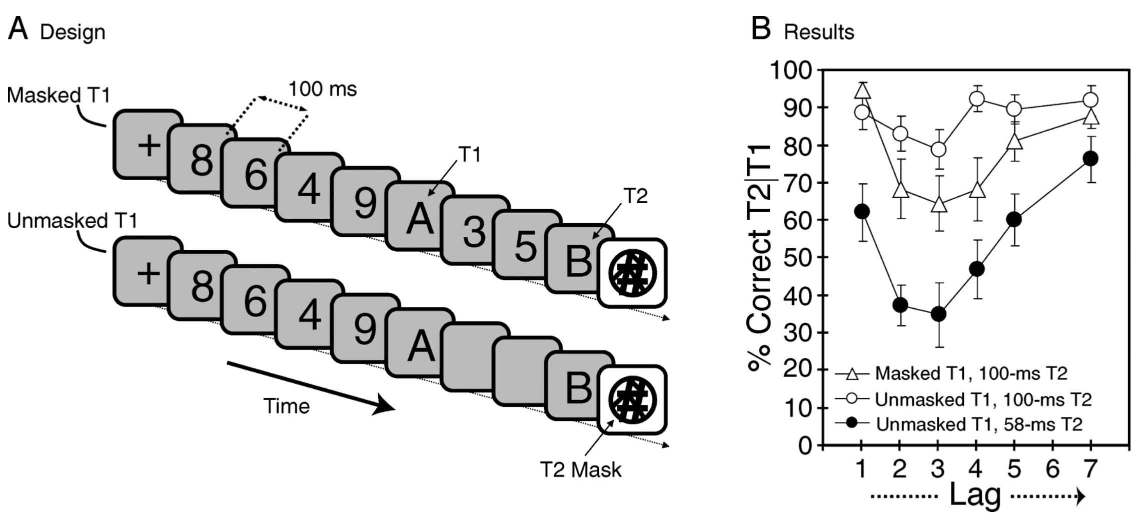

Figure 1. Design and results in Nieuwenstein et al. (2009, Experiment 1). A. Design of the experiment. Observers viewed RSVP sequences of digit distractors in which two letter targets were embedded. In the Masked T1 condition, T2 was always presented for 100 ms and the interval separating T1 and T2 was filled with distractors. In the Unmasked T1 condition, T2 was presented for 100 or 58 ms and the inter-target interval was left blank. The three types of trials were randomly intermixed. B. Results for identification of T2 for trials in which T1 was correctly identified (T2|T1) plotted as a function of Lag (i.e., the serial position of T2 relative to T1; for the conditions without inter-target distractors, the T1–T2 SOA increased with 100 ms for each lag). The results showed no significant effect of Lag when T1 was not masked and T2 was presented for 100 ms, whereas a 100-ms T2 did show an AB deficit when T1 was masked. However, when T2 was presented for only 58 ms, the results for the Unmasked T1 condition showed a substantial attentional blink effect for T2.

benefit that the observed fluctuations in T2 performance can only be ascribed to the way in which different stages of processing T1 affect perception of T2. In contrast, the effects observed with a masked T1 are open to several competing interpretations, with many different AB theories envisioning different mechanisms as to how the T1 mask interacts with processing of T1 and T2 (e.g., mask-induced suppression, conceptual masking, low-level masking, filter reconfiguration, competition for central processing resources, depletion of visual short-term memory capacity). Thus the AB observed with an unmasked T1 provides a novel and unique opportunity to study the operating characteristics and dynamics of processes involved in conscious visual perception, without the need to consider the variety of auxiliary effects that might come to play if T1 were to be masked.

In the present study, we sought to more closely circumscribe the root cause of the AB effect by examining its boundary conditions. To this end, we followed a condition-seeking approach in which we explored the effects of basic variations in the task we used in our previous study. More specifically, we began by examining if an AB still occurs when all distractors are omitted from the sequences shown in Figure 1A, thus leaving only T1, T2 and a trailing mask (a "skeletal" RSVP sequence, without a T1 mask). In subsequent experiments, we varied the exposure duration of T1 and the nature of the T1 task (identification, detection, no task), and, we used a near-threshold detection task as a means to manipulate and assess the effects of conscious awareness of T1.

Experiment 1

In our previous experiments (Nieuwenstein et al., 2009), the two letter targets followed after a sequence of digit distractors, with the interval separating the two targets left blank (see Figure 1A). Thus, although there were no distractors present in the interval separating T1 and T2, there were distractors present prior to the appearance of T1. In Experiment 1 we examined if the presence of distractors preceding T1 is required for the occurrence of an AB with an unmasked T1. To this end, we used what has been called a skeletal RSVP sequence that consisted only of T1, T2, and the T2 mask, thus excluding any potential for distractor interference during the encoding of T1.

Method

Twelve members of the Massachusetts Institute of Technology (MIT) community volunteered and were paid for participation. All had normal or corrected-to-normal vision, and none was color-blind. The stimuli used for T1 and T2 were uppercase letters (excluding I, O, W, and M) presented in a 20-point Helvetica font. These letters were presented in black on a dark gray background (RGB value 90 90 90). To mask T2, we used a pattern mask that was composed of a white square in which a circle, a pound sign, and some additional line segments were drawn in black (see Figure 2). The stimuli were presented on a 17-In. monitor that had a refresh rate of 75 Hz. The experiment was run on an Apple Macintosh G3 computer and it was programmed using MATLAB and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997).

Figure 2 shows the sequence of events on each of the trials. Each trial consisted of the successive presentation of a fixation cross, a blank interval, a first target letter (T1), a blank inter-target interval, a second target letter (T2), and the pattern mask. Observers began a trial by pressing the spacebar while they fixated the central fixation cross. After pressing the spacebar, the fixation cross remained on screen for another 400 ms. The offset of the fixation cross was then followed by a blank display (i.e., background only) of 160 or 640 ms, followed by the presentation of T1 for 40 ms. T1 was followed by a blank interval of 40, 120, 200, 280, 400, or 560 ms (yielding SOAs of 80, 160, 240, 320, 480, and 640 ms, respectively), the presentation of T2 (for 53 ms), and finally the pattern

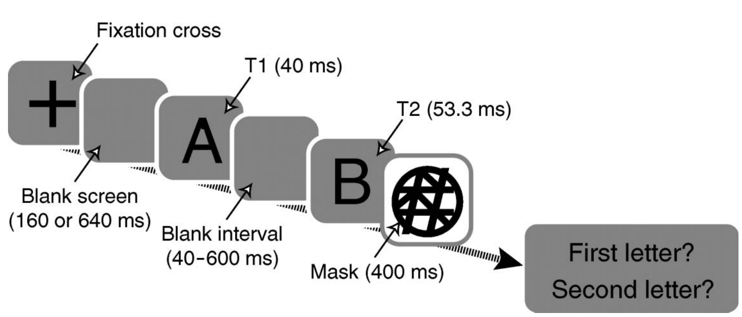

Figure 2. Sequence of trial events in Experiment 1. Observers had to identify two letters (T1 and T2), which were presented in isolation, with only T2 being followed by a backward mask.

mask which appeared for 400 ms in immediately following T2. At the end of each trial, the participants typed in the letters they saw using the keyboard. The experiment consisted of a single block of 288 trials, including 48 replications per SOA.

