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An attentional blink in the absence of spatial attention: a cost of awareness?

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Abstract

The attentional blink refers to the finding that when two visual targets appear within 200–500 ms, observers often miss the second target. In three experiments, we disentangle the roles of spatial attention to and conscious report of the first event in eliciting this cost. We show that allocating spatial attention to the first event is not necessary for a blink to occur: the full temporal pattern of the blink arises when the first event is consciously detected, despite the fact that it is not spatially attended, whereas no cost is observed when the first event is missed. We then show that spatial attention is also not sufficient for eliciting a blink, though it can deepen the blink when accompanied by conscious detection. These results demonstrate that there is no cost associated with the initiation of an attentional episode, whereas explicit conscious detection comes at a price. These findings demonstrate the temporal flexibility of attention and underscore the potential role of subjective awareness in understanding processing limitations, although this role may be contingent on the encoding in working memory necessary for conscious report.

Introduction

Our ability to monitor multiple events in a dynamic environment is severely limited. In particular, when two events occur in close temporal succession, our performance at detecting or identifying the second event is poor. In the lab, this phenomenon is most often studied using a paradigm known as

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the Attentional Blink (AB; e.g., Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992; Weichselgartner & Sperling, 1987). In a typical AB experiment, participants have to identify two targets embedded within a rapid serial visual presentation (RSVP) stream of distractors. Identification of the second target (T2) is most impaired when this target appears 200–300 ms after T1 (i.e., at T1–T2 lags 2 and 3) and typically returns to baseline after 600 ms (i.e., at lag 6 and above). When T2 immediately follows T1 and appears at the same location as T1, the blink is often absent. Such preserved T2 performance at lag 1 is referred to as lag-1 sparing (Chun & Potter, 1995). The attentional blink is one of the most robust phenomena in the field of cognitive psychology, and it informs many influential theories of attention, working memory and consciousness (see Dux & Marois, 2009; Martens & Wyble, 2010 for reviews).

What triggers the attentional blink?

The main focus of the present study is to clarify what specific aspects of T1 processing are responsible for the occurrence of the attentional blink. Many authors suggest that the AB occurs because the process of consolidating T1 information in visual short-term memory (VSTM) ties up a limited-capacity resource (e.g., Chun & Potter, 1995; Jolicoeur & Dell'Acqua, 1999; Jolicoeur, 1999; Vogel, Luck

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& Shapiro, 1998; Dux, Asplunt & Marois, 2008; but see Olivers, Stigchel & Hulleman, 2007). Some of them (e.g., Wyble, Bowman & Nieuwenstein, 2009, 2011) have further characterized the ensuing suppression of attention to T2 as a cognitive strategy aimed at facilitating the formation of episodically distinct representations within working memory. However, several findings have led to the suggestion that shifting attention to T1 and /or consciously perceiving T1 may be critical in triggering the AB.

In several studies, T1 is replaced with a distractor that does not require any response (e.g., Folk et al., 2009; Folk, Leber & Egeth, 2002; Leblanc & Jolicoeur, 2005; Wyble, Folk & Potter, 2013; Zivony & Lamy, 2016). For instance, Folk et al. (2002) had participants search for a target defined by its color in a central stream of colored letters. On distractor-present trials, a color-singleton distractor appeared in the periphery and either shared the target's color or did not. Participants were required to identify the central target and ignore the peripheral distractor. According to the contingent-capture account (e.g., Folk et.al., 1992), only the target-color distractor should capture attention because it matches the observer's attentional set. The results supported this prediction: target identification was impaired only when the distractor shared the target color. Critically, this impairment was modulated by the lag between the distractor and the target and followed the time course typical of the attentional blink. The authors concluded that the target-color distractor captured attention and as a consequence, triggered an attentional blink. This conclusion implies that finding an attentional blink can be taken as evidence that attentional capture occurred—in other words, it assumes that allocation of attention to T1 is a critical factor in eliciting the blink.

Nieuwenstein et al. (2009) raised the alternative suggestion that conscious perception of T1 is a necessary and sufficient condition for the blink to occur. In their study, participants were required to identify a letter (T2) that was masked after a brief interval. On two-thirds of the trials, the letter O (T1) appeared prior to T2 for 8.3 ms, with its luminance contrast set so as to allow a detection rate of about 50%. The SOA between the two letters varied between 200 and 1000 ms. At the end of each trial, observers indicated whether they had seen T1, and then identified T2. An attentional blink (i.e., a lag-dependent impairment in T2 identification) was observed when T1 was seen and was absent when T1 was missed. Importantly, when T1 duration was increased and T1 was, therefore, assumed to be fully visible, a blink was also observed although no task whatsoever was associated with T1. Nieuwenstein et al. (2009) concluded that awareness of T1 is both necessary and sufficient for the occurrence of an AB.

Spatial attention, conscious perception and consolidation in working memory are tightly related constructs and the mechanisms underlying the processes that support them are likely to overlap (Baars, 1997, Baars & Franklin, 2003; Koch & Tsuchiya, 2007; Lamme, 2006; Soto & Silvanto, 2014; Velichkovsky, 2017). It is, therefore, probable that they co-occurred in most studies that demonstrated an AB. For instance, in the classical attentional blink paradigm, in which both critical events are targets, T1 is (a) spatially attended: it typically appears within a single stream presented at fixation, and when it appears at a peripheral location, its identification requires that attention be moved to its location; (b) consciously perceived, since only trials in which T1 is correctly identified are considered; and (c) encoded in working memory, since it has to be reported.

Likewise, in studies in which T1 was replaced with a distractor (e.g., Folk, Leber & Egeth, 2002), conscious perception of the distractor was not measured, yet previous findings have shown that an object that shares the target's feature is more likely to gain conscious access than an object that does not share it (e.g., Most, Scholl, Clifford & Simons, 2005; Lamy, Alon, Carmel & Shalev, 2015). In addition, although encoding the distractor's information in working memory serves no obvious purpose when no task is associated with this distractor, it has been suggested that objects that happen to benefit from spatial attention are automatically encoded in working memory (e.g., Schmidt et al., 2002). Thus, in this case also, it is unclear whether a spatial shift of attention to T1, conscious perception of T1 or its encoding in working memory is responsible for the blink.

Finally, in Nieuwenstein's (2009) study, T1 always appeared in the focus of attention, since both T1 and T2 were presented at fixation. The finding that only a consciously perceived T1 elicited a blink in that study is, therefore, compatible with the notion that spatial attention may also be a necessary condition (albeit not a sufficient one) for the blink.

What triggers lag 1 sparing?

Lag-1 sparing has sparked extensive research that has largely shaped our understanding of the AB (e.g., Bowman & Wyble, 2007; Olivers, Van Der Stigchel & Hulleman, 2007; Dell'Acqua, Jolicoeur, Pascali & Pluchino, 2007). Several theories of the blink that explicitly link lag 1 sparing to attention to T1 (e.g., Bowman & Wyble, 2007; Chua, 2015; Nieuwenstein et al., 2005; Nieuwenstein et al., 2009; Olivers & Meeter, 2008; Shih, 2008). They posit that lag-1 sparing occurs because the transient attentional enhancement triggered by T1 also accrues to T2.

