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**Attentional capture and engagement during the Attentional Blink:
A “camera” metaphor of attention**

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RUNNING HEAD: Attentional capture and engagement during the blink

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Abstract

Identification of a target is impaired when it follows a previous target within 500ms, suggesting that our attentional system suffers from severe temporal limitations. While “control-disruption” theories posit that such impairment, known as the Attentional Blink (AB), reflects a difficulty in matching incoming information with the current attentional set, “disrupted-engagement” theories propose that it reflects a delay in later processes leading to transient enhancement of potential targets. Here, we used a variant of the contingent-capture RSVP paradigm (Folk, Ester & Troemel, 2009) in order to adjudicate these competing accounts. Our results show that a salient distractor that shares the target color captures attention to the same extent whether it appears within or outside the blink, thereby invalidating the notion that control over the attentional set is compromised during the blink. In addition, our results show that during the blink, not the attention-capturing object itself but the item immediately following it, is selected, indicating that the AB manifests as a delay between attentional capture and attentional engagement. We therefore conclude that attentional capture and attentional engagement can be dissociated as separate stages of attentional selection.

Introduction

Selective processes allow us to extract information from stimuli that are distributed in space or in time. Spatial attention is limited in the size of the region from which information can be maximally sampled, and must therefore be shifted from one relevant location to another, which incurs a cost. Recent research has demonstrated severe limitations also in purely temporal attention, namely, in our ability to process successive events occurring at the same, attended location.

A striking illustration of such temporal attention limitations is the attentional blink phenomenon (henceforth, AB): observers often fail to report the second of two targets that appear within 200ms-500ms from each other (Raymond, Shapiro & Arnell, 1992). Such failure is often absent when the second target immediately follows the first one (henceforth, lag 1 sparing, e.g., Dux, Wyble, Jolicoeur & Del Acqua, 2014; Olivers & Meeter, 2008; Potter, Chun, Banks, & Muckenhoupt, 1998; Visser, Zuvic, Bischof & Di Lollo, 1999). The attentional blink is one of the most robust phenomena in the field of cognitive psychology, and many influential models of attention, working memory and consciousness attempt to explain it (e.g., Shih, 2008; Bundesen, Vangkilde & Petersen, 2015; Hommel et al., 2006; Raffone, Srinivasan & van Leeuwen, 2014; Taatgen, Juvina, Schipper, Borst & Martens, 2009).

Since the discovery of the attentional blink phenomenon, numerous studies have strived to determine which processes are disrupted during the AB (see Dux & Marois, 2009, Martens & Wyble, 2010 for recent reviews). Evidence from behavioral (e.g., Shapiro, Driver, Ward & Sorensen, 1997; Maki, Frigen & Paulson, 1997) and neuroimaging (e.g., Luck et al., 1996; Rolke et al., 2001) studies have shown that a

blinked target can be processed to a late, semantic level, leading to the notion that the AB does not reflect a deficit in perceptual processing but a structural capacity limitation. Accordingly, early theories suggested that T2 is fully processed but the central resource that is required to consolidate its representation into a reportable working-memory representation is limited and is not available for T2 until consolidation of T1 is complete (e.g., Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998).

However, more recent findings have posed serious challenges for this view. For instance, several studies (Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Kawahara, Kumada & Di Lollo, 2006; Olivers, Van der Stigchel & Hulleman, 2007) have shown that a target letter is identified better when it is the last of three consecutive targets than when it is separated from a first target (T1) by a distractor (henceforth T3 sparing). In addition, the blink is reduced when the second target (T2) directly follows a distractor (or cue) that shares one of the target-defining features (henceforth, “sparing of the cued T2”). For instance, in Nieuwenstein, Chun, van der Lubbe and Hooge's (2005) study, the targets were two red digits and the distractors were black letters. Identification of T2 was better when the distractor preceding it was in the task-relevant color, that is, when it was also red relative to when it was black. If resources were depleted by T1 processing, neither the third of three consecutive targets nor a cued T2 should have been spared from the blink.

In the past decade, new theories (e.g., Dell'Acqua, Dux, Wyble & Jolicœur, 2012; Di Lollo et al., 2005; Nieuwenstein et al., 2005), as well as several computational models (e.g., Bowman & Wyble, 2007; Olivers & Meeter, 2008; Taatgen, et al., 2009) have been put forward to account for the growing body of AB findings. While these differ in many

respects, in the present study we focus on one distinction between them. Specifically, we suggest that theories of the attentional blink fall into two broad categories that we refer to as *disrupted-control* theories and *disrupted-engagement* theories, depending on whether or not, respectively, they assume the blink to prevent T2 from triggering an attentional episode.

Disrupted-control theories of the Attentional Blink

An attentional episode is initiated whenever a target is detected, that is, when a match is found between the information extracted from the RSVP stream and the target template (Sperling & Weichselgartner, 1995; Wyble, Potter & Bowman, 2011). Disrupted-control theories suggest that while T2 may be processed up to the semantic level (especially if it benefits from attention being spatially focused on one RSVP stream, as is the case in most AB studies), target detection does not occur during the blink due to a failure of attentional control and as a consequence, T2 is not selected for report.

While the two notable exemplars from this category, the Temporary Loss of Control theory (Di Lollo et al., 2005) and the Threaded Cognition model (Taatgen et al., 2009) converge on the idea that the AB reflects the disruption of target detection, they markedly differ in their accounts as to why this occurs. According to the Temporary Loss of Control theory (Di Lollo et al., 2005), processing of a target leads to temporary *loss of executive control* over the attentional set. Once control is lost, the attentional set is exogenously reconfigured by following distractors, leading to impaired identification of a subsequent target when the set is tuned to a non-target property. Lag 1 sparing and T3 sparing occur because no reconfiguration occurs: the item(s) following the first target

match the original attentional set. Sparing of the cued T2 occurs because the cue reconfigures the attentional filter to a property that also characterizes the second target, thereby allowing for efficient selection of this target.

Nieuwenstein (2006) challenged this claim by showing that distractors presented in a different color than T2 nevertheless spared T2 from the blink when their color matched one of two possible target colors. He concluded that the attentional set is not exogenously reconfigured by the distractors following T1. However, it remains possible that cues that match the attentional set reinstate executive control, and therefore allow for efficient target detection.

The Threaded-Cognition model (Taatgen et al., 2009) attributes the AB to a control process that suspends target detection when there is an apparent conflict between target detection and memory consolidation. Specifically, they propose that the AB results from *overexertion of control*, implemented by a production rule that blocks target detection (of T2) during memory consolidation (of T1). Lag 1 sparing and T3 sparing occur because the appearance of new targets continuously triggers the target-detection production rule, such that the control production rule that protects consolidation never activates. Although the Threaded-Cognition model in its present form does not explicitly address the sparing-of-the-cued-T2 finding, it can account for it by postulating that a cue sharing the target-defining feature reactivates the target-detection rule, so that the target following it (T2) is selected.

As is clear from the foregoing description, both the Temporary Loss of Control theory (Di Lollo et al., 2005) and the Threaded-Cognition model (Taatgen et al., 2009) suggest that the AB disrupts processes responsible for matching incoming information to the

attentional set and that sparing of a cued T2 occurs because the cue reinstates such target-detection processes. This view is broadly consistent with De Jong, Berendsen and Cools's (1999) claim that susceptibility to disruptions can be substantially reduced if goal representations are reactivated by explicit cues.

Disrupted-engagement theories of the Attentional Blink

According to disrupted-engagement theories, the AB does not impair target-detection processes, but the transient attentional enhancement of T2 that is responsible for granting the information extracted from T2 access to working memory and consciousness. The Delayed Attentional Engagement model (henceforth, DAE; Nieuwenstein et al., 2005; see also Nieuwenstein, 2006), the episodic simultaneous type serial token model (henceforth, eSTST; Wyble, Bowman & Nieuwenstein's, 2009; see also Dux et al., 2014), and the Boost and Bounce account (Olivers and Meeter's, 2008; see also, Lunau & Olivers, 2010) belong to this category, as do also Chun & Potter's (1995) two-stage model and Raffone et al.'s (2014) Theory of Attention and Consciousness. Following Nieuwenstein (2005; see also Posner & Petersen, 1990) we refer to the process of attentional enhancement as “engagement”, which is mediated by a “blaster”, according to Wyble et al. (2009) and by a “booster” according to Olivers and Meeter (2008).

These disrupted-engagement theories differ in important respects. For instance, while the Boost and Bounce theory proposes that the AB serves to protect targets from interference by upcoming distractors, the role that the eSTST model ascribes to the AB is the parsing of incoming information into temporally distinct attentional episodes, so as to allow veridical binding of the representation of the item's identity (type) and the

representation of the spatiotemporal event (token). In addition, while some models assume limitations in the rate of encoding into visual short-term memory (e.g., Dell'Acqua et al., 2012; Dux et al., 2014; Wyble et al., 2011), other models assume structural limitations only in the number of items that can be held in this short-term store (e.g., Nieuwenstein & Potter, 2006; Olivers & Meeter, 2008).

However, from the perspective of our research question, these models share several important premises. First, they postulate that during the blink, target-defining features are detected and matched with the attentional set. Second, consistent with the contingent-capture account of attentional capture (Folk, Remington & Johnston, 1992; see also Folk, Leber & Egeth, 2008), they suggest that the appearance of a target-defining feature automatically triggers an attentional episode. Finally, they claim that during processing of the first target, redeployment of attentional engagement is not withheld but effectively delayed¹. Consequently, while the second target initiates an attentional episode irrespective of whether it appears inside or outside the blink, attentional engagement is not fast enough during the blink for this target to be selected and the item following it is selected instead. Thus, according to these theories, Lag-1 and T3 sparing occur because the critical targets are processed during the same attentional episode. Sparing of the cued T2 occurs because a target-color matching cue initiates an attentional episode, but as it follows prior selection of the first target, engagement is not immediately deployed to the cue, but rather to the second target following the cue, which is selected instead.

As is clear from the foregoing review, both disrupted-control and disrupted-engagement theories can explain the key findings from the AB literature and specifically, how and when a target can be spared from the blink. In order to adjudicate the two views

and determine whether the AB prevents the second target from initiating an attentional episode, new tests yielding differential predictions are therefore required. The goal of the present study was to provide such tests.

Experiment 1

A core difference between disrupted-control and disrupted-engagement theories concerns the type of item that is selected, following a relevant-color cue: disrupted-engagement theories predict that attention will be involuntarily deployed following the cue. Thus, *any* item following a relevant-color cue should be selected, irrespective of whether it is a target or a distractor. In contrast, disrupted-control theories predict that, as the cue reactivates target-detection processes, attention will be deployed *only to a target* that follows it, whereas a distractor that does not share the target's color should be efficiently rejected as a non-target. However, because previous studies examined the effects of a relevant-color cue only on *target* processing, these predictions could not be tested against each other. In the present experiment, we thus investigated the effects of a relevant-color cue on *distractor* processing.