Results

The data from one observer were excluded from the analyses; this observer identified only 20% of the second targets while the average for the remaining observers was 79% correct. The analyses of T1 and T2 performance for the remaining observers showed no effects of the duration of the blank interval preceding T1 (all p's > .10). Accordingly, the data were collapsed across blank durations of 160 and 640 ms for our analyses of T1 and T2 performance. Analyses of T1 performance showed that T1 was correctly identified on 98.8% of the trials and that there was no effect of SOA on T1 identification, $F = 1.2$, $p = .31$. The analyses of T2 performance included only those trials on which T1 was correctly identified (T2|T1).

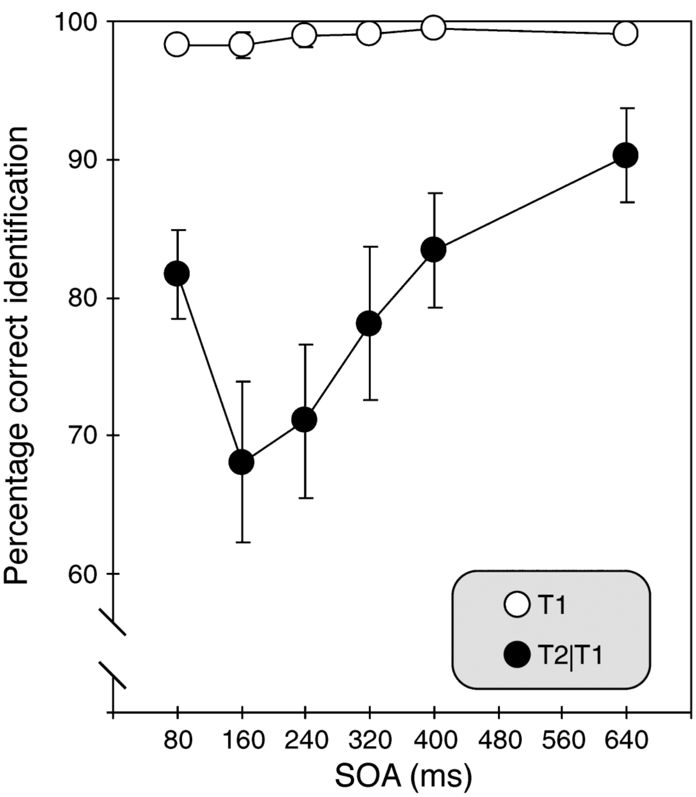

Figure 3. Results of Experiment 1. Identification performance for the first and second targets (T1 and T2) is plotted across stimulus onset asynchrony (SOA). The results for T2 performance are based on trials on which T1 was correctly identified, T2|T1. Error bars show standard errors of the mean.

As can be seen in Figure 3, identification of T2 showed a U-shaped function across SOA, with T2 sparing at the 80-ms SOA, followed by a drop in performance towards the 160-ms SOA, and then recovery up to the 640-ms SOA, $F(5, 50) = 9.1$, $MSE = 81.61$, $p < .001$.

Discussion

The results from Experiment 1 show that identification of an isolated letter causes an AB deficit, thus replicating the finding we obtained with an RSVP task in our previous study (Nieuwenstein et al., 2009). Indeed, the results nicely demonstrate the progression through different phases of the AB complex, with T2 performance showing an initial sparing effect, followed by an ensuing AB deficit and subsequent recovery across SOAs of 160–640 ms. Since this effect was obtained in the absence of any distractors that could interfere with processing T1, this finding confirms that distractor interference is not a necessary requirement for the occurrence of an AB effect.

Experiment 2

The results from Experiment 1 converge with our previous findings (Nieuwenstein et al., 2009) in showing that the basic task of identifying a briefly presented letter causes an AB deficit. In Experiment 2, we asked whether the occurrence of an AB deficit requires a brief exposure of T1. To address this question, we varied the exposure duration of T1 in a modified version of the skeletal task used in Experiment 1 (see Figure 2), with T1 being presented either for 50 ms or for nearly the full duration of the SOA leading up to T2. A key interest was to determine if the AB is contingent on a brief exposure of T1, or, whether it also occurs when T1 is viewed for a duration similar to the 200–300 ms duration of a typical eye fixation (e.g., Rayner, 1998).

Method

Experiment 2 was conducted at the Vrije Universiteit. Ten members of the VU-subjects pool volunteered to participate for a pay of €7.50 per hour. The task for the observers was to identify two successively presented letters. The letters included all letters of the alphabet, excluding I, O, M and W. The first letter, T1, was drawn in a black, 20-point Helvetica font and presented on a dark gray background. The second letter, T2, was drawn in a white 30-point Helvetica font, and presented on a dark gray background. The pattern mask used to mask T2 was the same as that used in Experiment 1, with the difference