Nieuwenstein et al. (2009) further suggested that lag-1 sparing occurs "regardless of whether T1 is consciously perceived" (p. 11). This conclusion relied on the finding that performance at identifying T2 was better when it trailed a liminally presented T1 at lag 1 than at lag 3, both when T1 was consciously detected and when it was missed. However, Nieuwenstein et al. (2009) did not manipulate attention, but

only assumed that T1 captured attention. Moreover, lag-1 sparing was numerically about twice as large when T1 was consciously perceived than when it was not (but this difference was not tested for significance). It thus remains unclear whether lag 1 sparing is related to attention or to conscious perception. Note also that lag-1 sparing is generally considered as a hallmark of the attentional blink (but see MacLean & Arnell (2012) for arguments that lag-1 sparing is neither necessary nor sufficient to indicate that an attentional blink has occurred), yet in Nieuwenstein et al.'s (2009) study, lag 1 sparing on missed-T1 trials occurred in the absence of a subsequent blink.

Dissociating conscious perception and spatial capture of attention

The objective of the present study was to clarify the respective contributions of spatial attention and conscious perception of T1 in eliciting the attentional blink. Crucially, here, we did not attempt to disentangle the roles of conscious perception and encoding in working memory for the report, as we explain in more detail in the general discussion. We are currently addressing this issue in a complementary study.

To achieve the present goal, we relied on dissociations between conscious perception and spatial attention recently reported by Lamy et al. (2015), who used a variant of the spatial cueing paradigm (for a more general discussion of shifts of attention elicited by objects that are not consciously perceived, see McCormick, 1997, Mulckhuyse & Theeuwes 2010). In one of the classical versions of this paradigm (e.g., Folk & Remington, 1998), participants search for a target defined by its known color. A spatially uninformative color singleton cue appears prior to the target. It is either in the same color as the target (target-color cue) or in a different color (nontarget-color cue). When the target appears among heterogeneously colored distractors, observers cannot monitor the displays for a color discontinuity to find it. Instead, they have to engage in "feature-search mode", that is, adopt an attentional set for a specific color (Bacon & Egeth, 1994). Several studies have shown that under such circumstances, singleton cues that match the attentional set capture attention, whereas singleton cues that do not share the target color do not capture spatial attention (e.g., Bacon & Egeth, 1994; Folk & Remington, 1998; Carmel & Lamy, 2014)[1].

In Lamy et al.'s (2015) study, the cue was rendered liminal using Continuous Flash Suppression (CFS, Tsuchiya & Koch, 2005), such that it was completely missed on a portion of the trials and seen with varying degrees of clarity on others. Participants first made a speeded discrimination response to the target shape and then rated the quality of their subjective perception of the color cue on a variant of the Perceptual Awareness Scale (PAS, Ramsoy & Overgaard, 2004) ranging from '0' if they had no conscious perception of the cue to '3' if they clearly perceived it. Cues that shared the target color captured attention: performance was higher when the cue and target appeared in the same location than when they appeared at different locations, indicating that attention was shifted to the cue. Critically, the magnitude of this cue location effect was independent of conscious perception of the cue. With nontarget-color cues, there was no cue location effect when the cue was missed and performance was actually worse on same-than on different-location trials when the cue was consciously perceived.[2]

Note that although Lamy et al. (2015) referred to this effect as "attentional capture" by the target-color cue, this was somewhat of a misnomer. Indeed, unlike in the classical paradigm, both the target- and non-target cues were task-relevant, since participants had to report their visibility. Of main interest for the current purposes, however, is the finding that the nontarget-color cue did not elicit an attentional shift, even if participants were explicitly required to respond to it. Thus, the requirement to rate the cue's visibility did not induce participants to shift their attention to the cue location, whereas detecting a match with the target's color did. In the remainder of this paper, we refer to attentional shifts rather than to attentional capture, yet for clarity purposes, we continue to refer to the first event as "the cue" rather than as "the first target".

Overview of the present study

In the three experiments reported here, we took advantage of the main features of Lamy et al.'s (2015) paradigm, while introducing changes designed to create a blink. We used a dual-stream variant of the classic RSVP paradigm (e.g., Holländer, Corballis & Hamm, 2005; Śmigasiewicz et.al., 2010; Verleger et al., 2010; Visser et al., 1999) in which a liminal,

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[1] Theeuwes and colleagues have claimed that salient irrelevant color cues mandatorily capture attention (e.g., Theeuwes, Atchley & Kramer, 2000; see Theeuwes, 2010, for a review). However, support for this claim comes almost exclusively from experiments in which the target had a unique feature and could be found by monitoring the displays for a featural discontinuity (i.e., using a search strategy known as the "singleton-detection mode", Bacon & Egeth, 1994). Evidence for attentional capture by a cue that has a salient feature outside the observer's attentional state is scarce and has been mostly reported for onset cues (e.g., Folk & Remington, 2015).

[2] This same-location cost has been reported in several previous studies (e.g., Anderson & Folk, 2012; Becker, Folk, & Remington, 2013, Experiment 3; Belopolsky et al., 2010; Carmel & Lamy, 2014; 2015; Eimer, Kiss, Press, & Sauter, 2009; Folk & Remington, 2008; Lamy et al., 2015; Lamy, Leber & Egeth, 2004; Schönhammer & Kerzel, 2013). Importantly, although the mechanisms underlying this same-location cost are debated, Carmel and Lamy (2014; 2015) demonstrated that this cost is unrelated to attention and is contingent on conscious perception of the cue.

spatially uninformative cue served as the first target (henceforth, the cue). Participants first identified T2 (henceforth, the target) and then reported their subjective perception of the cue. In this paper, a "blink" refers to any impairment in the identification of the target that is dependent on the lag between the cue and target (MacLean & Arnell, 2012). Spatial capture of attention by the cue refers to better performance when the target appears at the same location as the cue than when it appears at the alternative location (henceforth, cue location effect).

In Experiments 1 and 2, the cue did not share the target's color and was, therefore, not expected to trigger a spatial shift of attention to its location, irrespective of whether or not it was consciously perceived.[3] We could thus determine whether allocating spatial attention to the first event is a necessary condition for the blink, or whether alternatively, a consciously perceived cue can produce a blink in the absence of spatial attention.

In Experiment 3, the cue shared the target's color and was, therefore, expected to trigger a spatial shift of attention. This allowed us to investigate the role of spatial attention when the cue was missed relative to when it was visible. In particular, we could examine whether spatial attention in the absence of conscious perception is sufficient for the blink to occur.

Statistical analyses, power analysis and code sharing

In all experiments, all statistical analyses were carried out using "R" statistical software (version 3.3.2, R Core Team, 2015) and RStudio version 1.0.136 (http://www.rstudio.com).

Visibility ratings

To ensure that visibility ratings corresponded to different perceptual states rather than being randomly distributed, we tested their predictive value as to whether the cue was present or absent. Accordingly, given that the proportion of cue-present trials was 85% in all 3 experiments, if a visibility rating indicating some subjective awareness (all ratings except 0) is predictive of cue presence, more than 85% of the trials receiving this visibility rating should be cue-present trials. We thus compared the random distribution (85% vs. 15%) and the observed rating distributions in a series of binomial tests on the raw number of ratings for each visibility rating separately for on each experiment. The results showed that visibility ratings of 2 and 3 were predictive of cue presence in all the experiments, whereas visibility ratings of 1 were either not predictive of cue presence (Exps. 2 and 3), or predictive of cue absence (Exp. 1). Therefore, in all experiments, the "unaware" trials included trials in which the visibility of the cue was rated zero, and the "aware" trials included only trials in which its visibility was rated 2 or 3.