We used a variant of the attentional-blink paradigm developed by Folk and colleagues (Folk et al., 2008, 2009) in which the blink occurs following involuntary attentional capture by a distractor rather than following selection of a first target (see also Ghorashi, Zuvic, Visser & Di Lollo, 2003; Visser, Bischof & Di Lollo, 2004; Zivony & Lamy, 2014, for similar findings). These authors showed that when searching for a target defined by its known color and embedded within an RSVP stream of letters drawn in various non-target colors, a colored outline square distractor enclosing a non-target letter

captures attention and produces an AB only when it shares the target's color. Here, we used two distractors (D1 and D2) and a single target (as did Folk et al., 2009; Zivony & Lamy, 2014). Each distractor could be either in the target color (henceforth, relevant-color distractor) or in a different color (henceforth, irrelevant-color distractor). D1-D2 lag was set to 2 across the experiment. Crucially, unlike in Nieuwenstein's (2006) study, D2-target lag was set to 2 instead of 1. Thus, D2 (which corresponds to the cue in Nieuwenstein, 2006) never immediately preceded the target.

Our main interest was in the condition in which the first distractor (D1) was in the relevant color. In line with the contingent-capture hypothesis (Folk et al., 2008) both disrupted-engagement and disrupted-control theories predict that the relevant-color D1 should capture attention and D2 should therefore fall within the blink. Thus, both predict disrupted processing of the relevant-color D2 following a relevant-color D1 (i.e., within the blink) but for different reasons. According to disrupted-engagement theories, D2 captures attention, but attentional engagement is delayed, which prevents D2 from being selected. According to disrupted-control theories, as detection of objects possessing the target-defining feature is disrupted, D2 doesn't capture attention and is not selected. Thus, the different theoretical accounts differ as to whether a relevant-color D2 captures attention within the blink.

However, while the two accounts do not differ with regard to their predictions pertaining to the processing of the second distractor itself, they make opposite predictions regarding processing of the non-target letter immediately following D2 (henceforth, D2+1). According to disrupted-engagement theories, D2 should trigger an attentional episode (that is, capture attention) when it is in the relevant color, but engagement should

be delayed, resulting in selection of D2+1. By contrast, according to disrupted-control theories, a relevant-color D2 should reactivate target detection processes, so that only items that share the target's feature (which is not the case of D2+1) should be selected.

We measured processing of the second distractor (D2) as the target-identification benefit when the relevant-color D2 enclosed the same letter as the target vs. a different letter (henceforth, D2-target compatibility effect, see Zivony & Lamy, 2014). Both accounts predict a compatibility effect outside the blink (irrelevant-color D1 condition) and a reduced compatibility effect inside the blink (relevant-color D1 condition).

Crucially, however, we measured processing of the non-target letter following the second distractor (D2+1) as the percentage of D2+1 identity intrusions (i.e., the probability of erroneously reporting D2+1 instead of the target letter). The disrupted-engagement account predicts more D2+1 intrusions when D2 is in the relevant than in the irrelevant color, which would indicate that the relevant-color distractor captured attention within the attentional blink. By contrast, disrupted-control theories predict no difference between these conditions.

Method

Participants

Participants were 22 (15 women) Tel-Aviv University undergraduate students who participated for course credit. The participants' mean age was 24.22 (SD=1.45). All reported normal or corrected-to-normal visual acuity and color vision.

Apparatus

Displays were presented in a dimly lit room on a 23" LED screen, using 1920X1280 resolution graphics mode and 120Hz refresh rate. Responses were collected via the computer keyboard. Viewing distance was set at 50 cm from the monitor.

Stimuli and design

The sequence of events on each trial is presented in Figure 1. The fixation display was a gray $0.2^\circ \times 0.2^\circ$ plus sign against a black background. The stimulus sequence consisted of an RSVP stream of 15 frames, each containing a letter enclosed in an outline shape, centered at fixation. The letters were randomly selected without replacement from a 22-letter set (all English alphabet letters, excluding I, O, W and Z). They were drawn in bold "Courier New" font and subtended 1.3° in height. Two color palettes were used. For some of the participants ($N = 14$), the letters in the stream were magenta [RGB: 255,0,255], yellow [RGB: 255,255,0] or green [RGB: 0,255,0]. The target letter was orange [RGB: 255,128,0] for half of these participants and cyan [RGB: 0,255,255] for the other half. For the rest of the participants ($N = 8$), the letters in the stream were cyan, yellow and magenta. The target letter was red [RGB: 255, 0, 0] for half of these participants and green for the other half. The outline shapes (3-pixel thick) were all gray [RGB: 128,128,128] except for D1 and D2, which were either orange or cyan for the first group, and were either red or green for the second group, that is, either in the relevant or in an irrelevant color. The D2 shape was always a square (1.5° in side) and D1 was a circle (1.5° in radius) for half of the participants and a square for the remaining half. This D1-shape manipulation was included to control for possible effects of repetition blindness (Kanwisher, 1987). The letter inside D2 was either the same as the target letter or different from it (compatible vs. incompatible). The letter inside D2+1 was never the

same as the target letter. Conditions of D1 color, D2 color and D2-target letter compatibility were equiprobable and randomly mixed.

The experiment included 20 practice trials followed by 480 experimental trials divided into 40-trial blocks. Subjects were allowed a self-paced rest between blocks.

Procedure

Each trial began with a 500ms fixation display followed by a 500ms blank screen and an RSVP stream of fifteen 50ms frames, each followed by a 50ms blank screen². D1 appeared randomly between the third and ninth positions, D2 always followed D1 by exactly two frames, and the target followed D2 by exactly two frames. Participants had to search for the target-color letter and ignore other stimuli. They had to report the target's identity as accurately as possible with no time pressure, by typing the corresponding key on a standard keyboard, and to guess if unable to identify the target. They were instructed to focus their gaze on the fixation point. A new trial began 500ms after response.

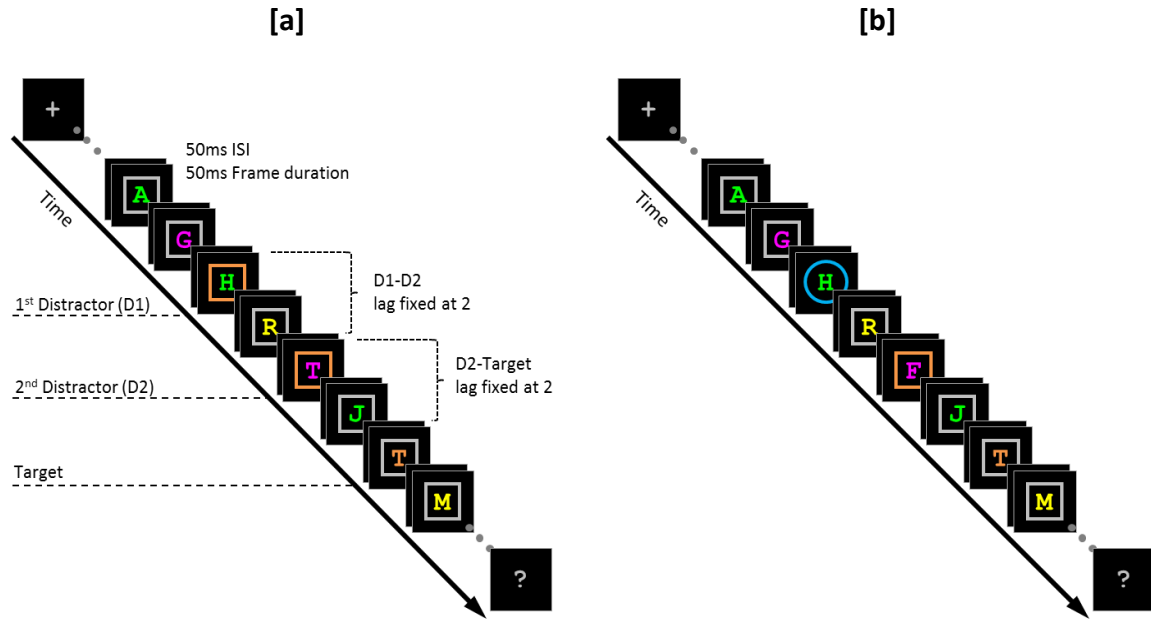


Figure 1. Illustration of the stimulus sequence in Experiment 1. D1 appeared randomly between the third and ninth positions in the RSVP stream. D2 always followed D1 by exactly two frames, and the target followed D2 by exactly two frames. The shape of D1 (square or circle) was manipulated between-subjects. The example in panel [a] corresponds to the orange-target, relevant-color square D1 and relevant-color D2 condition and the D2 letter is compatible with the target letter. The example in panel [b] corresponds to the orange-target, irrelevant-color circle D1 and relevant-color D2 condition and the D2 letter is incompatible with the target letter.

Results

In all experiments, analyses were conducted on arcsine square-root transformed mean accuracy rates³. Preliminary analyses revealed no significant effect involving color set, target color or D1 shape and the data was therefore collapsed across the conditions of these factors.

Attentional Blink (Table 1). When the first distractor (D1) was in the relevant color, it captured attention and produced an AB, as is clear from the reduced accuracy in the relevant- relative to the irrelevant-color D1 condition.

An analysis of variance (ANOVA) with D1 color (relevant vs. irrelevant) and D2 color (relevant vs. irrelevant) as within-subject factors revealed significant main effects of both D1 color, $F(1, 21) = 20.93$, $p < .001$, $\eta^2_p = .49$, and D2 color, $F(1, 21) = 6.94$, $p = .02$, $\eta^2_p = .24$. The significant interaction between these factors, $F(1, 21) = 23.45$, $p < .001$, $\eta^2_p = .52$, indicated that target identification accuracy was lower following a relevant- vs. an irrelevant-color D1, but only when D2 was in the irrelevant color, $F(1, 21) = 35.61$, $p < .001$, $\eta^2_p = .62$, and not when D2 was in the relevant color, $F < 1$, $\eta^2_p = .005$. This result replicates previous findings (Folk et al., 2009; Zivony & Lamy, 2014) showing that the identification impairments produced by a relevant-color D1 and a relevant-color D2 are not additive (see Zivony & Lamy, 2014 for a detailed discussion).

Table 1. Mean accuracy in Experiment 1 as a function of D1 color (relevant vs. irrelevant) and D2 color (relevant vs. irrelevant). Standard errors are presented in parentheses.

	Relevant-color D1	Irrelevant-color D1
Relevant-color D2	58.8% (4.4%)	59.8% (3.2%)
Irrelevant-color D2	56.1% (4.3%)	74.8% (3.4%)

D2 Compatibility effects⁴ (Figure 2a). Processing of the second distractor (D2) was disrupted during the blink: the compatibility between D2 and the target letter had a weaker effect inside than outside the blink (i.e., when D1 was in the relevant vs. in the irrelevant color, respectively).