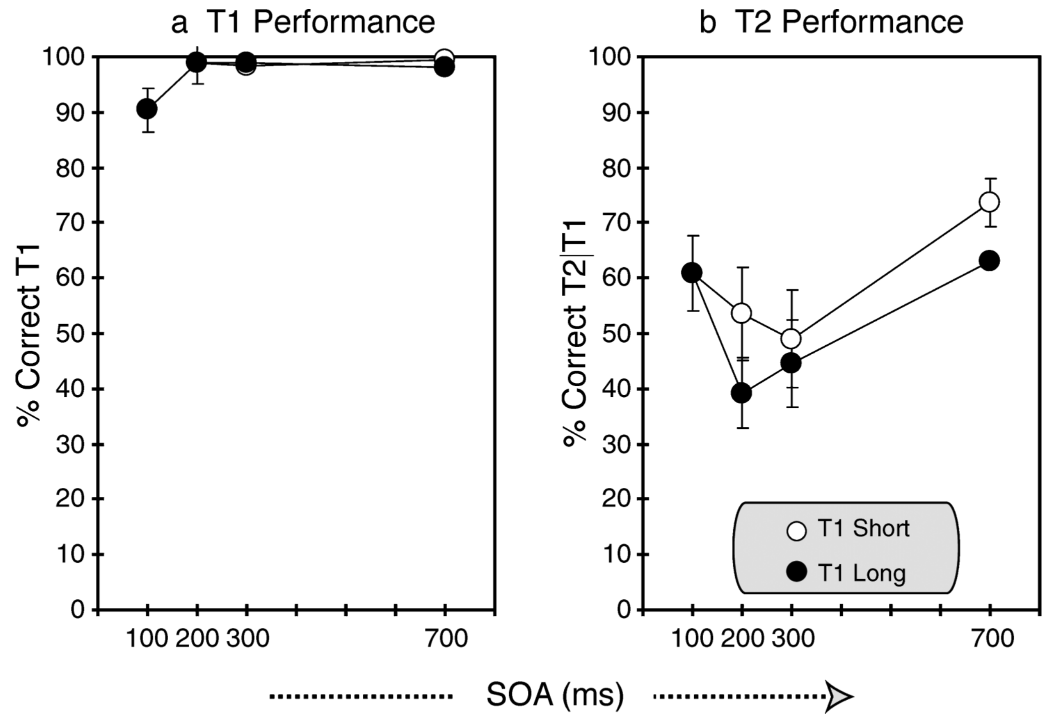

Figure 4. Results of Experiment 2. A. Performance for identification of T1. B. Performance for identification of T2. Open symbols show the results for trials in which T1 was presented for 50 ms, the closed symbols show performance for trials in which T1 was presented for the duration of the T1–T2 SOA minus 50 ms. Error bars show standard errors of the mean.

that the contrast was inverted so that the mask was drawn in white and displayed in a black square. The stimuli were presented on a 17-In. monitor that had a refresh rate of 120 Hz and the experiment was programmed in E-prime 1.2 (Psychological Software Tools, Pittsburgh, PA) and run on a PC.

Each trial began with a 500-ms presentation of a fixation cross, followed by the first letter, T1, which was presented either for 50 ms, or for the full duration of the SOA minus 50 ms. The SOA was 100, 200, 300 or 700 ms. This meant that for the condition in which T1 appeared for 50 ms, T1 was followed by a blank interstimulus interval of 50, 150, 250 or 650 ms. For the condition in which T1 appeared for the duration of the SOA minus 50 ms, T1 was presented for 50, 150, 250, or 650 ms, and it was always followed by a blank interstimulus interval of 50 ms. Thus, trials with a 100-ms SOA were identical in the two conditions. The duration of T2 was determined for each participant prior to beginning the actual experiment. In this procedure, we used the method of constant stimuli to determine the duration at which each observer reached about 80% accuracy for T2 when T1 was presented for 50 ms, and the T1–T2 SOA was 650 ms. The experiment consisted of a total of 210 trials, with 30 trials for each of the combinations of T1 duration (short versus long) and the SOAs of 200, 300, and 700 ms, and 30 trials for the condition with a 100-ms SOA. The different types of trials were randomly intermixed.

Results

The average presentation duration for T2 was 50 ms (range 25–67 ms). Figure 4 shows the results for Experiment 2. T1 was identified in 96.7% of the trials. Performance was worse at an SOA of 100 ms than at later SOAs, and whether T1 was presented for a short or a long duration had very little effect on T1 identification performance. The results for T2 performance revealed a T2-sparing effect at the 100-ms SOA, followed by an attentional blink. A repeated measures analysis using SOA (200, 300, and 700 ms) and T1 duration (short versus long) as factors revealed significant main effects of SOA and T1 duration, $F(2, 18) = 26.59$, $p < .001$, and, $F(1, 9) = 34.85$, $p < .001$, respectively. The interaction was not significant, $F(2, 18) = 1.33$, $p = .29$.

Discussion

The results from Experiment 2 show that a brief exposure of T1 is not required for the AB. In fact, the results show that a prolonged exposure of T1 leads to significantly worse, not better T2 performance. This finding makes an interesting contrast with our previous finding that the T2 sparing effect can be extended to a T1–T2 SOA of 200 ms when the inter-target interval is filled with an additional target instead of left blank (Nieuwenstein et al., 2009). Taken together, these findings suggest that the extended sparing effect seen with three consecutive targets is not driven by the prolonged presence of target information per se, but, rather, by the onset of new target stimuli. By implication, the present findings suggest that the extended sparing effect is most likely due to the fact the onset of a new (potentially) relevant stimulus prolongs the deployment of attention, thereby creating a situation in which successive targets can be encoded without suffering a blink of attention.

Experiment 3

In the previous two experiments, we found that an isolated to-be-identified letter produces an AB deficit regardless of whether it is in view for only 50 ms or for nearly the full interval leading up a trailing target. In Experiment 3, we asked if the occurrence of this effect requires that T1 is a target stimulus that has to be responded to. To address this question, we used a similar task as that used in Experiments 1 and 2, with the difference that T1 was always the same letter—an “O”—that was presented for 50 ms and that never had to be responded to. Thus, there was no task requirement associated with T1, rendering T1 the equivalent of an irrelevant exogenous cue that always appeared at the same location as the upcoming target, with an unpredictable interval separating T1 and T2.

Method

Experiment 3 was conducted at the Vrije Universiteit. Fifteen members of the VU subjects-pool volunteered to participate in the experiment, in return for pay of €7.50 per hour. The same equipment was used as in Experiment 2. The target could be any letter of the alphabet, excluding I, O, M, and W. The target mask was a pound sign that was drawn in black in a white outline frame. A trial began when the observer pressed the space bar of the keyboard. Each trial sequence began with a 400-ms blank interval, followed by the presentation of the letter “O” for 50 ms. After the offset of the “O”, there was a blank interval of 25, 200, or 700 ms followed by the presentation of the target. The target was presented for 58.3 ms for all participants and it was replaced by the mask which appeared for 400 ms. The task for the observers was to report the identity of the target. The experiment consisted of one block of 162 trials, with 54 replications for each T1–T2 SOA. The experiment began with 36 practice trials.