We excluded trials with a visibility rating of 1, because it was inappropriate to include them in the "aware" trials (since they were not predictive of the presence of the cue) or in the "unaware" trials (since it was important to remove any concern of contamination of the unaware-cue trials by partial conscious perception). Note, however, that including 1-visibility trials as aware-cue trials did not affect the pattern of results (see the Supplementary materials). We included 2-visibility trials rather than comparing 0 and 3-visibility trials to increase the number of trials entering the analyses, but similar main effects and interactions were observed here and in the following experiments when only the extreme visibility ratings (0 and 3) were included.

Lag-dependent cost of awareness

As is to be expected when using multi-point scales for subjective reports, different participants used each visibility rating on a different proportion of the trials. To overcome the resulting distortions and to avoid excluding participants based on considerations of balanced visibility rating distribution we used a generalized linear mixed-effects model (GLMM) to analyze the proportion of correct target letter identifications. Cue-absent trials were excluded from all analyses. The data was fitted by likelihood ratio test using the *glme* function and a *logit* link function (Jaeger, 2008) with cue-target location (same vs. different), cue-target lag (1 vs. 3 vs. 7) and cue visibility (unaware vs. aware) as fixed factors, and subject-specific intercept as a random factor. The resulting model was expressed as: glmer(accuracy ~ 1 + lag + visibility + location + lag*visibility + lag*location + visibility*location + lag*visibility*location + (1|subject), family = binomial). *p* values for the model were calculated using the Anova function in the Car package (vers. 2.0–25), and the *p* values for the paired comparisons were calculated using the glht function in the multcomp package (vers. 1.4.6). The *p* values for post-hoc

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[3] Note that these findings do not contradict the widely accepted idea that attention is necessary for conscious perception (e.g., Dehaene, Changeux, Naccache, Sackur & Sergent, 2006 but see Tsuchiya & Koch, 2016). Indeed, previous research has shown that a stimulus that must be responded to can be consciously detected even if it benefits only from very little—distributed—spatial attention (e.g., Mack & Rock, 1998; Fei-Fei et al., 2005). In Lamy et al.'s (2015) study, participants were asked to rate the irrelevant-color cue's visibility—a task that required no more than detecting a color singleton, and therefore, did not require spatial attention. By contrast, relevant-color cues captured attention, yet were sometimes missed. This finding is consistent with previous reports showing that spatial attention is not sufficient for conscious perception (e.g., Kentridge, Nijboer & Heywood, 2008).

comparisons are reported with Tukey adjustments. Note that as a cell could be empty for a given subject (if for instance, this subject did not report any visibility of 3 for a given condition of location or cue color), degrees of freedom may vary across effects. In all the reported experiments, preliminary analyses revealed no significant effect involving target color and the data were, therefore, collapsed across target color conditions.

Spatial shifts of attention

To verify that the nontarget-color cue did not elicit a spatial shift of attention to its location in Experiments 1 and 2, we conducted planned comparisons between same- and different-location trials, separately for unaware- and aware-cue trials. Only lag-1 trials were entered in these analyses because attention may be redirected to a different location at longer lags.

In the present study, showing that attention was not shifted to the location of nontarget-color cues was of high theoretical importance. We, therefore, used Bayesian statistics (BayesFactor package with the default parameter settings and the BAS package with the uniform prior) to assess the likelihood of the null hypothesis. We compared the null model (which included only subjects as a random effect) to a model including also cue-target location as a fixed effect and report separate BF01 for aware-cue and unaware-cue trials. Following Kass and Raftery (1995; see also Jeffreys, 1998) we consider a BF of less than 3 as "weak" evidence, a BF between 3 and 10 as "substantial" evidence, a BF between 10 and 100 as "strong" evidence, and a BF greater than 100 as "decisive".

Power analysis and sample size

We calculated the effect size of the cue-target lag effect reported in a comparable study ($dz = 1.06$, Zivony & Lamy 2016, single-cue condition in Experiment 2), where the attentional blink was induced by a cue in a dual RSVP paradigm. Using G*Power 3.1.9.2 (Faul, Erdfelder, Lang, & Buchner, 2007, t-test for matched pairs, one-sided) we determined that to achieve power of 0.80 with a type I error probability of $\alpha = 0.05$, the required sample size was $n = 8$. Since we were interested in the interaction between the effects of cue-target lag and cue awareness, the sample size required to achieve the same power was twice as large (i.e., $n = 16$).

Experiment 1

Following Lamy et al. (2015), we used CFS to render the cue liminal. The displays presented to the unsuppressed eye consisted of two streams of heterogeneously colored letters.

The target, defined by its known color, was embedded in one of the two streams. At lags 1, 3 or 7 prior to the target, a uniquely colored circle not sharing the target color, the cue, enclosed one of the distractor letters, either in the same stream as the target or in the alternative stream. This cue was presented only in the suppressed eye and was, therefore, perceived at various degrees of clarity across trials. On each trial, participants first made an unspeeded identification response to the target and then rated their subjective visibility of the cue on a PAS scale.

We first examined whether the cue captured spatial attention. We did not expect it to, since it did not share the target color (e.g., Bacon & Egeth, 1994; Carmel & Lamy, 2014; Folk & Remington, 1998; Lamy et al., 2004; 2015). This finding was crucial for our argument. We thus verified that target identification performance was similar whether the cue and target had appeared at the same or at different locations. We restricted this comparison to lag 1 because longer lags should give participants enough time to disengage their attention from the cue location.

Second, we set out to determine under what conditions a blink occurred. If conscious perception of the first stimulus is necessary for the AB, we should observe a blink only when the cue is consciously perceived, that is, poorer target identification performance on aware-cue trials than on unaware-cue trials at lag 3, with no such difference at lag 7, irrespective of whether the cue and target appear in the same or in different streams. We henceforth refer to the poorer performance on aware-relative to unaware-cue trials as the cost of awareness (CoA). Alternatively, if spatial attention to T1 is necessary for the blink to occur, we should find no blink irrespective of whether or not the cue is consciously perceived.

Finally, we examined under what conditions lag 1 sparing (Chun & Potter, 1995), that is, poorer performance on lag 3 relative to lag 1, would be observed. Previous studies showed that lag 1 sparing occurs only when T1 and T2 share the same location (e.g., Visser et al., 1999). We, therefore, expected lag 1 sparing only on same cue-target location trials. Of main interest was whether lag 1 sparing would be related to attention or to conscious perception of the cue.