We conducted an ANOVA with D1 color and D2 color as within-subject variables, and D2-target compatibility (i.e., the mean difference in accuracy between trials in which the letter enclosed in D2 was incompatible with the target letter and trials in which it was

compatible with it) as the dependent variable. The main effect of D2 color was significant, $F(1, 21) = 17.30$, $p < .001$, $\eta^2_p = .45$, while the main effect of D1 color was not, $F(1, 21) = 2.25$, $p = .15$, $\eta^2_p = .08$. The interaction between the two factors was significant, $F(1, 21) = 12.74$, $p = .002$, $\eta^2_p = .37$. Follow-up analyses revealed that the compatibility effect was larger in the relevant- than in the irrelevant-color D2 condition, but only outside the blink, that is, when D1 was in the irrelevant color, $F(1, 21) = 20.15$, $p < .001$, $\eta^2_p = .49$ ($M = 22.3\%$, $SE = 3.1\%$ vs. $M = 5.8\%$, $SE = 1.4\%$), and not inside the blink, that is, when D1 was in the relevant color, $F < 1$, $\eta^2_p = .01$ ($M = 11.4\%$, $SE = 1.7\%$ vs. $M = 10.4\%$, $SE = 1.8\%$). The compatibility effect, which significantly differed from 0 in all conditions, all $ps < .05$, was largest in the irrelevant-color D1/relevant-color D2 condition and did not differ between the remaining three conditions (Figure 2a).

D2+1 identity intrusions (Figure 2b). The item immediately following the second distractor (D2+1) was selected, thus suggesting that D2 captured attention during the blink but attentional engagement was delayed: there were more D2+1 intrusions when D2 was in the relevant vs. in the irrelevant color.

We conducted an ANOVA with D1 color and D2 color as within-subject variables and D2+1 intrusions as the dependent variable (i.e., the mean proportion of error trials in which D2+1 was reported instead of the target). The main effect of D2 color was significant, $F(1, 21) = 22.25$, $p < .001$, $\eta^2_p = .51$, indicating that participants were more likely to erroneously report the D2+1 letter as the target when D2 was in the relevant vs. in the irrelevant color. The main effect of D1 color was also significant, $F(1, 21) = 4.78$, $p = .04$, $\eta^2_p = .18$, with fewer D2+1 intrusions outside than inside the blink. The interaction between the two factors approached significance, $F(1, 21) = 3.55$, $p = .07$, $\eta^2_p = .14$.

Follow-up analyses indicated that identity intrusions following the relevant-color D2 were equally high whether D2 appeared inside or outside the blink (i.e., regardless of D1 color), $F < 1$, $\eta^2_p = .001$. In contrast, identity intrusions following the irrelevant-color D2 were higher when D2 appeared inside than outside the blink, that is, when D1 was in the relevant color relative to when it was in the irrelevant color, $F(1, 21) = 8.08$, $p = .009$, $\eta^2_p = .27$. Crucially, a planned comparison showed that even when D1 was in the relevant color (i.e., inside the blink), D2+1 intrusions were significantly more frequent following a relevant- than an irrelevant-color D2, $F(1, 21) = 40.51$, $p < .001$, $\eta^2_p = .66$, indicating that the relevant-color D2 initiated an attentional episode during the blink.

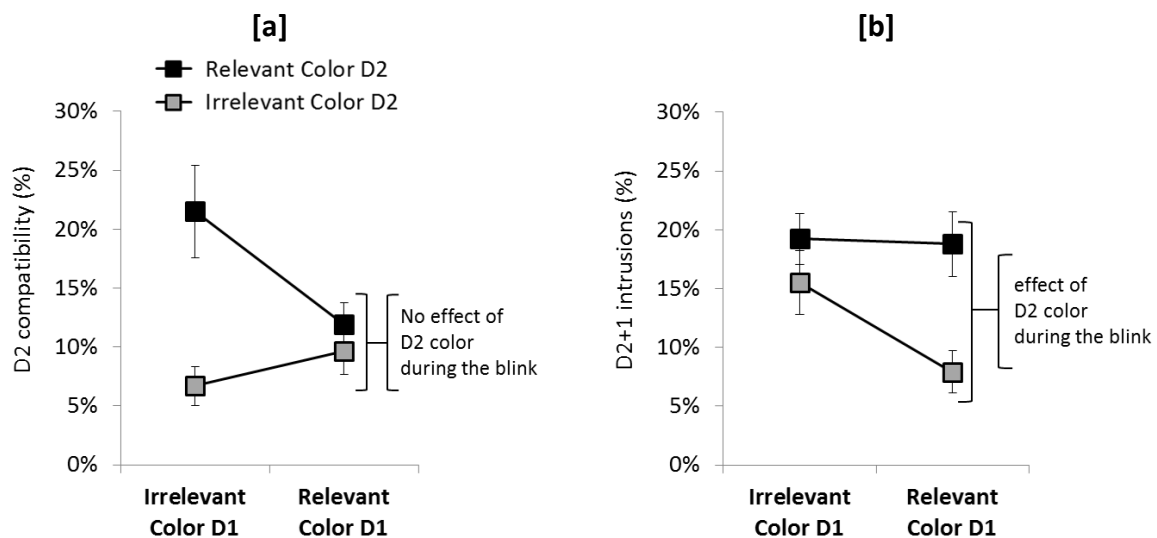


Figure 2. Results from Experiment 1 by conditions of D1 color (relevant vs. irrelevant) and D2 color (relevant vs. irrelevant). [a] Compatibility effect, measured as the mean accuracy on compatible D2-target trials minus the mean accuracy on incompatible D2-target trials. [b] D2+1 intrusions, measured as the mean percentage of error trials in which the letter following D2 (D2+1) was reported as the target. Error bars denote standard errors.

Discussion

Experiment 1 yielded three main findings. Analyses of D2-target letter compatibility effects revealed that D2 processing was impaired when D2 followed a relevant-color D1 relative to when it followed an irrelevant-color D1, confirming that the relevant-color D1 produced an attentional blink. Crucially, regardless of D1 color, D2+1 intrusions were more frequent following a relevant- than an irrelevant-color D2. This result indicates that D2 captured attention within the blink, in line with previous studies (Moore & Weissman, 2010; Wee & Chua, 2004; Zivony & Lamy, 2014) and that attentional engagement was delayed, such that D2+1 was erroneously selected instead, as predicted by disrupted-engagement theories. However, the results also showed that D2+1 intrusions following a relevant-color D2 were equally frequent inside as they were outside the blink. This finding that is not readily accounted for by current disrupted-engagement models of the AB and is further discussed in the General Discussion.

An unexpected finding is that D2+1 intrusions following an irrelevant-color D2 were more frequent when D2 appeared outside the blink than inside the blink. Chun (1997) showed that identity intrusions are redistributed during the blink, such that intrusions from the item preceding the target are more likely outside the blink (i.e., here, in the irrelevant-color D1 condition) than inside the blink (i.e., here, in the relevant-color D1 condition). Thus, the temporal proximity of D2+1 rather than attentional capture by D2 is more likely to account for our finding⁵. This account predicts that a similar rate of intrusions from the distractor preceding the target should be observed if it follows an irrelevant-color cue or no cue at all.

Experiment 2

In Experiment 1, the conclusions that attentional capture occurred during the blink and that attentional engagement was delayed both relied on the pattern of intrusions from the non-target that followed the relevant-color D2 (D2+1). Because the two processes were indexed by the same measure, we could not isolate the effects of the AB on each of them and specifically, we could not determine the extent to which attentional capture was modulated – if at all – by the attentional blink. The answer to this question is important because disrupted-engagement theories make the strong claim that detection of the target-defining features not only occurs during the AB but is *unaffected* by the AB. In contrast, disrupted-control theories postulate that the process of matching target-defining features with the attentional set is disrupted – thus predicting reduced attentional capture by relevant-color distractors during the blink.

Experiment 2 was therefore designed to provide separate measures of attentional capture and attentional engagement, as well as to provide converging evidence for the findings of Experiment 1. The following changes were introduced in order to meet these goals. First, we adopted a different manipulation of the attentional blink. In Experiment 1, we compared a relevant- and an irrelevant-color D1 conditions; attentional capture by D1 was expected in the former condition, which served as our blink-present condition, and not in the latter, which served as our no-blink condition. In Experiment 2, we relied on the lag effect, which is the hallmark of the attentional blink. Specifically, D1 was always in the relevant color, and the lag between D1 and D2 was manipulated (either 2 or 7). For lag 2, D2 was inside the blink, whereas for lag 7 it was outside the blink.

On each trial, the display contained two streams instead of just one (see Figure 3). D2 appeared in the frame immediately prior to the target (D2-target lag 1) instead of being separated from it by a non-target (D2-target lag 2). Thus, the target appeared during the attentional episode triggered by D2 and as such, when it appeared at the same location (Visser et al., 1999) we expected it to be spared from the AB produced by D2 (i.e., to enjoy lag-1 sparing). Both D1 and D2 appeared unpredictably in one of the two streams and D2 could therefore appear either at the same location as the target or at the alternative location, in which case it preceded the non-target letter opposite the target (henceforth, simultaneous non-target, e.g., the letter “R” in figure 3).

The letter enclosed in D2 and the target letter were both randomly selected from the letter set instead of having a 50% probability of being the same, such that their identities were no longer correlated. Accordingly, we used D2 identity intrusions instead of D2 compatibility as our measure of attentional engagement in D2. We expected D2 intrusions to be reduced during the blink, a result that is predicted by both control- and disrupted-engagement theories and is in line with the findings of Experiment 1 (see the introduction to Experiment 1 for a justification of this prediction).

In Experiment 1, a larger D2+1 intrusion rate during the blink when D2 was in the relevant vs. in the irrelevant color was taken to index delayed attentional engagement following capture by D2. In Experiment 2, the comparison between simultaneous non-target intrusions when D2 (at the non-target’s location) was in the relevant vs. in the irrelevant color served the same purpose. A higher rate of simultaneous non-target intrusions in the former condition would indicate that, as found in Experiment 1, D2

captured attention inside the blink but attentional engagement was delayed and deployed only to the letter following it.

Crucially, our design allowed us to specifically measure the effect of the AB on spatial attentional capture by the relevant-color D2. Our measure of such capture was a benefit in target identification when the relevant-color D2 appeared at the same location as the target vs. at the opposite location (henceforth, target vs. non-target location conditions, e.g., Folk et al., 1992; Posner, 1980). If detection of the target-defining feature is disrupted during the blink, this spatial benefit should be smaller when D2 appears within than outside the blink, but if attentional capture is unaffected by the blink, as predicted by disrupted-engagement theories, no such difference should be observed.