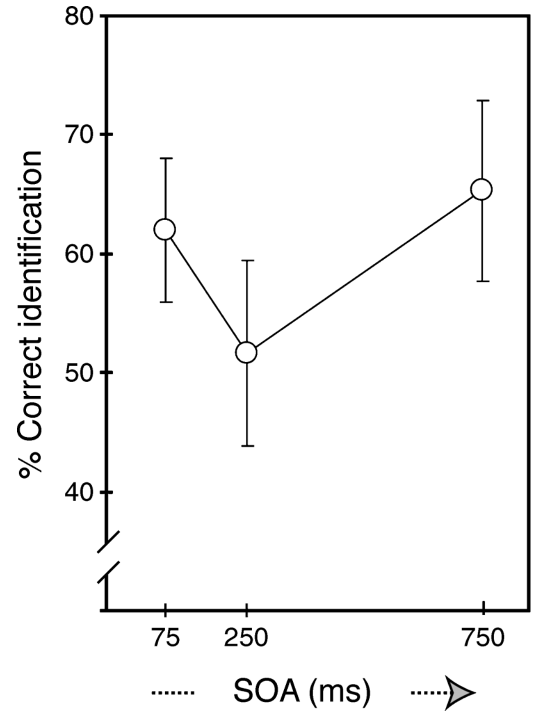

Figure 5. Results of Experiment 3. Performance for target identification in Experiment 3. Error bars show standard errors of the mean.

Results

Five observers terminated the experiment after the practice trials because the target identification task was too difficult for them. The results for the remaining 10 observers are shown in Figure 5. As can be seen in this graph, target identification performance showed the typical U-shaped AB function, with initial sparing followed by a blink and subsequent recovery. This was confirmed by a significant main effect of SOA, $F(2, 15) = 5.61$, $p = .013$, and significant pair-wise differences between identification performance at SOAs of 75 vs. 250 ms (M = 62.0 vs. M = 51.7% correct, respectively, $t[9] = 2.89$, $p = .018$) and at SOAs of 250 and 750 ms (M = 51.7 vs. M = 65.3% correct, respectively, $t[9] = 3.61$, $p = .006$).

Discussion

The results from Experiment 3 show that the occurrence of an AB deficit is not contingent on the requirement to respond to T1. Instead, the mere registration of a first

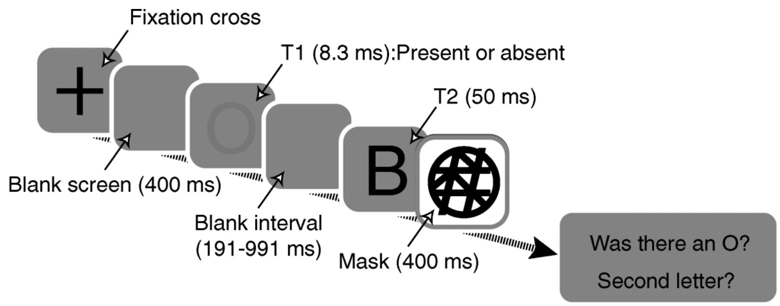

Figure 6. Design of Experiment 4. On each trial, subjects indicated whether the letter "O" was present or absent (the first target; T1), and they reported the identity of the second target (T2), a letter that was presented for 50 ms and followed by a pattern mask. The luminance contrast of T1 was set per observer at a level that allowed for approximately 50% detection. This threshold was determined for each individual observer using the method of constant stimuli. In this procedure, the stimulus sequences were the same as those used in the actual experiment, but observers only had to respond to the first target. The contrast of T1 was varied across trials and the average detection performance was examined to determine the contrast level at which observers could detect the target in approximately 50% of the trials.

stimulus appears to be sufficient to elicit an AB. Indeed, in our previous study (Nieuwenstein et al., 2009) we observed a similar effect in a single-target RSVP task in which the target—a letter masked by a pattern mask—followed at different SOAs from the last digit distractor in the RSVP sequence; the results showed an AB deficit timelocked to the onset of the last, unmasked distractor. Thus, an AB effect appears to be elicited whenever a stimulus reaches awareness, regardless of whether that stimulus is task relevant, and regardless of whether the onset of that stimulus is salient (as in Experiment 3) or pre-masked by a preceding RSVP sequence (as in Experiment 2 in Nieuwenstein et al., 2009).

Experiment 4

The results from the preceding experiments suggest that any visual stimulus that is consciously registered elicits an AB deficit. In Experiment 4, we tested this conjecture directly by examining if visual awareness is indeed a boundary condition for the AB. To this end, we used a near-threshold detection task for T1 (the letter "O" presented for 8.3 ms, at a luminance contrast set to allow for approximately 50% detection) and we compared trials on which T1 was missed or detected to examine how conscious awareness of T1 impacts identification of a trailing second target.

Methods

Experiment 4 was conducted at the Massachusetts Institute of Technology. Ten members of the MIT subjects-pool volunteered to participate in the experiment, in return for pay of $10 per hour. The first target was the letter "O" whereas the second target could be any letter of the alphabet, excluding I, O, M, and W. The targets were presented in a 20-point Helvetica font and they were presented in black on a dark gray background (RGB value 90 90 90). To mask T2, we used a pattern mask that consisted of a white square in which a circle, a pound sign, and some additional line segments were drawn in black (see Figure 6). The stimuli were presented on a 17-In. monitor that had a refresh rate of 120 Hz. The experiment was run on an Apple Macintosh G3 computer and it was programmed using MATLAB and the Psychophysics physics Toolbox (Brainard, 1997; Pelli, 1997).

Each trial began with an initial blank interval of 400 ms. On two-thirds of the trials, the blank was followed by the presentation of T1: the letter "O", presented for one frame—8.3 ms—at a luminance contrast set to allow for approximately 50% detection. This luminance contrast was determined prior to the actual experiment using the method of constant stimuli (see Figure 6). On the remaining 33% of the trials, T1 was replaced by a single-frame blank interval. The remainder of the trial sequence consisted of a blank inter-stimulus interval of 191.7, 391.7, 591.7 or 991.7 ms (yielding SOAs of 200, 400, 600 and 1000 ms), followed by the second target (T2) for 50 ms, and the pattern mask, which was presented for 400 ms. The experiment consisted of a total of 480 trials, with 80 T1-present and 40 T1-absent trials per SOA. At the end of each trial, observers indicated whether they had seen T1, and they had to report the identity of T2 by typing in the corresponding letter. Before beginning the experiment, observers viewed a number of trial sequences in which the contrast of T1 was reduced with each trial up to the point where T1 was absent because it was presented in the same shade of gray as the background. Having experienced what a low contrast T1 looks like, the observers began the calibration trials in which we used the method of