The predictions relative to lag 1 sparing are complicated by the fact that in the present study, both lag 1 sparing and attentional capture were expected to manifest as better performance on same- than on different-location trials at lag 1. Nevertheless, finding no cue location effect and no difference between performance on lag 1 and lag 3 on same-location trials on either aware- or unaware-cue trials would be consistent with the notion that lag 1 sparing is contingent on attending to T1. By contrast, if lag 1 sparing is contingent on conscious perception of T1, we should observe better performance at lag 1 than at lag 3 on same-location trials on aware—but not on unaware-cue trials.
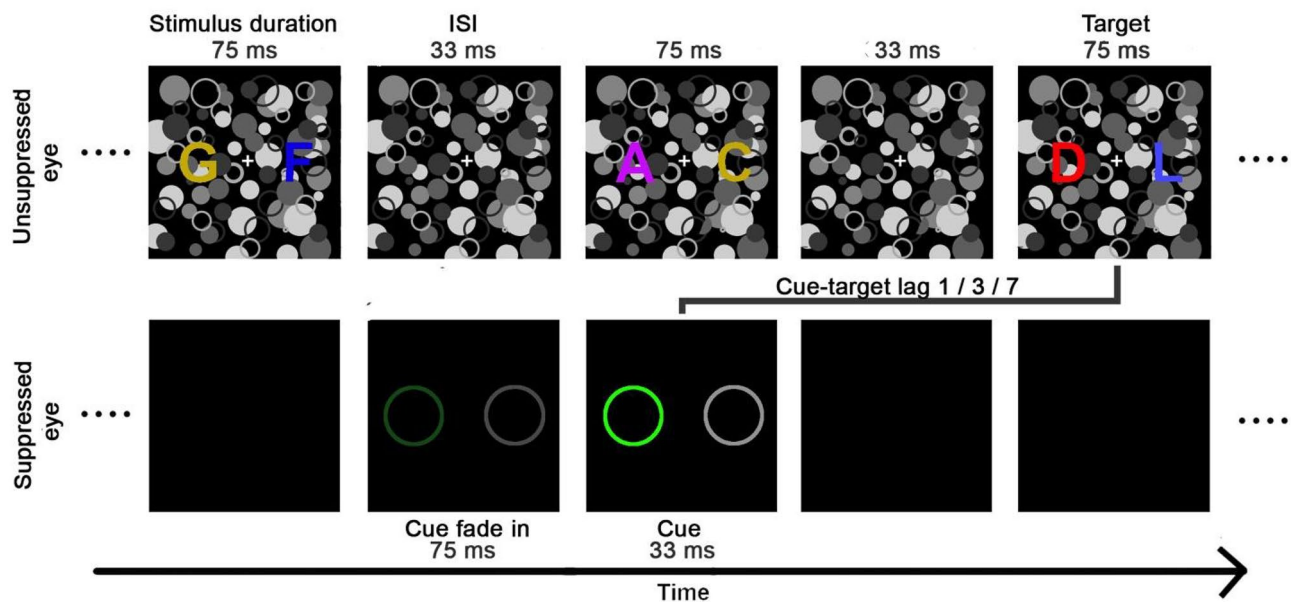
Fig. 1 Sample trial sequence in Experiment 1. In the unsuppressed eye, a dynamic Mondrian pattern was presented and a target letter in a known color was embedded within two streams of heterogeneously colored letters. In the suppressed eye, two circles were faded in 1, 3 or 7 letters prior to the target, starting at the beginning of the ISI prior to the trial and reaching their full color in the last 33 ms of their respective letters. On cue-present trials, one circle was colored in a non-target color and the other circle was gray. On cue-absent trials, both circles were gray. Participants first made an unspeeded response to the target's identity, and then rated the visibility of the cue on a scale ranging from 0 (not visible at all) to 3 (clearly visible). This example corresponds to the lag 1, cue-present, same-location condition for the red target (green cue) group

Such awareness-dependent lag 1 sparing would mimic a cue-location effect at lag 1 on aware-cue trials. However, based on the finding that attentional capture is independent of conscious perception (Lamy et al., 2015; see also Zivony & Lamy, 2016), if this effect occurred only on aware-cue trials, it could be attributed to lag 1 sparing rather than to attentional capture by the cue—because the location effect at lag 1 on *unaware*-cue trials can serve as an uncontaminated measure of attentional capture.

Methods

Participants

The participants were 18 Tel-Aviv University undergraduate students (mean age = 24.73 years, SD = 2.42, 10 females) who participated in the experiment for course credit. All reported normal or corrected-to-normal visual acuity and normal color vision.

Apparatus

Stimuli were presented on an LCD monitor (23-in. Samsung SyncMaster) with a 1920 × 1080-pixel resolution and 120-Hz refresh rate. To create a stereoscopic perception, participants viewed stimuli through Samsung SSGM3150GB 3-D Active Glasses, which let an image through to one eye while blocking stimulation to the other, with a 120-Hz rate of alternation between the two eyes that is beyond the perceptual threshold. Responses were collected via the computer keyboard. Viewing distance was set at 50 cm from the monitor.

Stimuli and procedure

The sequence of events is illustrated in Fig. 1. In the unsuppressed eye, two RSVP streams were presented as the succession of 17 frames along with a gray 0.2° × 0.2° fixation ("+") sign against a black background. Each frame consisted of two letters appearing at a center-to-center distance of 2.1° to the left and right of fixation. Each frame appeared for 75 ms and was separated from the next frame by a 33 ms blank screen, yielding an SOA of 108 ms between successive frames. In each frame, the two letters were randomly drawn from the English alphabet (excluding I, O, X, T and Z), with the constraints that two letters in the same stream, as well as two letters presented simultaneously or sequentially in the different streams could never be the same. All letters were drawn in bold Courier New font and subtended 1.4° in height. The target letter was defined by its color. For half of the subjects it was red (RGB = 207, 32, 32) and for the other half, it was green (RGB = 0, 238, 0). On each trial, the target appeared randomly in the ninth, eleventh or

thirteenth position in one of the two streams. The remaining (non-target) letters in the streams were randomly blue (RGB = 106, 106, 255), purple (RGB = 140, 0, 175) or yellow (RGB = 222, 205, 112).[4]

A cue display was presented to the suppressed eye and consisted of two circles (1.2° in radius) surrounding the locations of the two letters of the RSVP streams showed to the non-suppressed eye. On cue-present trials (85% of the trials), one of the circles was gray, while the other circle (the cue) was colored. The cue was green (RGB = 0, 255, 0) for the red-target group and red (RGB = 255, 60, 60) for the green-target group. The non-cue (gray) and the cue (colored) circles were equiluminant. On cue-absent trials (15% of the trials), both circles in the cue display were gray. The cue display appeared at lag 1, 3 or 7 from the target. Specifically, the two circles in the cue display were faded in for 75 ms and then presented at full luminance during the last 33 ms of the presentation of the letter pair appearing at lag 1, 3 or 7 prior to the target display. The cue display was offset simultaneously with these letters. Conditions of cue-target lag (1, 3 or 7) and cue-target location (same vs. different) were equiprobable and randomly mixed.

The sequence of events on each trial consisted of the fixation frame (500 ms), followed by the RSVP streams. Then, a question mark appeared on a blank screen, prompting the participant to identify the target letter as accurately as possible and with no time pressure, by typing the corresponding key on a standard keyboard with their right hands. In case the participants were unable to identify the target, they were encouraged to guess. No feedback was given on accuracy. Following the first response, two question marks appeared on the screen. They prompted the participants to report on the quality of their subjective experience of a red (or green) circle preceding the target using a scale ranging from 0 (not visible at all) to 3 (clearly visible). This second response was provided by pressing the 'z', 'x', 'c' or 'v' key on the computer keyboard (which were relabeled 0, 1, 2 and 3, respectively, using stickers) with their left hands. A new trial began 500 ms after the second response.