Method

Participants

Participants were 16 (12 women) Tel-Aviv University undergraduate students (mean age=25.06, SD=4.31) who participated for course credit. All reported normal or corrected-to-normal visual acuity and color vision.

Apparatus, Stimuli, design and Procedure

The apparatus, stimuli, design and procedure were similar to those of Experiment 1, except for the following differences: the stimulus sequence consisted of two RSVP streams of 16 frames each, appearing 3° to the left and right of fixation. The letters in each stream were randomly selected without replacement with the sole restriction that the same letter could not appear in both streams at the same frame. The target letter was red [RGB: 190, 40, 40] for half of the subjects and green [RGB: 0,150,0] for the other half. The remaining letters were magenta [RGB: 140,0,175], lilac [RGB: 105,105,255] or yellow [RGB: 220,205,115]. D1 was always in the relevant color, whereas D2 was in the relevant color (40% of trials), in the irrelevant color (40% of trials) or remained gray (no-D2 baseline condition, 20% of the trials). The experiment included 10 practice trials followed by 500 experimental trials divided into 50-trial blocks. Each frame appeared for 42ms and was followed by a 58ms blank screen. This reduction in exposure duration was introduced in order to reduce overall accuracy, and therefore allow for more identity intrusions. The target appeared in the 10th, 12th or 14th position. D2 always appeared immediately prior to the target, and D1 appeared at either 2 or 7 frames prior to D2 (corresponding to D1- target lag 3 or 8, respectively). The target, D1 and D2 appeared unpredictable and independently in either the left or the right stream. Thus, D1 appeared either at the same or a different location relative to the target, and so did D2. Participants were specifically instructed to focus their gaze on the fixation point.

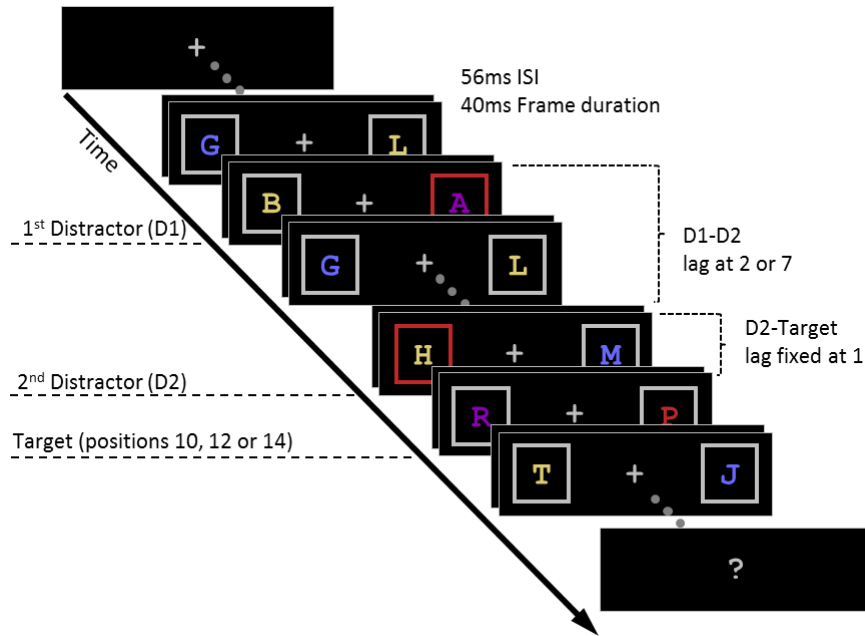


Figure 3. Illustration of the stimulus sequence in Experiment 2. The target appeared at temporal position 10, 12 or 14. D2 preceded the target by exactly one frame and D1 preceded D2 by either 2 or 7 frames. This example corresponds to the red-target, relevant-color D2, and non-target D2 location condition.

Results

All data were collapsed across conditions of target color and D1 location because preliminary analyses revealed no significant effects involving these variables.

Attentional Blink by D1 (Table 2). The first distractor (D1) captured attention and produced an attentional blink, as is clear from the reduced accuracy at the short relative to the long D1-target lag.

We conducted an ANOVA with D1-target lag (lag 3 vs. lag 8) and D2 color (D2 absent, relevant-color, irrelevant-color) as within-subject variables, and accuracy as the dependent variable. The main effect of lag was significant, $F(1, 15) = 16.11, p < .001, \eta_p^2 = .51$, and so was the main effect of D2 color, $F(2, 30) = 30.65, p < .001, \eta_p^2 = .67$. The

interaction between the two factors was significant, $F(2, 30) = 6.77, p = .004, \eta^2_p = .31$, indicating that the effect of lag was significant in the D2-absent condition, $F(1, 15) = 17.45, p < .001, \eta^2_p = .53$, as well as in the irrelevant-color D2 condition, $F(1, 15) = 40.92, p < .001, \eta^2_p = .73$, but not in the relevant-D2 condition, $F(1, 15) = 1.42, p = .25, \eta^2_p = .08$. As in Experiment 1, these findings indicate that D1 produced an AB, while also replicating previous findings (Folk et al., 2009; Zivony & Lamy, 2014) showing that the identification impairments produced by a relevant-color D1 and a relevant-color D2 are not additive.

[Table 2 here]

Attentional Capture by D2 (Table 2). Attentional capture was measured as the spatial benefit when D2 appeared in the same stream as the target vs. the opposite stream. The relevant-color D2 captured attention to the same extent within and outside the blink.

We conducted an ANOVA with D1-target lag (lag 3 vs. 8, corresponding to D1-D2 lag 2 vs. 7, for which D2 was within vs. outside the blink produced by D1, respectively) and D2 color (relevant-color vs. irrelevant-color) as within-subject variables, and D2 location effects (i.e., the mean difference in accuracy when D2 appeared in the same location as the target relative to when it appeared in the different location) as the dependent variable. D2-absent trials were excluded because location benefits could not be calculated in this condition.

The main effect of D2 color was significant, $F(1, 15) = 62.98, p < .001, \eta^2_p = .80$, with a significant location effect when D2 was in the relevant color [$M = 21.4\%$, $SE = 3.0\%$, t-test against zero: $t(15) = 7.12, p < .001$] and no significant effect when it was in

the irrelevant color [$M = 1.6\%$, $SE = 1.7\%$, t-test against zero: $t(15) = 0.92$, $p = .36$]. The main effect of lag was not significant, $F(1, 15) = 1.09$, $p = .32$, $\eta^2_p = .06$, and neither was the interaction between the two factors, $F < 1$, $\eta^2_p = .0001$. Importantly for the present purposes, when D2 was in the relevant color, the effect of lag was not significant, $F < 1$, $\eta^2_p = .02$ ($M = 22.4\%$ vs. $M = 20.4\%$, for lag 3 vs. lag 8, respectively), indicating that the attentional blink did not modulate spatial capture by the relevant-color D2.

D2 intrusions (Figure 4). Processing of the second distractor (D2) was disrupted during the blink: there were fewer intrusions from the D2 letter inside than outside the blink (i.e., for the short than for the long lag).

We calculated D2 intrusion rates (i.e., the mean proportion of error trials in which the letter inside D2 was reported instead of the target), while excluding all trials in which there was any ambiguity as to the source of the error, namely, when the letter inside D2 was the same as the letter opposite the target or as the letter immediately following the target⁶. We conducted an ANOVA with D1-target lag (lag 3 vs. lag 8), D2 color (relevant vs. irrelevant) and D2 location (same vs. different relative to target) as within-subject variables, and D2 intrusions as the dependent variable.

All main effects were significant, $F(1, 15) = 37.76$, $p < .001$, $\eta^2_p = .71$, $F(1, 15) = 39.87$, $p < .001$, $\eta^2_p = .73$, and $F(1, 15) = 15.76$, $p = .001$, $\eta^2_p = .51$, with more intrusions for lag 8 than for lag 3, when D2 was in the relevant color than in the irrelevant color and when it appeared at the target's location than at the alternative location, respectively.

The interaction between lag and color was also significant, $F(1, 15) = 12.81$, $p = .003$, $\eta^2_p = .46$. Follow-up analyses revealed that there were more D2 intrusions when D2 was in the relevant than in the irrelevant color for both lags, but this difference was larger for

lag 8, $M = 27.5\%$, $SE = 3.4\%$ vs. $M = 9.8\%$, $SE = 2.2\%$, $F(1, 15) = 47.18$, $p < .001$, $\eta^2_p = .75$ than for lag 3, $M = 12.1\%$, $SE = 2.0\%$ vs. $M = 5.1\%$, $SE = 1.0\%$, $F(1, 15) = 13.37$, $p < .001$, $\eta^2_p = .47$. This result replicated the finding of Experiment 1 showing that processing of the letter enclosed in the relevant-color D2 was impaired during the blink.

The interaction between lag and D2 location was also significant, $F(1, 15) = 11.15$, $p = .004$, $\eta^2_p = .42$, indicating that the preponderance of D2 intrusions on same- relative to different-location trials was larger when D2 appeared outside the blink, $F(1, 15) = 23.56$, $p < .001$, $\eta^2_p = .61$, than inside the blink, $F(1, 15) = 5.11$, $p = .04$, $\eta^2_p = .24$.

Finally, the two-way interaction between D2 color and D2 location was not significant, $F < 1$, $\eta^2_p = .03$, and neither was the three-way interaction, $F < 1$, $\eta^2_p = .01$.

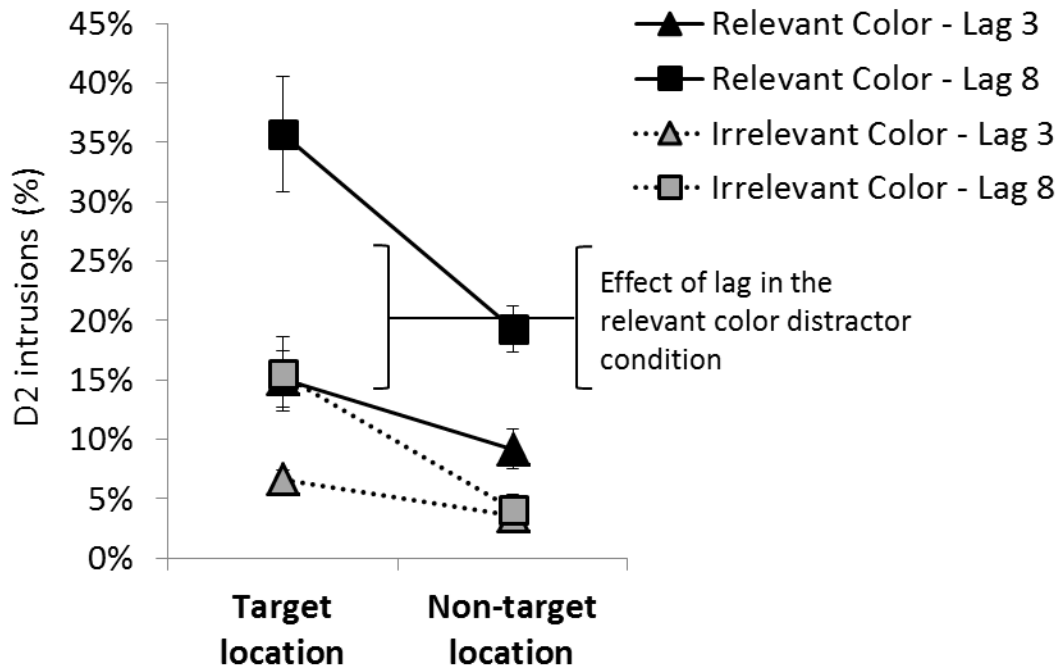


Figure 4. Percentage of D2 intrusions as a function of D1-target lag, D2 color and D2 location in Experiment 2. Error bars denote standard errors.