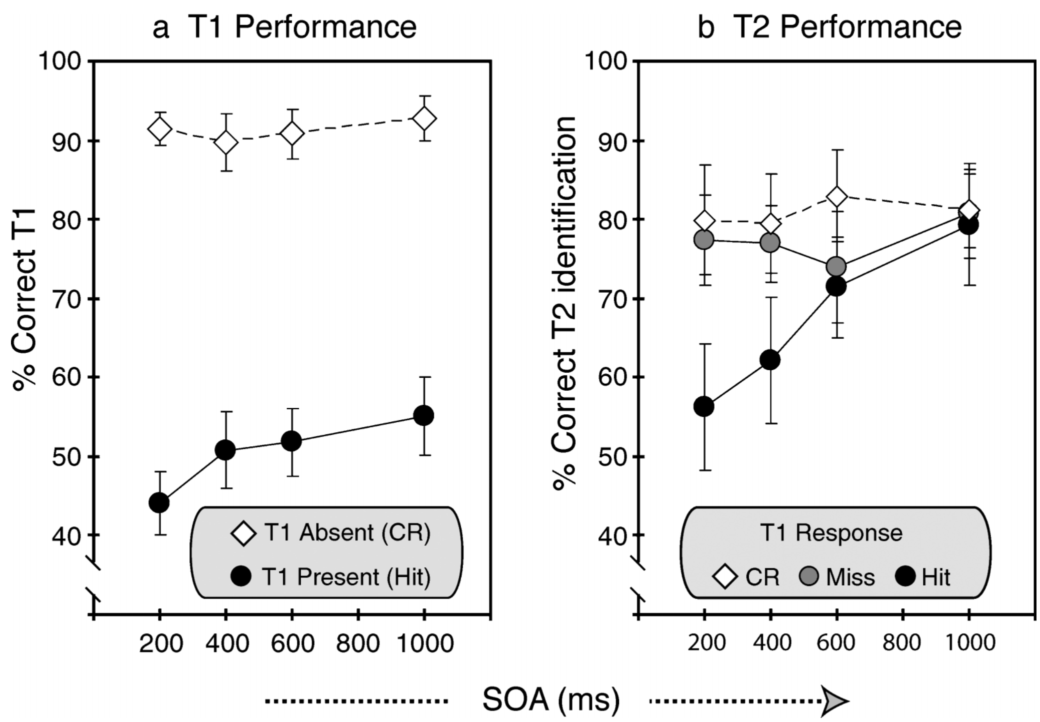

Figure 7. Results of Experiment 4. A. Responses for the first target (T1). Percentage of hits and correct rejections is shown across stimulus onset asynchrony (SOA) for the T1-Present and T1-Absent trials, respectively. B. Performance for identification of the second target (T2). Percentage correct identification is shown across SOA, for trials on which the T1 response was a correct rejection (CR), a miss, or a hit. Error bars show standard errors of the mean.

constant stimuli to determine the T1 luminance contrast that yielded a hit-rate of about 50%.

Results

Figure 7 shows the results for the T1 and T2 tasks. For the T1 task, the target was detected on 50.4% (range: 27–69%) of the T1-present trials, with the percentage of hits showing an increase across SOA, M = 44.1, 50.8, 51.8, 55.1% hits for SOAs of 200, 400, 600, and 1000 ms, respectively, $F(1, 9) = 17.6$, $p = .002$. The average false alarm rate for T1-absent trials was 9% (range: 2–26%), with little variation across SOA ($p = .62$). For the analysis of T2 identification, we compared the effects of SOA across trials on which the T1 response was a hit, a miss, or a correct rejection.[1] There was a significant interaction of SOA and T1 response type, $F(6, 54) = 5.16$, $p < .001$, with the main effect of interest being that T2 performance showed an attentional blink only when T1 was correctly detected. For these trials, T2 performance increased linearly with SOA, M = 56.2, 62.1, 71.4, and 79.3% correct for SOAs of 200, 400, 600, and 1000 ms, respectively, $F(1, 9) = 18.39$, $p = .002$. When T1 was missed, T2 identification showed no sign of interference time-locked to T1 onset ($F = 1.02$, $p = .4$, for the effect of SOA), indicating a qualitative difference between the effects caused by unseen and seen T1s. There was, however, a difference between T2 identification performance when T1 was missed versus when the T1 response was a correct rejection, M = 77.2 versus 80.9% correct T2 identification, respectively, $F(1, 9) = 6.16$, $p = .035$. This effect was mainly driven by the difference in performance at the 600-ms SOA; excluding this cell from the analyses rendered the difference between T1-miss and correct rejection trials non-significant, $F(1, 9) < 1$.

Discussion

The results from Experiment 4 suggest that awareness of T1 is both necessary and sufficient for the occurrence of an AB. In this regard, the results deviate from those obtained in previous AB studies that examined T2 performance as a function of whether a preceding backward masked T1 was correctly identified (Broadbent & Broadbent, 1987; Chun & Potter, 1995; Moroni, Boucart, Humphreys, Henaff, & Belin, 2000; see also, Nieuwenstein, 2006; Shapiro, Driver, Ward, & Sorenson, 1997). In particular, these previous studies found that the AB deficit was attenuated—not eradicated—following a backward masked target that was not correctly identified. In explaining this difference, an important issue that needs to be taken into account is that a failure to identify a backward masked T1 does not imply a lack of awareness. Instead, such a failure might arise due to problems in extracting the identity of T1 from a corrupted, but consciously accessible representation, or, from object-substitution causing participants to perceive the mask instead of the target (e.g., Giesbrecht & Di Lollo, 1998). In contrast, however, a failure to detect an isolated, near-threshold T1 can only be ascribed to the fact that the activation evoked by T1 failed to reach the threshold for awareness. Accordingly, we maintain that the difference in effects observed with seen and missed T1s in Experiment 4 is due to whether T1 did or did not elicit a noticeable sensation, the implication being that the occurrence of an AB is contingent on conscious awareness of T1 (but see Experiment 5).