Participants were informed that a red (or green) circle would appear on a proportion of the trials and were shown an image of it prior to the experiment. They were instructed

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[4] The reason why the cue color in one group did not exactly match the target color in the other group is that different factors constrained the choice of the target and cue colors. On the one hand, the target color had to be discriminable enough for baseline performance to remain relatively high, as is characteristic of previous AB studies. On the other hand, the cue color had to be faint enough for participants to be entirely unaware of its presence (and rate its visibility as null) on a sizeable proportion of the trials. Note that the latter constraint differed in this experiment relative to the previous one, in which CFS was used: in Experiment 3, the cue had to be strong enough to overcome suppression on enough trials to elicit above 0 visibility ratings.
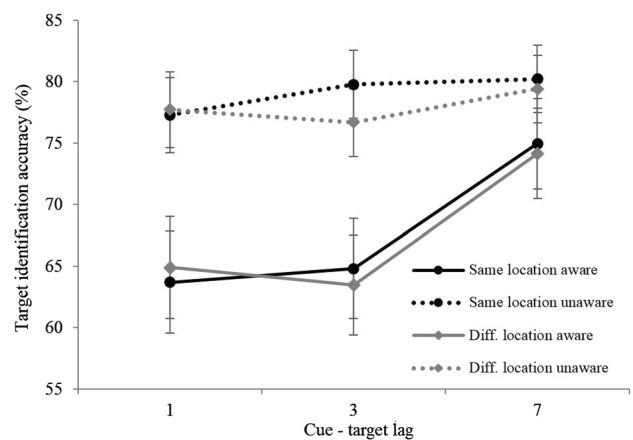

Fig. 2 Mean target identification accuracy rates (in percentages) in Experiment 1 by conditions of cue-target lag, cue-target location and cue awareness. Error bars represent standard errors

to focus their gaze on the fixation cross and to search only for the target in the streams. They were specifically instructed to search only for the target and only to signal to what extent they had seen a red (or green) circle, if at all. The experiment started with a 10-trial practice block, followed by 420 experimental trials divided into six 70-trial blocks. Participants were allowed a short rest between blocks. All protocols were approved by Tel Aviv University ethics committee.

Results

Visibility ratings

The participants rated cue visibility to be 0, 1, 2 and 3 on 47%, 7%, 7%, and 39% of the trials, respectively, on cue-present trials and on 80%, 8%, 3% and 9%, respectively, on cue-absent trials. Binomial tests revealed that visibility ratings of 2 and 3 were predictive of cue presence, $p(550/595, 85\%) < 0.0001$ and $p(2980/3095, 85\%) < 0.0001$, respectively, while visibility ratings of 1 were actually predictive of cue absence, $p(114/608, 15\%) < 0.01$.

Lag-dependent cost of awareness

Mean accuracy rates are presented in Fig. 2. The main effects of awareness and lag were significant, $\chi^2(1) = 45.02$, $p < 0.0001$, and $\chi^2(2) = 24.78$, $p < 0.0001$, respectively: performance was poorer in the aware than in the unaware-cue trials, and for lags 1 and 3 than for lag 7, $Z = 4.6$, $p < 0.0001$ and $Z = 4.31$, $p < 0.0001$, respectively, with no difference between lag 1 and lag 3, $Z < 1$. The two-way interaction between cue awareness and cue-target lag was also significant, $\chi^2(2) = 10$, $p = 0.006$. Follow-up comparisons indicated that performance was unaffected by lag when subjects were

unaware of the cue, with no difference between either lag 1 and lag 3 or lag 3 and lag 7, both Zs < 1. In contrast, when subjects were aware of the cue there was a blink without lag-1 sparing: performance was significantly lower for lag 1 and lag 3 than for lag 7, $Z = 5.03$, $p < 0.001$ and $Z = 5.08$, $p < 0.001$, respectively, with no difference between lag 1 and lag 3, $Z < 1$. There was no other significant effect, that is, no effect involving cue location, all ps > 0.46.

Spatial shifts of attention

Same- and different-location trials did not differ in either the unaware-cue trials, 77.28% vs. 77.73%, respectively, or the aware-cue trials, 63.69% vs. 64.89%, respectively, both Zs < 1. The Bayes Factor analysis provided strong evidence for this null effect in both the aware and unaware-cue trials, $BF01 = 97.23$ and $BF01 = 96.27$, respectively.

Discussion

In this experiment, performance was similar whether the target appeared at the same location as the cue or at the alternative location. This finding indicates that attention was not shifted to the location of the nontarget-color cue. It replicates previous findings (Lamy et al., 2015) supporting the contingent-capture account (e.g., Folk & Remington, 1998) and its extension to cases in which the cue is task-relevant but does not possess the color in which participants are required to engage their attention (Lamy et al., 2015).

Crucially, target identification accuracy was lower when it followed a consciously perceived color cue at lag 1 or 3 than at lag 7, whereas performance remained high across lags when the cue was entirely missed. These findings are the first report of a lag-dependent impairment in observers' performance that is triggered by an event that is not spatially attended and is contingent on explicit conscious detection of this event.

Finally, lag 1 sparing occurred on neither aware- nor unaware-cue trials: in both cases, performance was as poor at lag 1 as it was at lag 3. Since the cue did not capture attention, this finding supports Nieuwenstein et al.'s (2009) claim that lag 1 sparing is related to attention and not to conscious perception. Before we can accept this conclusion, however, an alternative account must be considered. The CFS paradigm used to impair the conscious perception of the cue in Experiment 1 is not typical of attentional blink studies and might explain why we failed to observe lag 1 sparing in that experiment. For instance, the binocular rivalry on which the CFS paradigm relies may have resulted in suppression of the target when the cue was consciously perceived and was close to the target in time (i.e., at lag 1). It is also possible that the dynamic Mondrian itself abolished lag 1 sparing. Consistent with this conjecture, Chua (2015) found that a

moving overlay of dots presented on top of an RSVP stream presented centrally to both eyes can both attenuate the blink and eliminate the sparing. We tested these possibilities in Experiment 2.

Experiment 2

Experiment 2 was similar to Experiment 1, except that we removed the CFS procedure and rendered the cue liminal using masks and by reducing the exposure duration of the color-cue. We expected to replicate the main findings of Experiment 1, namely, a lag-dependent cost of awareness and the absence of attentional capture by the color cue on unaware-cue trials at lag 1. Of particular interest was whether lag-1 sparing would be observed in this experiment.

Methods

Participants

The participants were 16 Tel-Aviv University undergraduate students (mean age = 23.21 years, SD = 2.12, 10 females) who participated in the experiment for course credit. All reported having normal or corrected-to-normal visual acuity and normal color vision.

Apparatus, stimuli, procedure, and design

The sequence of events is illustrated in Fig. 3. The apparatus, stimuli, procedure, and design were similar to those of Experiment 1 except for the following changes: We no longer used Continuous Flash Suppression (CFS) to manipulate the conscious perception of the cue.