Simultaneous non-target letter intrusions (Figure 5). Intrusions from the distractor letter immediately following D2 (in the location opposite the target) were larger when D2 was in the relevant than in the irrelevant color, indicating that attentional capture occurred during the blink and engagement was deployed to the following stimulus.

We calculated simultaneous non-target letter intrusion rates (i.e., the mean proportion of error trials in which the letter opposite the target was reported instead of the target). Again, trials in which the source of the error was ambiguous were excluded, namely, when the simultaneous non-target was the same as the letter that appeared immediately prior or after the target. These intrusion rates were entered as a dependent variable in an ANOVA with D1-target lag (lag 3 vs. lag 8), D2 color (relevant vs. irrelevant) and D2 location (same vs. different relative to target, i.e., when it appeared in the target vs. non-target locations) as within-subject variables.

All main effects were significant, $F(1, 15) = 5.30, p = .03, \eta^2_p = .26$, $F(1, 15) = 33.59, p < .001, \eta^2_p = .69$, and $F(1, 15) = 12.37, p = .003, \eta^2_p = .45$, with more intrusions for lag 8 than for lag 3, when D2 was in the relevant color than in the irrelevant color and when it appeared at a different location relative to the target than at the same location, respectively.

The interaction between D2 color and D2 location was also significant, $F(1, 15) = 11.08, p = .004, \eta^2_p = .42$. Follow-up analyses revealed that the likelihood of reporting the simultaneous non-target was higher when D2 was in the relevant than in the irrelevant color, but only when D2 appeared at the location of the simultaneous non-target, $F(1, 15) = 25.99, p < .001, \eta^2_p = .63$ ($M = 8.6\%$, $SE = 1.1\%$ vs. $M = 3.1\%$, $SE = 0.6\%$), and not when it appeared at the same location as the target, $F < 1, \eta^2_p = .0001$ ($M = 2.7\%$, $SE =$

0.8% vs. $M = 2.5\%$, $SE = 1.1\%$). None of the other interactions were significant, all p s $> .25$.

Finally, simultaneous non-target letter intrusion rates in each condition of D1-target lag, D2 color and D2 location were compared to the baseline intrusion rate, calculated as the frequency of intrusions when D2 was absent. Baseline intrusion rates did not differ across lags, $t(11) = 0.66$, $p = .51$, and were therefore collapsed across the 2 lag conditions ($M = 1.2\%$). Simultaneous non-target letter intrusion rates were higher than the baseline when D2 was in the relevant color and at the non-target location, in both D1-target lag conditions, both p s $< .0001$, and did not differ from the baseline in all other conditions, all p s $> .14$.

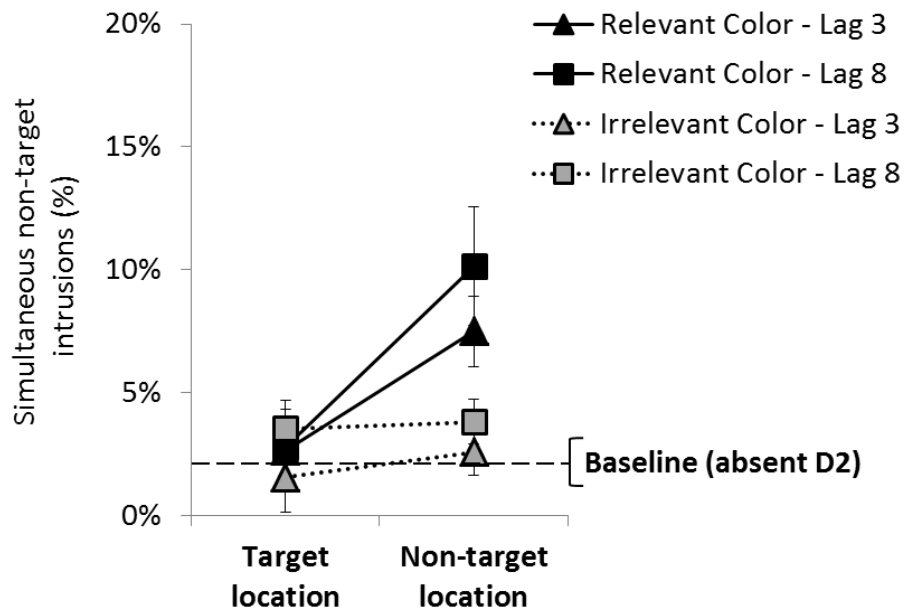


Figure 5. Percentage of simultaneous non-target intrusions as a function of D1-target lag, D2 color and D2 location in Experiment 2. The results show that there were more simultaneous non-target intrusions when D2 was in the relevant than in the irrelevant color, only when D2 was in the non-target location and regardless of whether D2 was inside or outside the blink. Intrusion rates were significantly higher than baseline only when D2 was in the relevant color at the non-target location, on both D1-target lag conditions.

Discussion

The key novel finding of Experiment 2 is that, as predicted by disrupted-engagement theories, a relevant-color D2 captured attention to the *same extent* whether it appeared inside or outside the blink. Target identification was better when D2 appeared at the target's location than at the location of the non-target only when D2 was in the relevant color, in line with the contingent-capture account (e.g., Folk et al., 2008). Crucially, this spatial benefit was not modulated by D1-D2 lag, that is, by the blink. In addition, the main findings from Experiment 1 were replicated: (1) the AB impaired processing of D2, as indicated by the reduced rate of intrusions inside the blink than outside the blink from the letter enclosed in the relevant-color D2 (D2-intrusions); (2) the AB delayed attentional engagement following attentional capture by the relevant-color D2: the letter *following* D2 (the simultaneous non-target) produced more intrusions when D2 captured attention (relevant-color D2) than when it did not (irrelevant-color D2). Thus, Experiment 2 also provides strong support for disrupted-engagement theories.

An additional finding requires some explanation. D2 intrusions were higher when D2 appeared at the same location as the target than at the non-target location. Botella, Barriopedro and Suero (2001) have proposed a model to explain the high likelihood of identity intrusions from temporally adjacent distractors. According to their model, whenever the target's temporal position is detected but its identity is not fully processed, subjects resort to a sophisticated guessing mechanism aimed at maximizing their accuracy. This mechanism takes into account all the processed (and therefore available) response features, but also weighs in the temporal position of the distractor relative to the

target, such that temporally adjacent distractors are selected more often. Botella et al.'s model can readily be extended to include a spatial component. Whenever the location of the target is processed but its identity is not, distractors that share the target's location are more likely candidates. Accordingly, if a fully processed distractor does not share the target's location, subjects assume that this distractor's identity is an unlikely candidate, hence the reduced rate of intrusions by this distractor.

Experiment 3

Experiments 1 and 2 established that the attentional blink triggered by a relevant-color distractor (D1) does not weaken the ability to detect target-matching features but delays attentional engagement: a relevant-color distractor (D2) captured spatial attention to the same extent whether it appeared within or outside the blink, yet the pattern of intrusion errors revealed that during the blink, not D2 itself but the item immediately following it, was selected. However, both the Temporary Loss of Control (Di Lollo et al., 2005) and Threaded Cognition (Taatgen et al., 2009) models rely on findings from the classical AB paradigm, in which the AB is triggered by goal-directed allocation of attention to a first *target*. As several studies showed that T1 type modulates the severity of the AB (e.g., Jolicœur, 1998, 1999; Ouimet & Jolicœur, 2007; Visser & Ohan, 2007), it could be argued that disruption of target detection might occur only when a first *target* is selected and maintained in working memory – and not when attention is captured by a distractor, as was the case in our experiments. We tested this possibility in Experiment 3 by replacing D1 with a target.

Method

Participants

Participants were 16 (10 women) Tel-Aviv University undergraduate students (mean age=22.81, SD=2.07) who participated for course credit. All reported normal or corrected-to-normal visual acuity and color vision.

Apparatus, stimuli, design and procedure

The apparatus, stimuli, design and procedure were similar to those of Experiment 2 (see Figure 6), except for the following differences. The two RSVP streams included 20 stimuli each instead of 15 and consisted of letters (selected from the same pool as in Experiments 1 and 2) as well as digits ranging from 1 to 9. The letters in each stream were randomly selected without repetition, whereas the digits were randomly selected with repetition. Participants were instructed to search for a pair of target digits (T1) and one target letter (T2) all defined by their known color (red for half of the participants and green for the other half). T1 was a pair of digits that appeared simultaneously in both streams, and were unpredictably either identical (e.g. "5" and "5") or different (e.g. "5" and "6"). T1 appeared 3 or 8 frames prior to T2 (T1-T2 lag 3 or 8). T2 appeared randomly in the 12th, 14th or 16th positions.

On 80% of the trials, a colored distractor (in either the relevant color or an irrelevant color) appeared immediately prior to T2, either in the same stream as T2 (same-location condition) or in the opposite stream (different-location condition). The remaining 20% of the trials were absent-distractor trials. Participants were asked to first report the identity of the target letter (T2) and then report whether the two digits (T1) were identical or different. The two tasks were performed without time pressure. The experiment included 10 practice trials followed by 300 experimental trials divided into 50-trial blocks.

Several steps were taken in order to better control the sources of identity intrusions. First, while the two characters that appeared simultaneously in non-target frames were always one digit and one letter (i.e., they were never of the same category), the T2+1 frame always included two digits, which ensured that identity intrusions from the frame following the target, which make up the majority of identity intrusions in RSVP paradigms (e.g., Botella et al., 2001; Chun, 1997) could not occur. In addition, on half of the trials the stimulus inside the distractor frame was a letter, whereas the simultaneous non-target was a digit, and the reverse was true on the other half of trials. Thus, the distractor and simultaneous non-target never shared the same category and intrusions on any given trial could therefore originate from only the one or the other, independently.