Experiment 5

Although the results from Experiment 4 indicate that awareness of T1 is both necessary and sufficient for eliciting an AB, one might object that the combination of a detection and an identification task entails that observers need to switch from the task of looking for an "O" to the task of identifying any trailing letter, and that the observed T2 deficit reflects the amount of time that is needed to switch from one task to the other. Thus, according to this account, the observed AB deficit is not a proper AB in the sense it has little to do with interference between the actual processing of the two targets. The goal of Experiment 5 was to determine if task switching contributed to the AB observed in Experiment 4. To this end, we reran a second version of Experiment 4 that included a shorter SOA (i.e., 100 ms). The main issue of interest was to determine if there would be a T2 sparing effect. If so, then this would strongly argue against a task-switching account because this account predicts a monotonic improvement in T2 report across increasing SOAs, with no T2 sparing effect at the shortest SOA (e.g., Potter, Chun, Banks, & Muckenhoupt, 1998; Visser, Bischof, & Di Lollo, 1999).

Method

Experiment 5 was conducted at the Vrije Universiteit, Amsterdam, The Netherlands, using the same equipment as that used for Experiment 2. Fifteen members of the VU subjects-pool volunteered to participate in the experiment, in return for pay of €7.50 per hour. The stimuli used in Experiment 5 were identical to those used in Experiment 4, except for the following changes. The T2 task was a 3-alternative forced choice task that required observers to indicate whether an A, B, or C was presented. This letter was presented in gray (RGB 75/75/75) and it was masked by a pound sign that was drawn in a white square. Both T1 and T2 were presented in a 20-point Helvetica font, and the pound sign used for the T2 mask was drawn in a 36-point Helvetica font. The design and procedure used in Experiment 5 were identical to those of Experiment 4, except for two differences. The first difference was that we included SOAs of 100, 200, 400, 600, and 800 ms in Experiment 5 while the SOAs used in Experiment 4 were 200, 400, 600, and 1000 ms. A second difference was that we also used the method of constant stimuli to determine the presentation duration at which observers could identify T2 in about 80% of the trials. The experiment consisted of 7 blocks of 90 trials. As in Experiment 1, T1 was present on 2/3 of the trials, yielding 84 T1-present and 42 T1-absent trials per SOA. At the end of each trial, observers first indicated whether T1 was present or absent using two appropriately labeled keys on the numpad of the keyboard. Then, they indicated whether T2 was an A, B, or C, again using three appropriately labeled keys on the numpad. This brings us to the main reason for using only three letters for T2: This allows all responses to be recorded with the numpad, thus reducing the amount of time required to type in the two responses.

Results

The results from three participants were excluded from the analyses. Two of these participants scored exceptionally high on the T1-detection task (90 and 86% correct detection), leaving too few T1-miss trials to analyze the effects of SOA. A third participant was excluded because of an exceptionally high false alarm rate (64% false alarms on T1-absent trials). For the remaining observers, the average presentation duration of T2 was 58.3 ms (range 50–83.3 ms). Figure 8 shows the results for performance in the T1 and T2-tasks.

For T1-present trials, the average percentage hits for T1 was 44.8% (range 21–64%). There was a significant improvement in detection performance across SOAs of 100–300 ms (p = .002 and p = .018 for the differences between SOAs of 100 vs. 200, and 200 vs. 400 ms, respectively) followed by stable performance across SOAs of 400–800 ms (the Bonferroni-corrected p-values for each of the pair-wise comparisons between SOAs of 400–800 ms were all equal to 1). The average percentage of false alarms on T1-absent trials was 10.8% (range: 4–24%), with no significant effect of SOA (p = .46).

Performance for identification of T2 was analyzed using repeated measures analyses of variance with SOA (100, 200, 400, 600, or 800 ms) and T1 response type (hit, miss, or correct rejection) as factors.[2] These analyses revealed significant main effects of SOA and T1 response type, $F(4, 44) = 2.72$, $p = .041$, and, $F(2, 22) = 11.07$, $p < .001$, respectively, as well as a significant interaction of these factors, $F(8, 88) = 3.44$, $p = .002$. Further analyses examining the effect of SOA for each T1 response type

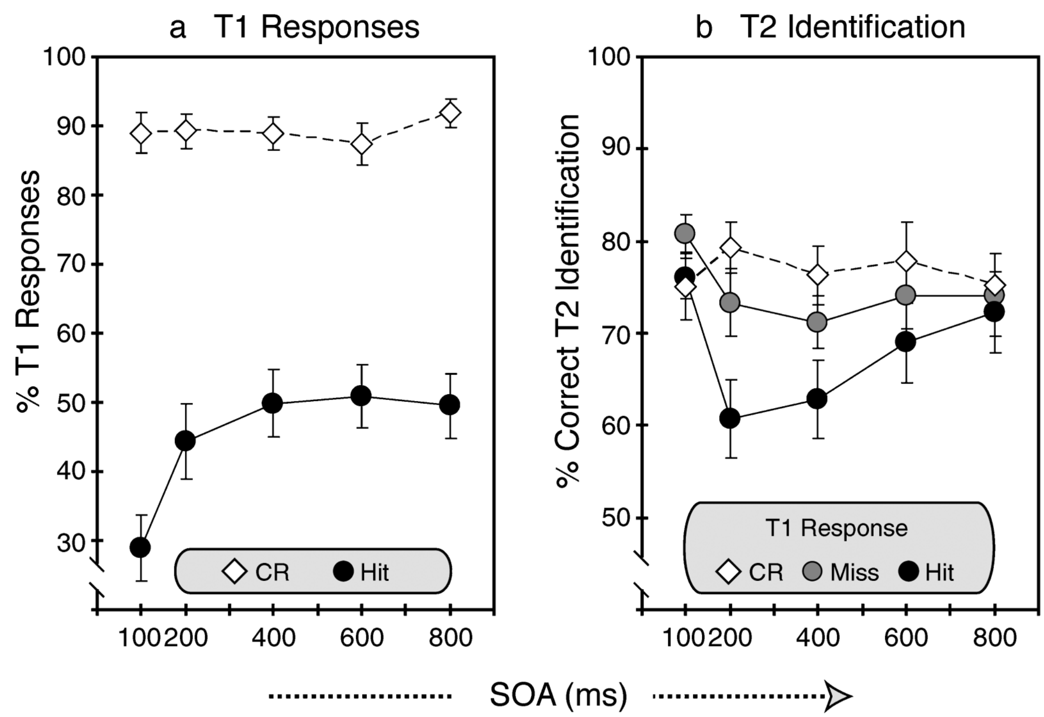

Figure 8. Results of Experiment 5. A. Responses for the first target (T1). Percentage of hits and correct rejections is shown across stimulus onset asynchrony (SOA) for the T1-Present and T1-Absent trials, respectively. B. Performance for identification of the second target (T2). Percentage correct identification is shown across SOA, for trials on which the T1 response was a correct rejection (CR), a miss, or a hit. Error bars show standard errors of the mean.