Thus, the participants no longer wore glasses, displays no longer included the Mondrian, and all stimuli were presented binocularly. In this experiment, the center-to-center distance between the two streams was increased to 3°. Each letter in a stream was surrounded by a gray outline square (3-pixel thick and subtending 1.2° in the side, RGB = 117, 117, 117), which appeared and disappeared together with the letter it enclosed. Each frame appeared for 58 ms and was separated from the next frame by a 50 ms blank screen, yielding the same 108-ms SOA as in Experiment 1. In the cue display, the two outline squares were gray for the first 25 ms. On cue-present trials (85% of the trials), one of them (the cue) became colored during the last 33 ms, whereas on cue-absent trials (15% of the trials), both squares remained gray throughout the 58-ms exposure duration. The cue was liminal because of its short exposure duration and of forward and backward masking by the gray squares that preceded and followed it, respectively. It was always green (RGB = 0, 255, 0) for the red (RGB = 207, 32, 32) target group, and was
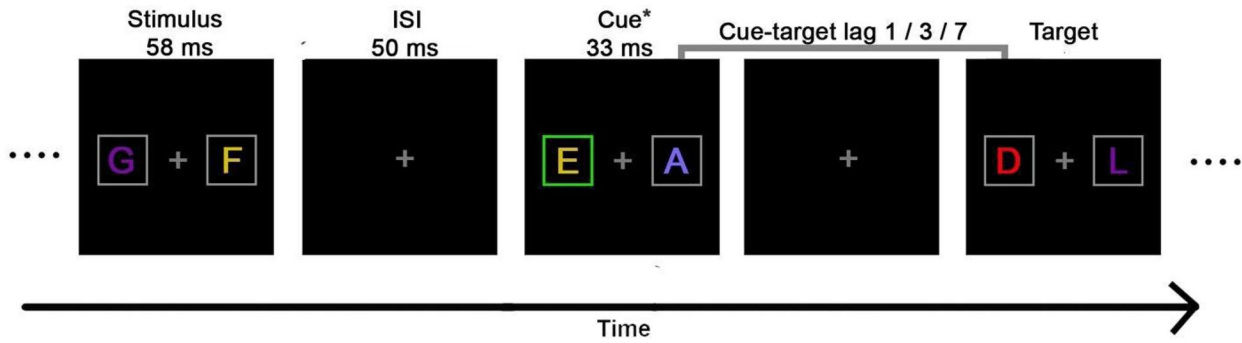
Fig. 3 Sample trial sequence in Experiments 2 and 3. The color of the cue was either different from the target color (Experiment 2) or the same (Experiment 3). Participants first made an unspeeded response to the target's identity (here, D), and then reported their subjective perception of the colored cue on a scale ranging from 0 (not visible at all) to 3 (clearly visible). This example corresponds to the lag 1, cue-present same-location condition for the red target (green cue) group
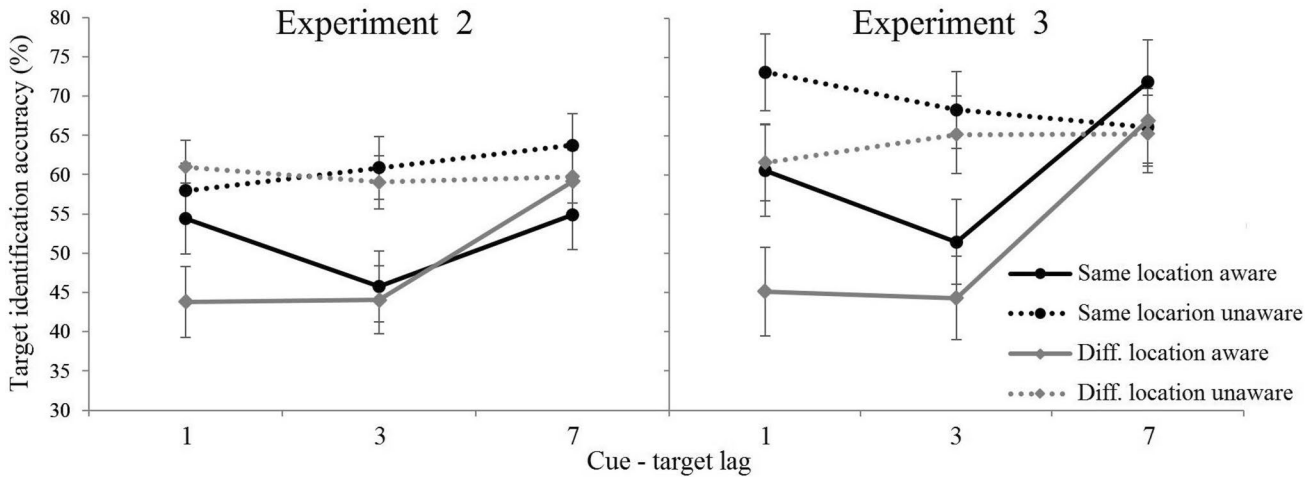

Fig. 4 Mean target identification accuracy rates (in percentages) in Experiment 2 (left panel) and Experiment 3 (right panel) by conditions of cue-target lag, cue-target location and cue awareness. Error bars represent standard errors

always red (RGB = 255, 60, 60) for the green (RGB = 0, 238, 0)[7] target group.

Results

The data from one participant were removed from analysis because this participant's accuracy exceeded the group's average by more than 2 standard deviations ($M = 87.2\%$ vs. $M = 57.4\%$, SD = 9.8%). The results were nevertheless similar when these data were included.

Visibility ratings

The participants rated cue visibility to be 0, 1, 2 and 3 on 60%, 16%, 9%, and 15% of the trials, respectively, on cue-present trials and on 76%, 14%, 6% and 4%, respectively, on cue-absent trials. Binomial tests revealed that visibility ratings of 2 and 3 were predictive of the cue presence $p(675/758, 85\%) < 0.0001$ and $p(1080/1126, 85\%) < 0.0001$, respectively, whereas visibility ratings of 1 were not, $p(1074/1246, 85\%) > 0.12$.

Lag-dependent cost of awareness

Mean accuracy rates are presented in Fig. 4 (left panel). The main effect of cue awareness was significant $\chi^2 (1) = 29.99$, $p < 0.001$, with poorer performance on aware- relative to unaware-cue trials, 50.41% vs. 60.41%, respectively. The main effect of lag was also significant, $\chi^2 (2) = 9.33$, $p = 0.009$. Post-hoc analyses indicated that performance was poorer for lag 1 and lag 3 than for lag 7, 56.5% vs. 60.4%, $Z = 2.65$, $p = 0.02$, and 55.6% vs. 60.4%, $Z = 3.66$, $p < 0.001$, respectively, with no significant difference between lag 1 and lag 3, $Z < 1$.

The two-way interaction between lag and cue awareness was significant, $\chi^2 (2) = 7.01$, $p = 0.03$ and was modulated by a significant three-way interaction with location, $\chi^2 (2) = 8.31$, $p = 0.015$. Post-hoc analyses clarified this interaction. When subjects were unaware of the cue, performance was independent of lag, with no difference between lag1 and lag 3 or between lag 3 and lag 7, in both the same-location condition, both $ps > 0.3$, and the different-location condition, both $Zs < 1$. When subjects were aware of the cue, the interaction between location and lag approached significance, $\chi^2 (2) = 5.52$, $p = 0.06$. Planned comparisons revealed that in the same-location condition, performance was significantly better for lag 1 than for lag 3, $Z = 1.66$, $p = 0.048$ and significantly poorer for lag 3 than for lag 7, $Z = 1.9$, $p = 0.028$. In the different-location condition, performance was poorer for lag 3 than for lag 7, $Z = 3.49$, $p < 0.001$, and did not differ significantly between lag 1 and lag 3, $Z < 1$. Thus, the cost of awareness exhibited the full time course typical of the AB, including lag-1 sparing when the cue appeared at the same location as the target.