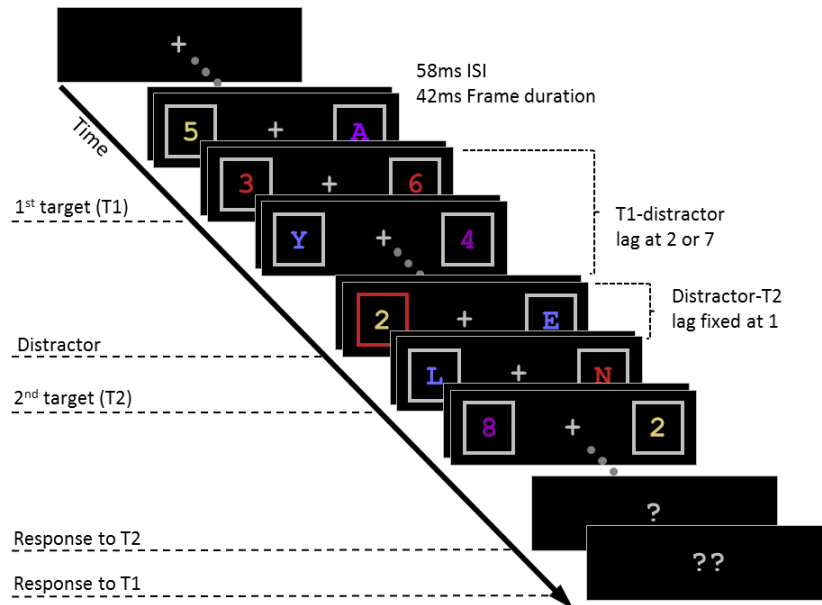


Figure 6. Illustration of the stimulus sequence in Experiment 3. The 2nd target (T2) appeared at positions 12, 14 or 16. The distractor preceded the target by exactly one frame, and the 1st target (T1) preceded the target by either 2 or 7 frames. This example corresponds to the red-target, relevant-color distractor, different-location condition. The character inside the distractor was a digit in this example, whereas the simultaneous non-target was a letter.

Results

Preliminary analyses revealed no significant effects involving the between-subject variable of target color (red vs. green), and we therefore collapsed the data across conditions of target color. Overall accuracy for T1 reports was 62%, which was significantly higher than chance, $t(15) = 4.01$, $p = .001$, and did not differ across conditions of T1-T2 lag, $F(1,15) = 1.43$, $p = .24$, $\eta^2_p = .08$, or distractor color, $F < 1$, $\eta^2_p = .02$. We remind the reader that T1 reports were provided after T2 reports, which could explain the relatively low accuracy rate. Trials in which the response to T1 was inaccurate were nevertheless included in the analyses reported below (but the pattern of results was the same when these trials were excluded).

Attentional Blink by T1 (Table 3). T1 produced an AB., as is clear from the reduced T2 accuracy for the short relative to the long T1-T2 lag.

We conducted an ANOVA with T1-T2 lag (lag 3 vs. lag 8) and distractor color (absent distractor, relevant color, irrelevant color) as within-subject variables, and T2 accuracy as the dependent variable. The main effect of T1-T2 lag was significant, $F(1, 15) = 28.40$, $p < .001$, $\eta^2_p = .65$, and so was the main effect of distractor color, $F(2, 30) = 13.94$, $p < .001$, $\eta^2_p = .48$. The interaction between the two factors was significant, $F(2, 30) = 4.52$, $p = .01$, $\eta^2_p = .23$, indicating that the AB was smallest when the distractor color was relevant, although it was significant in all distractor-color conditions (all $ps < .001$).

[Table 3 here]

Attentional Capture by the distractor (Table 3). The relevant-color distractor captured attention (as measured by the spatial benefit when this distractor appeared in the same stream as the target vs. in the opposite stream) and to the same extent within and outside the blink.

We conducted an ANOVA with T1-T2 lag (lag 3 vs. 8, corresponding to T1-distractor lag 2 vs. 7, for which the distractor was within vs. outside the blink produced by T1, respectively) and distractor color (relevant vs. irrelevant, that is, excluding absent-distractor trials) as within-subject variables, and distractor-location effects as the dependent variable. The main effect of distractor color was significant, $F(1, 15) = 25.01$, $p < .001$, $\eta^2_p = .62$, with a significant location effect when the distractor was in the relevant color [$M = 14.2\%$, $SE = 2.4\%$, t-test against zero: $t(14) = 5.96$, $p < .001$] and no significant effect when it was in the irrelevant color [$M = -2.9\%$, $SE = 3.1\%$, t-test against zero: $t(11) = -0.59$, $p = .56$]. The main effect of T1-T2 lag was not significant, and neither was the interaction between the two factors, both $F_s < 1$. Crucially, when the distractor was in the relevant color, the effect of T1-T2 lag was not significant, $F < 1$, $\eta^2_p = .0001$ ($M = 14.9\%$ vs. $M = 16.4\%$, for lag 3 vs. lag 8, respectively), indicating that the relevant-color distractor captured attention to the same extent whether it was inside or outside the blink.

Distractor intrusions (Figure 7). Processing of the non-target letter within the relevant-color distractor was disrupted during the blink: there were fewer intrusions from this letter when it appeared inside than outside the blink (i.e., for the short than for the long lag).

We calculated distractor-intrusion rates (i.e., the probability of erroneously reporting the letter inside the distractor instead of the target), excluding all trials in which the distractor was a digit. We conducted an ANOVA with T1-T2 lag (lag 3 vs. lag 8), distractor color (relevant vs. irrelevant) and distractor location (same vs. different relative to the target) as within-subject variables, and distractor intrusions as the dependent variable. The main effect of distractor color was significant, $F(1, 15) = 14.13$, $p = .002$, $\eta^2_p = .48$, and interacted with T1-T2 lag, $F(1, 15) = 8.35$, $p = .01$, $\eta^2_p = .35$. Follow-up analyses revealed that the relevant-color distractor produced more intrusions than the irrelevant-color distractor only for lag 8, $F(1, 15) = 19.55$, $p < .001$, $\eta^2_p = .56$ ($M = 18.7\%$, $SE = 2.8\%$ vs. $M = 5.4\%$, $SE = 1.0\%$) and not for lag 3, $F(1, 15) = 1.12$, $p = .30$, $\eta^2_p = .05$ ($M = 10.9\%$, $SE = 2.1\%$ vs. $M = 7.3\%$, $SE = 1.3\%$).

The main effect of distractor location approached significance, $F(1, 15) = 4.01$, $p = .06$, $\eta^2_p = .21$. However, unlike in Experiment 2, this effect interacted with distractor color, $F(1, 15) = 4.65$, $p = .049$, $\eta^2_p = .25$. Follow-up analyses indicated that when the distractor was in the irrelevant color, there were more distractor intrusions in the same- than in different-location conditions, $F(1, 15) = 10.65$, $p = .005$, $\eta^2_p = .42$ ($M = 8.9\%$, $SE = 1.3\%$ vs. 3.6% , $SE = 0.8\%$), whereas there was no such difference in the relevant-color distractor condition, $F < 1$, $\eta^2_p = .001$ ($M = 15.2\%$, $SE = 3.1\%$ vs. $M = 14.1\%$, $SE = 1.8\%$). This result suggests that the letter inside the relevant-color distractor was processed and confused with the target *regardless* of its position, while the letter inside the irrelevant-color distractor was reported mainly when it was in the target's position. No other effect was significant: The main effect of T1-distractor lag was not significant,

$F(1,15) = 1.48$, $p = .24$, $\eta^2_p = .08$, and neither were the interaction between T1-distractor lag and distractor location and the three-way interaction, both $F_s < 1$.

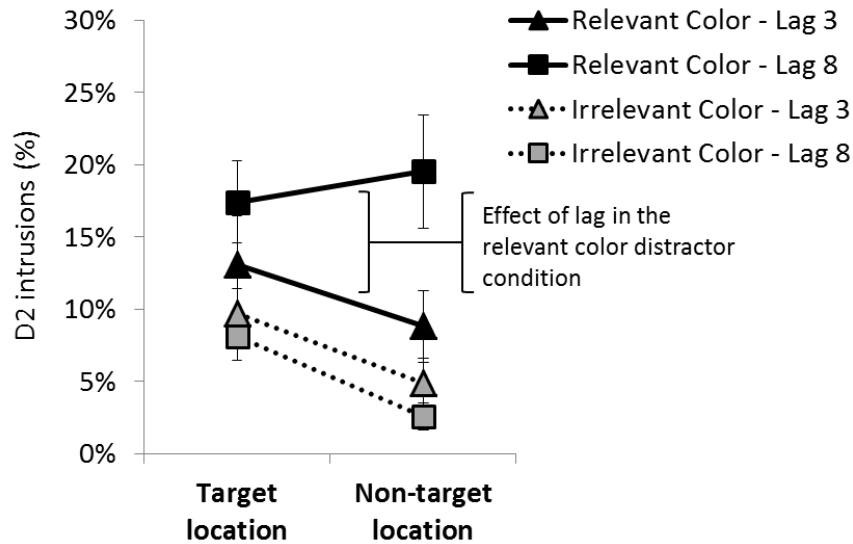


Figure 7. Percentage of distractor intrusions as a function of T1-T2 lag, distractor color and distractor location in Experiment 3. Intrusions were more frequent when the distractor was in the relevant than in the irrelevant color and when it was inside than outside the blink. Distractor intrusions were more frequent when the distractor appeared in the target's location only in the irrelevant- but not in the relevant-color condition.

Simultaneous non-target intrusions (Figure 8). Again, attentional capture was independent of the blink, while attentional engagement was delayed during the blink, as is clear from the larger proportion of intrusions from the letter immediately following a relevant-color distractor when this distractor captured attention (i.e., when it was in the relevant color) relative to when it did not (i.e., when it was in the irrelevant color).

We calculated simultaneous non-target intrusion rates, that is, the likelihood of erroneously reporting the simultaneous non-target instead of the target, excluding all trials where the simultaneous non-target was a digit. We conducted an ANOVA with T1-T2 lag (lag 3 vs. lag 8), distractor color (relevant vs. irrelevant) and distractor location

(same as target vs. different relative to the target) as within-subject variables and simultaneous non-target intrusion rate as the dependent variable. The main effects of distractor color and distractor location were both significant, $F(1, 15) = 12.78$, $p = .003$, $\eta^2_p = .46$, and $F(1, 15) = 18.17$, $p < .001$, $\eta^2_p = .54$, respectively, and so was the interaction between the two factors, $F(1, 15) = 7.83$, $p = .01$, $\eta^2_p = .34$. Follow-up analyses revealed that simultaneous non-target intrusions were more frequent when the distractor was in the relevant than in the irrelevant color, but only on different-location trials (i.e., when the distractor appeared in the same stream as the simultaneous non-target), $F(1, 15) = 22.64$, $p < .001$, $\eta^2_p = .59$ ($M = 11.3\%$, $SE = 2.1\%$ vs. $M = 4.2\%$, $SE = 0.7\%$) and not on same-location trials (i.e., when D2 appeared in the same stream as the target), $F < 1$, $\eta^2_p = .01$ ($M = 2.9\%$, $SE = 0.7\%$ vs. $M = 3.3\%$, $SE = 0.6\%$). No other effect was significant, all F s < 1 .