separately showed that there was a significant effect of SOA on T1-hit trials, $F(4, 44) = 5.46$, $p = .001$. In this case, T2 performance followed a U-shaped function across SOAs, with initial T2-sparing followed by an attentional blink and subsequent recovery. Trials on which T1 was present but not consciously detected (i.e., T1-miss trials) revealed an effect of SOA that approached significance, $F(4, 44) = 2.56$, $p = .051$. This effect was driven by the difference between performance at an SOA of 100-ms and the longer SOAs—there was a significant difference between performance at SOAs of 100 vs. 200 ms, $p = .004$, but there was no difference between performance at SOAs of 200–800 ms, all p's > .32. Thus, the results for T1-miss trials revealed an enhancement for T2 identification when T2 appeared within 100 ms from T1, followed by a flat performance function for SOAs of 200–800 ms. The results for T1-absent trials on which observers correctly judged T1 to be absent (correct rejections, CR) did not show a significant effect of SOA, $F < 1$. A comparison of T1-miss and T1-CR trials revealed a significant interaction of T1-response type and SOA, $F(4, 44) = 2.67$, $p = .045$ and non-significant effects of SOA and T1-response type (both p's > .22). At the 100-ms SOA, performance was enhanced for T1-miss trials, but there was a slight impairment in this condition for the later SOAs. Indeed, excluding the 100-ms SOA from the analysis rendered the interaction non-significant and it rendered the main effect of T1-response type significant, $F(1, 11) = 8.5$, $p = .014$), with M = 73% versus M = 77% correct for T2 performance on trials in which the T1-response was a miss or a hit, respectively.

Discussion

In spite of differences in procedure, equipment, and study population the results from Experiment 5 replicate those obtained in Experiment 4 in showing that a near-threshold T1 triggered an attentional blink when it was seen, but not when it went unnoticed. Indeed, a combined analysis of these two experiments that included the SOAs of 200, 400, and 600 ms (i.e. the SOAs that were used in both experiments) revealed no significant differences between the results of the two experiments.[3] An important addition of the results from Experiment 5 is that they show a clear T2 sparing effect, both when T1 was missed, and when T1 was seen. This finding suggests that the AB observed on T1-hit trials is unlikely to have been due to a task switching cost, as such a cost would be expected to prevent the T2 sparing effect. Instead, the results from Experiment 5 strengthen the case that the observed impairment in perception of T2 is a consequence of the processing involved in generating awareness of T1. Indeed, the finding that T1 miss trials revealed a T2 sparing effect without an ensuing blink can also be taken as support for this contention as it demonstrates that a

T1 that just misses awareness still captures attention but without producing an AB (for further evidence that unseen visual stimuli can produce a transient cuing benefit see McCormick, 1997; Mulckhuyse, Theeuwes, & Talsma, 2007; Wyble, Bowman, & Potter, 2009).

General discussion

The goal of the present study was to determine the minimum stimulus and task requirements for eliciting an AB deficit for perception of a very brief and strongly masked T2. Across five experiments, we found that the AB is a highly robust phenomenon that is elicited by even the most basic visual tasks. In particular, Experiments 1 and 2 showed that identification of an isolated letter causes a substantial AB deficit regardless of whether the letter is presented for only 50 ms or for 200–300 ms. These findings show that neither distractor interference nor a brief exposure is required for T1 to induce an AB. The results from Experiment 3 extend these conclusions in showing that an AB occurs even when there is no task to be performed for T1, thus suggesting that the mere registration of a first visual stimulus suffices to produce an AB for a trailing target. Indeed, the results from Experiments 4 and 5 suggest that awareness of the first of two stimuli is both necessary and sufficient for the occurrence of an AB deficit. In these experiments, we used an extremely brief and low contrast T1 to examine how T2 is affected by awareness of T1. The results showed an AB deficit when T1 was seen, but not when T1 was missed, thus leading us to conclude that awareness of T1 is a minimum requirement for the occurrence of an AB.

In demonstrating that an unmasked T1 produces an archetypal U-shaped AB effect regardless of the exposure duration and task relevance of T1, the present findings move well beyond the conventional wisdom that the occurrence of an AB deficit requires both a T1 task and mask (Raymond et al., 1992). The primary reason why our experiments revealed an AB under conditions where previous studies did not find this effect lies in the presentation parameters used for T2. In contrast to the T2 presentation parameters used in most previous AB research, we used a shorter exposure duration than the conventional duration of about 100 ms and we used a salient, high-contrast pattern stimulus as the T2 mask. The fact that these modifications have such a profound effect on the degree to which the T2 task is sensitive to the AB effect fits well with theories that assume that the locus of the AB deficit lies in a failure of timely attentional enhancement of T2-evoked activation (e.g., Nieuwenhuis et al., 2005; Nieuwenstein, 2006; Nieuwenstein et al., 2005, 2009; Wyble, Bowman, & Nieuwenstein, 2009). This is because the ability to identify a briefly presented and strongly masked visual stimulus requires the rapid extraction of visual information, and one of the well-established effects of attention is that it boosts the rate of information acquisition (e.g., Alexander & Reinitz, 2000; Carrasco & McElree, 2001). Accordingly, we conclude that the main reason why our experiments revealed an AB under conditions where none has been found before lies in the fact that the T2 task we used was more sensitive to the effects that T1 processing has on the allocation of attention required for perceptual identification of T2. Evidently, future research examining the boundary conditions for the occurrence of an AB would benefit from using such a sensitive T2 task.