Spatial shifts of attention

To verify that spatial attention was not shifted to the cue location in this experiment, we conducted planned comparisons between same- and different-location trials in which the target immediately followed the cue (lag 1). On unaware-cue trials, performance did not differ between the same- and different-location conditions, 57.9% vs. 60.9%, respectively, $Z = 1.05$, $p > 0.95$. The Bayes Factor analysis provided substantial evidence for this null effect, $BF01 = 8.22$. On aware-cue trials, performance was higher on same-than on different-location trials, $Z = 2.19$, $p = 0.01$.

Discussion

The results of Experiment 2 replicated the main findings of Experiment 1. There was no performance benefit when the target appeared at the same location as a cue rated to be invisible, indicating that again, the cue did not capture attention. Target identification accuracy was again lower when it followed a consciously perceived color cue at lag 3 than at lag 7, whereas performance remained high across the two lags when the cue was not consciously perceived. In addition, there was no cue location effect at lag 1 when the cue was missed. Finally, unlike in Experiment 1, a lag-1 sparing effect was observed in the same-location condition, when participants reported seeing the cue.

Taken together, the findings of this experiment show that there was a lag-dependent cost of awareness with lag-1 sparing with a cue that did not benefit from spatial attention. We thus conclude that spatial attention is not necessary for lag-1 sparing and that our failure to observe lag-1 sparing in

Experiment 1 is likely to have resulted from using Continuous Flash Suppression (CFS).

Experiment 3

In Experiments 1–2, we investigated the blink when the cue did not benefit from spatial attention. Yet, in all previous AB studies, the object eliciting the blink was spatially attended because (a) all stimuli appeared at fixation (e.g., Raymond et al., 1992; Nieuwenstein et al. 2009), (b) identification of T1 required that attention be moved to its location (e.g., Visser et al., 1999), or (c) the first target was replaced with a distractor that did not require any response but captured attention (e.g., Folk, Leber & Egeth, 2002). Thus, spatial attention may be sufficient, albeit not necessary, for the blink to occur. The main objective of Experiment 3 was to determine whether the conscious perception of the first event is necessary for the blink to occur or if, instead, attention is sufficient.

Experiment 3 was similar to Experiment 2 except that the cue shared the target color and was, therefore, expected to trigger a spatial shift of attention both when it was consciously perceived and when it was not (e.g., Lamy et al., 2015). Thus, unlike in Experiment 2, we expected better performance for same- than for different-location trials on both aware- and unaware-cue trials. We also expected consciously perceived cues to produce a blink, as in Experiments 1 and 2. Of main interest was whether a blink would be observed for target-color cues that were not consciously perceived.

An additional goal of this experiment was to examine whether the magnitude of the blink is larger when the cue benefits from spatial attention than when it does not. To do that, we followed the guidelines suggested by MacLean and Arnell (2012). Specifically, we measured the blink depth as the performance increment between lag 3 and lag 7 for consciously perceived cues across locations, and the magnitude of lag-1 sparing as the decrement in performance from lag 1 to lag 3 on same-location trials and compared them for target-color cues (Experiment 3) vs. non-target-color cues (Experiment 2). We also verified that target-color cues elicited spatial shifts of attention to their location, whereas nontarget-color cues did not, by comparing the cue location effect on unaware-cue trials in Experiments 2 vs. 3.

Methods

Participants

The participants were 16 Tel-Aviv University undergraduate students (mean age = 23.21 years, SD = 2.12, 10 females) who participated in the experiment for course credit. All

reported having normal or corrected-to-normal visual acuity and normal color vision.

Apparatus, stimuli, procedure, and design

The apparatus, stimuli, procedure, and design were similar to those of Experiment 2, except that the cue color always matched the target color. Thus, half of the participants were presented only with red cues and red targets and the other half only with green cues and green targets.

Results

The data from one participant were excluded from all analyses because she did not seem to comply with the instructions, as suggested by her extremely low accuracy rate relative to the group, $M = 2.5\%$ vs. $M = 64.2\%$, $SD = 8.0\%$.

Visibility ratings

Participants rated cue visibility to be 0, 1, 2 and 3 on 66%, 10%, 10%, and 14% of the trials, respectively, on cue-present trials and on 82%, 11%, 4% and 3%, respectively, on cue-absent trials. A series of binomial tests revealed that visibility ratings of 2 and 3 were predictive of the cue presence, $p(616/668,85\%) < 0.0001$ and $p(897/927,85\%) < 0.0001$, respectively, whereas visibility ratings of 1 were not, $p(680/800,85\%) > 0.52$.

Lag-dependent cost of awareness

Mean accuracy rates are presented in Fig. 4 (right panel). All main effects were significant, $\chi^2 (1) = 28.66$, $p < 0.0001$, $\chi^2 (1) = 22.97$, $p < 0.0001$ and $\chi^2 (2) = 11.43$, $p < 0.0001$ for cue awareness, location and lag, respectively. Participants were less accurate when they were aware of the cue than when they were unaware of it, on different-than on same-location trials, and for lag 1 and lag 3 relative to lag 7, $Z = 3.71$, $p < 0.0001$, and $Z = 5.56$, $p < 0.0001$, respectively, with no significant difference between lag 1 and lag 3, $Z = 1.48$, $p > 0.29$. The two-way interaction between lag and awareness was significant $\chi^2 (1) = 41.91$, $p < 0.0001$. Post-hoc comparisons revealed that while performance was unaffected by lag on unaware-cue trials, with similar performance on lags 1, 3 and 7, all $Zs < 1$, in the aware-cue trials, accuracy was poorer for lag 3 than for lag 7, $Z = 7.04$, $p < 0.0001$, with no difference between lag 1 and lag 3, $Z = 1.452$, $p > 0.68$.

The two-way interaction between cue-target lag and location was also significant, $\chi^2 (2) = 11.95$, $p < 0.003$, indicating that the cue location effect waned as the lag increased. Post-hoc comparisons revealed a significant effect of the location at lag 1, 12.8%, $Z = 4.73$, $p < 0.0001$ that diminished at lags 3 and 7, 4.3%, $Z = 2.02$, $p > 0.32$, and 2.1%, $Z = 1.2$, $p > 0.8$,

respectively. Neither the interaction between location and awareness nor the three-way interaction were significant, $\chi^2 (1) = 1.3$, $p > 0.25$ and $\chi^2 < 1$, respectively, indicating that the magnitude of the cue location effect and its time course were independent of cue awareness. As expected, planned comparisons on aware-cue trials revealed a lag-1 sparing in the same-location condition, $Z = 1.787$, $p = 0.037$, but not on different-location trials, $Z < 1$.

Spatial shifts of attention

Planned comparisons for the lag-1 condition confirmed that the target-color cue triggered a spatial shift of attention: accuracy was higher in the same- than in the different-location condition, both on aware-cue trials, $Z = 2.89$, $p = 0.0018$ and on unaware-cue trials, $Z = 4.65$, $p < 0.0001$, with no significant difference between these conditions, $p > 0.7$. The Bayes Factor analysis provided substantial evidence for the presence of a cue location effect on both aware-cue trials, $BF10 = 5.78$ and unaware-cue trials, $BF10 > 100$.