Finally, simultaneous non-target letter intrusion rates in each condition of T1-T2 lag, distractor color and distractor location were compared to the baseline intrusion rate. Baseline intrusion rates did not differ across lags, $t(13) = 1.36$, $p = .20$, and were therefore collapsed across the 2 lag conditions. Simultaneous non-target letter intrusion rates were higher than the baseline ($M = 3.8\%$) when the distractor was in the relevant color and at the non-target location, in both lag conditions (both p s $< .05$), and did not differ from the baseline in all other conditions (all p s $> .15$).

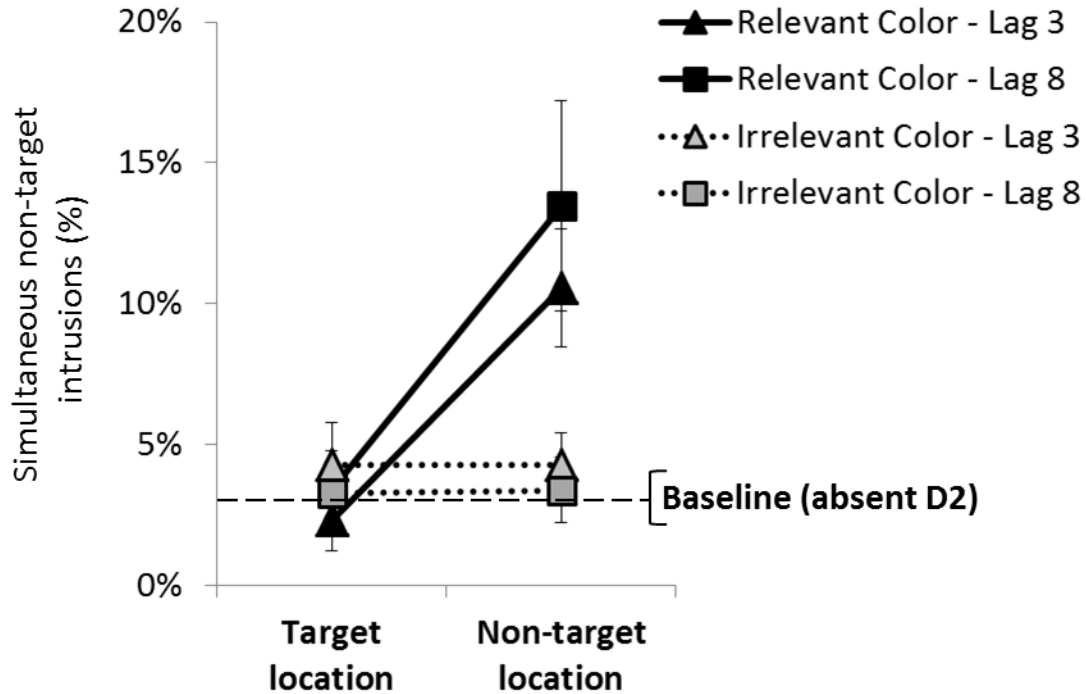


Figure 8. Percentage of simultaneous non-target intrusions as a function of T1-T2 lag, distractor color and distractor location in Experiment 3. There more intrusions when the distractor was in the relevant than in the irrelevant color only when the distractor appeared at the same location as the simultaneous non-target. This effect occurred regardless of whether the distractor was inside or outside the blink. Intrusion rates were significantly higher than baseline only when the distractor was in the relevant color and at the non-target location, in both T1-T2 lag conditions.

Discussion

The findings from Experiment 2 were fully replicated when, as is the case in traditional AB experiments, a target rather than a relevant-color distractor triggered the blink. Specifically, the blink did not prevent or even modulate attentional capture and attentional engagement following such capture was delayed during the blink (with only the letter immediately following the distractor rather than the distractor itself benefitting from enhanced processing) but not outside the blink (with both the distractor and the letter following it benefitting from enhanced processing). All these findings strongly support disrupted-engagement theories over disrupted-control theories.

Experiments 2 and 3 differed only in the fact that the first distractor (D1) in Experiment 2 was replaced with a target in the same color (T1) in Experiment 3. Thus, we could compare the attentional blink produced by a target vs. by a distractor. The data show that the blink was deeper when it was initiated by a target - with an accuracy decrement from 46.1% outside the blink to 27.3% inside the blink across conditions of distractor color in Experiment 3 - than when it was when initiated by a distractor (D1) - 50.7% vs. 40.7%, respectively, in Experiment 2. The significant interaction between Experiment and lag, $F(1, 30) = 5.34$, $p = .027$, $\eta^2_p = 0.15$, confirmed the reliability of this observation.

General discussion

Our objective was to characterize the temporal limitations of attentional allocation by elucidating the mechanisms underlying the attentional blink (Raymond et al., 1992). Specifically, we investigated whether the AB reflects a disruption of target-detection processes (e.g., Di Lollo et al., 2005; Taatgen et al., 2009) or a disruption of the deployment of attentional engagement (e.g., Nieuwenstein, 2006; Olivers & Meeter, 2008; Wyble et al., 2009). Our findings unambiguously support disrupted-engagement theories of the attentional blink.

Summary of the findings

We manipulated the occurrence of an attentional blink so as to create a situation in which a critical distractor was either within or outside the blink. This distractor was either in the target color (and thus had the potential to capture attention) or in an irrelevant color

(in which case, it was expected not to capture attention). Our main interest was in how this distractor would affect the processing of a subsequent stimulus.

As expected from previous reports when the relevant-color distractor was outside the blink, it captured attention and benefitted from attentional engagement, as manifested in the higher probability of erroneously reporting the critical distractor's identity instead of the target's when this distractor was in the relevant color than when it was in the irrelevant color. However, this difference was smaller inside than outside the blink, indicating that processing of the critical distractor was impaired during the blink.

Our experiments yielded two main novel findings. First, during the blink, intrusions from the letter immediately following the critical distractor (which we referred to as D2+1 intrusions in Experiment 1 and simultaneous non-target intrusions in Experiments 2 and 3) were far more frequent following a relevant- than an irrelevant-color distractor. This finding indicates that the relevant-color distractor captured attention within the blink, and as predicted by disrupted-engagement theories, attentional engagement was delayed, such that the subsequent item was selected instead. Secondly, we reported direct evidence that the AB did not only fail to prevent attentional capture by the relevant-color distractor but did not even modulate such capture: we independently manipulated the distractor and target locations and found target identification to be better when these coincided, irrespective of whether the relevant-color distractor appeared within or outside the blink.

Our findings were replicated across different instantiations of the Attentional Blink. A similar pattern was observed (1) whether the blink was initiated by a relevant-color distractor (Experiments 1 and 2) or by a target (Experiment 3) and (2) whether the blink

manipulation consisted in varying the lag between the blink inducer (either D1 in Experiment 2 or the first target, in Experiment 3) and the critical distractor, or in keeping a fixed lag between them but varying the ability of a first distractor to induce a blink (relevant- vs. irrelevant-color D1 conditions in Experiment 1).

Implications for the Attentional Blink

Taken together, our findings demonstrate that target-detection processes are unaffected by the blink, and thus invalidate disrupted-control theories (e.g., Di Lollo et al.'s (2005) Temporary Loss of Control account and Taatgen et al.'s (2009) Threaded Cognition model). In addition, they suggest that the AB produces a delay between detection of target-matching features and attentional engagement in objects to be selected for consolidation in short-term memory, in line with disrupted-engagement theories of the AB (e.g., Nieuwenstein et al., 2005; Olivers & Meeter, 2008; Wyble et al., 2009), while arguing against recent (e.g., Raffone et al., 2014) and older (e.g., Chun & Potter, 1995) accounts that hold attentional engagement to be altogether withheld during the AB.

Our findings are compatible with the results reported by Ghorashi and colleagues (Ghorashi, Enns, Spalek & Di Lollo, 2009; Ghorashi, Spalek, Enns & Di Lollo, 2009; Ghorashi, Enns, Klein & Di Lollo, 2010). In these studies, the first target appeared in a central position, while the second target appeared in the periphery. While identification of the second target was overall impaired inside the blink (i.e., when it followed the first target by a lag of 3 vs. 7), it was improved to the same extent inside and outside the blink when its location was pre-cued by an abrupt onset. This cueing benefit occurred, both with 100%-valid cues and with uninformative cues (Ghorashi et al., 2010). Ghorashi and

colleagues concluded that spatial selection and identification are separable processes that reflect the independent operations of the dorsal and ventral visual pathways.

Our conclusion (as well as Ghorashi et al.'s, 2009a; 2009b; 2010) that attentional capture is unaffected by the blink appears to be at odds with the findings reported by Jolicoeur, Sessa, Dell'Acqua and Robitaille (2006; see also Dell'Acqua, Sessa, Jolicoeur, & Robitaille, 2006). These authors found the amplitude of the N2pc component to be reduced during the blink and concluded that spatial attention “freezes” during the AB. However, while it is widely agreed that the N2pc is related to spatial attention, which attentional process this component reflects remains a matter of debate. In the attentional-capture literature, the N2pc is often assumed to index shifts of attention (e.g., Hickey, McDonald & Theeuwes, 2006). However, this assumption has not gone unchallenged. For example, Kiss, Van Velzen and Eimer (2008) showed that the availability of an endogenous spatial cue that allowed preparatory shifts of attention did not affect the N2pc. They concluded that the N2pc is not associated with attentional shifts, but instead reflects “spatially specific processing of stimulus features at task-relevant locations” (p. 240), which is akin to attentional engagement. Accordingly, Jolicoeur et al. (2006, p.574) suggested that their findings implied either that (a) the AB prevented the deployment of spatial attention for some period of time or (b) the AB did not inhibit attentional shifts *per se* but processes taking place downstream from the shift of spatial attention. Thus, if the latter interpretation is correct, there is no contradiction between our findings and Jolicoeur et al.'s (2006).

The combined results of Experiments 2 and 3 show that attentional capture by a relevant-color distractor (D1) and allocation of attention to a target (T1) produce a similar

behavioral pattern, namely poorer accuracy at identifying a subsequent target and a delay in attentional engagement (see also: Folk et al., 2008, 2009; Ghorashi et al., 2003; Visser, et al., 2004; Wee & Chua, 2004; Zivony & Lamy, 2014). This finding suggests that, following Raymond et al.'s (1992) terminology, any stimulus possessing the target-defining feature opens the attentional gate and accesses high-level processes. This occurs because matching of the target-defining feature determines whether an object is a potential target. If it is, the attentional gate closes in order to reduce interference from further distractors, while the status of this potential target is clarified, resulting in the Attentional Blink. Nevertheless, we also found that the more extensive processing required by a target relative to a distractor once attention had been shifted to it, resulted in a larger attentional blink. The finding that distractor-induced AB and target-induced AB have similar consequences has potentially useful methodological implications: distractor-induced AB can be used when experimental length is an issue or when requiring participants to produce two responses is not desirable.