Bearing in mind that the U-shaped function of T2 performance may reflect the variation in the availability and agility of attentional enhancement (see also, Nieuwenstein, 2006; Nieuwenstein et al., 2005; Vul, Nieuwenstein, & Kanwisher, 2008), we now turn to the issue of which aspects of T1 processing might be responsible for the fluctuations in T2 performance observed across T1–T2 SOAs of 100–600 ms. Regarding the initial phase of the AB complex—i.e., the T2 sparing effect—the present findings support the proposal that this effect occurs because a T2 that follows within less than about 100 ms from T1 can benefit from a transient attentional enhancement effect triggered by T1. This explanation of the T2 sparing effect is shared by several recently proposed computational models of the AB (e.g., Bowman & Wyble, 2007; Nieuwenhuis et al., 2005; Olivers & Meeter, 2008; Shih, 2008; Wyble, Bowman, & Nieuwenstein, 2009) and it derives from the idea that target detection evokes a similar transient attentional enhancement effect as that which is commonly observed in studies of spatial attentional capture (e.g., Nakayama & Mackeben, 1989; Wyble, Bowman, & Potter, 2009). Indeed, our results reveal several properties of the T2 sparing effect that closely resemble the properties of transient attentional enhancement commonly observed in studies of spatial attentional capture. To wit, our findings show the T2 sparing effect is time-locked to T1 onset (i.e., sparing was not extended when T1 was presented for a longer duration; Experiment 2), and that it occurs regardless of the nature of the T1 task (Experiments 3 and 5), and regardless of whether T1 is consciously perceived (Experiment 5). Each of these characteristics also holds true for the transient attentional enhancement effect elicited by an exogenous spatial cue; this effect too is transient and time-locked to the onset of the cue, it occurs even though the cue is task-irrelevant, and it occurs even when the cue is not seen (McCormick, 1997; Mulckhuyse et al., 2007; Wyble, Bowman, & Potter, 2009). Taken together, these similarities suggest that the T2 sparing effect may indeed be due to a similar transient enhancement effect as that which is observed in spatial cuing studies, thus arguing against the proposal that the occurrence of a T2 sparing effect is contingent on the requirement to identify both T1 and T2 (Dell'Acqua, Jolicoeur, Pascali, & Pluchino, 2007).

With regard to the question of which aspect of processing T1 is responsible for the second phase of the AB complex—i.e., the AB deficit—the finding of an all-or-none contingency between T1 awareness (i.e. reportability) and the occurrence of an AB deficit makes clear that the processes that mediate T1 awareness are directly responsible for this effect. Taken together with our previous findings showing attenuation of the AB when an additional target is presented just prior to T2 (Nieuwenstein et al., 2009) this finding poses an interesting challenge to the various models of the AB. While the present findings show that mere awareness of a first isolated stimulus suffices to trigger an AB, our previous findings suggest that the occurrence of this effect can be cancelled out by precuing T2, or by presenting a rapid sequence of successive targets, that is, by manipulations that involve adding more targets to the trial sequence! Indeed, most of the models do not appear able to explain this conundrum because they assume that the AB either derives from a disruptive effect of the T1 mask (refuted by the finding of an AB in the absence of a T1 mask), or from a fundamental limitation inherent to the processes required for target reportability (refuted by the finding that inserting additional targets into the inter-target interval attenuates the AB).

One model that is capable of explaining both why the AB can be evoked in the absence of post-T1 distractors and why additional targets can attenuate the effect is the episodic simultaneous type—serial token model proposed by Wyble, Bowman, and Nieuwenstein (2009). As most models of the AB, the eSTST model distinguishes between a fleeting but high-capacity stage of visual and conceptual representation (Stage 1), an ensuing stage of working memory consolidation (Stage 2) that is required for input from Stage 1 to be transformed into a durable, reportable representation, and an attentional enhancement mechanism that controls the transfer of information from Stage 1 to Stage 2. What differentiates eSTST from the other blink models is its assumption that the attentional enhancement mechanism is subject to competing inhibitory and excitatory inputs from Stage 2 and Stage 1, respectively. More specifically, eSTST assumes that while detection of a potentially relevant stimulus in Stage 1 triggers attentional enhancement—an effect implemented as a transient, non-selective amplification of activation in Stage 1, the ongoing processing of a target in Stage 2 has an inhibitory effect on attentional enhancement.[4] Thus, whether or not the model provides attentional enhancement to a target detected in Stage 1 depends on whether Stage 2 is occupied, such that more target input is needed to trigger attentional enhancement once Stage 2 is occupied by a preceding target. With this assumption, the model meets the challenge posed by our findings as it predicts that conscious perception (Stage 2 processing) of T1 causes the AB by inhibiting attention while this effect may be overruled by a rapid sequence of successive targets or by precuing T2 (because new targets work against Stage-2 induced inhibition through the excitatory connection between Stage 1 target representations and the attentional enhancement mechanism; for details about the model and simulations of the cuing effect and the extended sparing effect, see Wyble, Bowman, & Nieuwenstein, 2009). Under these conditions of extended sparing and temporal cuing, the model allows for multiple targets to be encoded in parallel, with only minor costs to reportability of the individual target identities. A final noteworthy finding that is also covered by eSTST model is the present finding of an all-or-none contingency between T1 awareness and the occurrence of an AB deficit. This finding is predicted by eSTST because it assumes that Stage 2 processing is initiated whenever a representation activated in Stage 1 reaches a certain activation threshold (see also, Sergent & Dehaene, 2004).

In summary, the present study shows that the AB is a highly robust effect that is triggered whenever a newly encountered stimulus enters visual awareness, regardless of the exposure duration and task-relevance of that stimulus, and regardless of whether that stimulus is masked. In this regard, the present findings defy the general consensus that has resulted from 20 years of research on the AB by demonstrating that neither a T1 mask, nor a demanding T1 task is in fact necessary for the elicitation of an AB deficit. Instead, mere perception of a first visual stimulus suffices to produce an archetypal U-shaped attentional blink effect consisting of both a T2 sparing effect and an ensuing AB deficit. Crucially, however, whether these effects are observed depends critically on the exposure duration of that stimulus, such that the behavioral manifestation of the AB evoked by an unmasked and familiar first stimulus requires a highly sensitive probe task. An interesting venue for future research will be to further explore the generality of the AB observed with an unmasked T1.

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Footnotes

[1]A meaningful analysis of T2 performance on trials with a false alarm for the T1 task (T1-FA trials) was not

possible because there were too few such trials, with only 2 out of 10 observers having at least 4 T1-FA trials per SOA and the remaining observers having at least one SOA at which they did not produce any false alarms for T1 absent trials.

[2] As in Experiment 4, there were too few T1-absent trials with a false alarm to allow for a meaningful analysis of the effects of SOA on T2 performance.

[3] This analysis also provided some reassurance regarding the null effect we observed in the T1 miss trials of both experiments. To wit, the more powerful combined analysis also showed no effect of SOA on T1 miss trials, with M = 74, M = 73, and M = 74% correct T2|T1 miss for SOAs of 200, 400, and 600 ms, respectively ($F = .11$, $p = .83$).

[4] eSTST does not assume a strict capacity limitation of Stage 2 processing. Rather, it assumes that any ongoing processing in Stage 2 will inhibit attention even when there are still sufficient resources available for processing another target (for more details, see Wyble, Bowman, & Nieuwenstein, 2009).

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