Differences among disrupted-engagement theories: late onset versus inhibition

While the different disrupted-engagement theories (Nieuwenstein et al., 2005; Olivers & Meeter, 2007; Wyble et al., 2009) differ in several important respects as explained in the introduction, the point of divergence that is most relevant for the present purposes is what mechanisms they postulate to explain how the AB delays engagement of attention – that is, the transient enhancement of processing that occurs during an attentional episode (see figure 9). According to the DAE, the attentional blink occurs because the *onset* of attentional engagement following attentional capture happens later, and as a consequence,

so does the peak of the transient enhancement of processing. This account further suggests that attentional enhancement is also diffused, that is, less precise during the blink (Vul, Nieuwenstein and Kanwisher, 2008). According to both the Boost-and-Bounce and the eSTST models, the AB results from an inhibitory process that is triggered by the detection of a distractor and brings activation *below baseline levels* (see Olivers & Meeter, 2007, Figure 5, panel B3; Wyble et al., 2009, Figure 4). Thus, the AB occurs because the second target does not produce sufficient enhancement to overcome inhibitory deactivation.

These accounts yield opposite predictions with regard to the processing of a non-target immediately following a relevant-color cue (or distractor). According to the DAE, as the peak of attentional enhancement resulting from the attentional episode initiated by the cue is delayed during the blink, more activation should accrue to the subsequent non-target when the cue appeared inside than outside the blink (see figure 9a for an illustration). In contrast, according to the eSTST and Boost and Bounce accounts, the inhibition set off during the blink brings activation below baseline levels. Therefore, the attentional enhancement accruing to the non-target following attentional capture by the relevant-color cue should be smaller when the cue appeared inside than outside the blink (see figure 9b).

The findings from the present study do not conform to either prediction: the rate of intrusions from the non-target following a relevant-color distractor (i.e., D2+1 intrusions in Experiment 1, and simultaneous non-target intrusions in Experiments 2 and 3) was not significantly different when this distractor appeared outside versus inside the blink. In our experiments this intrusion rate tended to be smaller inside vs. outside the blink (7.1% vs.

10.1% in Experiment 2, and 10.1% vs. 12.6% in Experiment 3, respectively) in line with the inhibition account, but this pattern was not observed in Experiment 1 (19.4% vs. 19.2%).

Thus, while our data provide clear support for disrupted-engagement accounts, they are inconclusive with regard to the mechanism that produces the delay between attentional capture and attentional enhancement. Further studies that clarify the exact time course of attentional engagement following capture during the blink are needed in order to test the DAE on the one hand and the eSTST and Boost and Bounce accounts on the other hand, against each other.

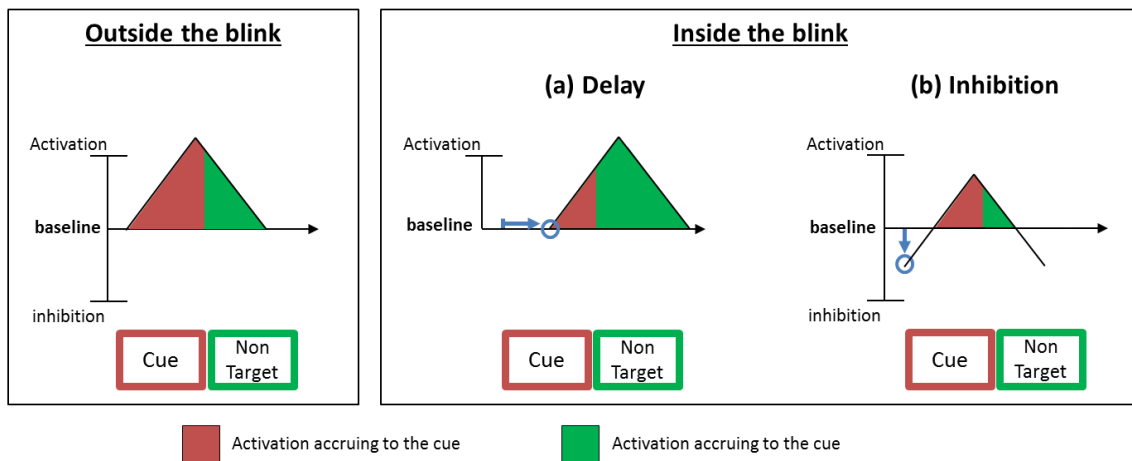


Figure 9. Illustration of the transient enhancement following a relevant-color cue outside and inside the blink. According to the Delayed Attentional Engagement account (Nieuwenstein et al., 2005) attentional enhancement is delayed during the blink. Thus, as attentional engagement onsets with a delay, more activation should accrue to the non-target following the cue when the cue appears inside than outside the blink. According to the eSTST (Wyble et al., 2009) and Boost and Bounce (Olivers and Meeter, 2008) models, activation is at baseline level outside the blink and below baseline during the blink. Therefore, even though the onset of enhancement is the same during and outside the blink, the activation accruing to the non-target should be reduced during the blink.

Dissociation between attentional capture and attentional engagement

Posner (1980) was the first to explicitly suggest a theoretical distinction between different stages in the deployment of spatial attention. He proposed that when a stimulus summons attention, spatial attention is first disengaged from its current location, then shifted to the stimulus location, and finally engaged in that location. Neuropsychological evidence supported the distinction between these processes (Posner & Petersen, 1990). Patients with lesions in the pulvinar could execute normal shifts of attention but showed selective impairment in the “engage” operation. By contrast, patients with parietal lesions were impaired in shifting their attention from its current locus but once their attention was focused on a location, they had no difficulty reading out the information from it. These findings suggest that attentional engagement can be dissociated from the detection of objects and the shifting of attention towards them. However, evidence for such dissociation in healthy participants is lacking. In fact, a shared assumption in many models of visual attention is that under normal conditions, once an attentional episode is initiated, attentional engagement will necessarily follow in a rigid and immediate sequence (Sperling & Weichselgartner, 1995). Accordingly, many studies have shown that when a distractor matching the current task set captures attention, attention is engaged in this distractor (e.g., Carmel and Lamy, 2014). In the context of stimuli appearing in an RSVP stream, attentional engagement is typically expected to be deployed to the very stimulus that captured attention.

Our results show that attentional capture and attentional engagement can be dissociated in healthy individuals. Specifically, the AB did not affect attentional capture,

whereas it disrupted attentional engagement. These findings are in line with previous evidence showing that attentional capture is impervious to resource limitations. For example, Braun and Sagi (1991) showed that detection of a feature gradient was unaffected by the addition of an attention-demanding concurrent task. In the same vein, Lamy, Alon, Carmel and Shalev (2015) recently showed that attentional capture occurs *independently* of conscious perception of the attention-grabbing object: the spatial benefit in target identification when the target appeared at the same location as a liminal cue was of the same magnitude whether or not this cue was consciously perceived.

In contrast to attentional capture, attentional engagement appears to require central resources. Accordingly, we speculate that paralleling our findings with regard to the influence of the AB, attentional engagement should be impaired by resource-related manipulations such as dual tasks as well as by manipulations that prevent consciousness.

A “camera” metaphor of attention

The most widely used metaphors to describe the effects of attention on visual processing are the spotlight (Posner, 1980) and zoom lens (Eriksen & James, 1986) metaphors. Both describe the spatial limitations of attention, yet fail to describe its temporal characteristics. Relying on the findings of the present study, which distinguish between attentional-capture and attentional-engagement stages of the selection process, we suggest a “camera” metaphor that encompasses both the spatial and temporal aspects of attention. In the process of taking a picture of a dynamic object, the camera zoom lens is first aligned with the object of interest, but only when the shutter button is pressed is the information going through the lens registered. If the shutter-button press is delayed,

the dynamic object is missed, and the information occupying its initial location is registered instead. If exposure is too long, several objects are blurred into one.

Accordingly, we suggest that the initiation of an attentional episode corresponds to the alignment of the zoom lens, while the deployment of attentional engagement corresponds to the shutter-button press. Delayed engagement corresponds to a delayed shutter-button press, while diffused engagement (e.g, Vul et al., 2008) as well as lengthening of an attentional episode by the presentation of multiple targets (e.g., Wyble et al., 2011; Dux et al., 2009), which may lead to binding errors, correspond to protracted exposure. This metaphor can be useful for generating novel predictions with regard to attentional selection, beyond the attentional blink. For example, the distinction between two separate stages in the operation of the camera implies that it is possible to direct the lens towards an object and decide *not* to press the shutter button at all. Accordingly, it would be interesting to examine whether conditions can be found in which, following attentional capture, attentional engagement is withheld completely, rather than merely delayed.

Conclusion

While a wealth of research has demonstrated severe limitations in our ability to attend to successive stimuli, we show that such limitations do not pertain to our ability to maintain search goals: even when attentional resources are committed to processing a first event, a new event that matches our current goals triggers a new attentional episode and summons spatial attention. The cost of processing the first event, however, is a delay

in engaging attention to the new event, if the latter occurs within half a second or so from the former.

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Footnotes

1. Unlike the other models in this category, Chun and Potter's (1995) two-stage model and Raffone et al.'s (2014) Theory of Attention and Consciousness suggest that attentional engagement is prevented rather than delayed. Specifically, they claim that during the blink, "amplification and ignition processes related to attention cannot take place" (Raffone et al., 2014, p. 11).
2. Nieuwenstein (2006) found sparing of a cued T2 even when a distractor was interleaved between the relevant-color cue and this second target. This finding suggests that the interleaved distractor did disrupt control over target detection. However, unlike the 100ms presentation rate used in most RSVP studies, the inter-item stimulus onset asynchrony (SOA) was of only 53ms. As the AB often disappears with short inter-item SOAs (Potter, Staub, & O'Connor, 2002), it remains possible that the interleaving distractor had no effect because of the short SOA used.
3. The same tests performed on untransformed data yielded the same findings with comparable significance levels. The data presented in the figures correspond to the untransformed scores.
4. We also analyzed D2 intrusions, as a converging measure of D2 processing. They closely mirrored the results on the D2-target compatibility measure.
5. Note that this redistribution-of-intrusions account cannot explain our critical finding, namely, the higher rate of D2+1 intrusions following a relevant-color than following an irrelevant-color D2 when D2 appeared during the blink. Such redistribution should affect the two conditions (relevant- and irrelevant-color D2

conditions) to the same extent and therefore only attentional capture by a stimulus sharing the target's defining feature (Folk et al., 1992) can account for the difference between these conditions.

6. Including these trials did not change the results.