Comparisons between Experiments 2 and 3 (Fig. 4, left vs. right panel)

Blink depth

We compared the blink depth, that is, the increment in performance from lag 3 to lag 7 when the cue was consciously perceived in Experiments 2 vs. 3. The interaction between experiment and lag was significant, $\chi^2 (1) = 5.41$, $p < 0.02$ and was not modulated by cue-target location, $\chi^2 (1) < 1$. Thus, across cue-target locations, the blink was significantly deeper when the cue was in the target color and benefitted from spatial attention (Exp.3) than when it was in a different color and did not benefit from spatial attention (Exp.2).

Lag 1 sparing

We compared the decrement in performance from lag 1 to lag 3 when the cue appeared at the same location as the target and was consciously perceived in Experiments 2 vs.3. We found no difference in the magnitude of the lag-1 sparing between the two experiments, $\chi^2 (1) < 1$.

Spatial shifts of attention

Our previous analyses already revealed a significant cue location effect (i.e., a performance advantage of the target appearing in the same vs. in the alternative stream relative to the cue) at lag 1 in Experiment 3, but not in Experiment 2. A between-experiments analysis confirmed that the cue location effect was significantly larger in Experiment 3 than in Experiment 2, $\chi^2 (1) = 14.32$, $p = 0.0001$.

Discussion

The results of Experiment 3 replicated the findings from previous studies: attention was shifted to the location of a target-color cue, this effect was independent of conscious perception of the cue (Lamy et al., 2015) and lag-1 sparing occurred only when the cue and target appeared in the same stream (e.g., Visser et al., 1999b). This experiment yielded three novel findings.

First, a spatially attended cue (just as a cue that did not benefit from spatial attention in Experiments 1 and 2) produced no blink unless it was consciously perceived. This finding clearly indicates that shifting spatial attention to the location of a potentially relevant object does not suffice to produce a blink.

Second, we found the blink to be deeper when the cue shared the target color (and benefitted from spatial attention) relative to when did not share the target color (and did not benefit from spatial attention). Two interpretations of this finding are possible. One is that spatially focused attention directly enhanced the blink. The other is that objects are perceived more vividly when they benefit from spatial attention and that the effect of attention was in fact mediated by the quality of conscious perception. We could not compare Experiments 2 and 3 to test this possibility because the target- and nontarget-color cue conditions were not administered in the same context and were run on different participants. Hence, a rating of '2', for example, in Experiment 2 does not necessarily correspond to a rating of '2' in Experiment 3, thereby precluding any meaningful comparison of visibility ratings between the two conditions. Further research is needed to clarify this issue.

Finally, lag-1 sparing occurred only when the cue was consciously perceived and was of the same magnitude for target- and nontarget-color cues. These findings suggest that spatial attention is neither necessary nor sufficient for lag-1 sparing, whereas conscious perception of the cue is crucial.

General discussion

Summary of the findings

The present study is the first systematic attempt to disentangle the contributions of conscious perception and spatial attention in eliciting the attentional blink. In three experiments, we found the conscious perception of a first event to be a necessary condition for a lag-dependent impairment at identifying a subsequent event (the blink).[5] In sharp contrast,

Table 1 Conscious perception of a first event is a necessary condition for the blink (defined as a lag-dependent perceptual cost in processing a subsequent event). Spatial attention is neither sufficient nor necessary, although a consciously perceived event produces a larger blink when it benefits from spatial attention than when it does not

	Awareness	No awareness
No spatial attention	Blink	No blink
Spatial attention	Larger blink	No blink

a shift of spatial attention to the first event was neither necessary nor sufficient for the blink, although it enhanced the blink's depth elicited by a consciously perceived event. Table 1 provides a summary of the effects of spatial attention and conscious perception on the blink.

The blink and spatial attention

Our conclusion that spatial attention is not necessary for the blink is contingent on the claim that nontarget-color cues did capture attention in our experiments. For unaware-cue trials, the results of Experiments 1 and 2 unambiguously demonstrated that nontarget-color cues did not elicit spatial shift of attention to their location, since we found positive evidence for a null cue location effect in both experiments. For aware-cue trials, however, performance was higher when the cue shared the target location at lag 1 in Experiment 2, as would be expected if it benefitted from spatial attention.

Two arguments lead us to conclude that this finding reflects lag-1 sparing rather than spatial attention. First, we found that when a cue summons attention to its location, the cue location effect is of the same magnitude when the cue if consciously perceived and when it is not (Exp.3, see also Lamy et al., 2015). Thus, the cue location effect on unaware-cue trials provides a clean estimate of attentional capture on aware-cue trials. Second, in Experiment 1, there was no trace of either a cue location effect or lag-1 sparing on aware-cue trials at lag 1. We surmised that the use of CFS may have obliterated lag-1 sparing in that experiment and can reject the alternative account according to which CFS prevented attentional shifts to the cue, because such shifts were observed using CFS in previous studies (e.g., Lamy et al., 2015).

One could still argue that attention was shifted to the location of the nontarget-color cues but attention was quickly reoriented away before the target appeared, even at

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[5] Previous studies reported the incidental finding that RTs to a target are slower when this target follows a prime that is consciously perceived relative to when this prime escapes awareness (e.g., Lamy et al., 2015; Peremen & Lamy, 2014a, b; see also Van den Bussche

Footnote 5 (continued)

et al., 2013). As the time interval between the prime and target in these studies typically fell within the range of the blink period, the observed impairment is likely to reflect, at least in part, the same cost of awareness as reported in the present study.

lag 1 (e.g., Theeuwes, Atchley & Kramer, 2000). However, several studies, using both behavioral (e.g., Chen & Mordkoff, 2007; Gaspelin, Ruthruff & Lien, 2016; Lamy, 2005) and electrophysiological measures (e.g., Eimer, Kiss, Press & Sauter, 2009) invalidated the fast-disengagement account. We thus conclude that the nontarget-color cues did not benefit from spatial attention in the present study.

A cost of conscious perception or a cost of conscious report?

Many models assign a critical role to the process of consolidating T1 information in working memory in creating the blink (e.g., Chun & Potter, 1995; Jolicoeur & Dell'Acqua, 1999; Jolicoeur, 1999; Vogel, Luck & Shapiro, 1998). However, these models generally do not explicitly specify the role of consciousness, and this role cannot be easily inferred because the interplay between consciousness and working memory is not fully understood as of yet. For example, though items held in WM are readily accessible for conscious perception (Andrade, 2001), crucial aspects of WM are thought to reside outside the scope of consciousness (see Velichovsky, 2017). In addition, it is not clear whether conscious perception necessarily entails encoding into WM (Baars & Franklin, 2003), or whether stimuli that are not consciously perceived can be encoded into WM (Soto, Mäntylä & Silvanto, 2011, but see Stein, Kaiser & Hesselmann, 2016).

In the present study, participants were required to report on the quality of their subjective experience of the cue. Thus, conscious perception of the cue was inevitably confounded with encoding the cue representation in working memory for the report. It may thus seem trivial to claim that the attentional blink is a cost of awareness.

However, a blink has often been also observed when T1 is replaced with a distractor that is entirely irrelevant to the task and does not require any response (e.g., Folk et al., 2002; Folk et al., 2009; Leblanc & Jolicoeur, 2005; Wyble et al., 2013; Zivony & Lamy, 2014; 2016)—unlike in the present study in which participants had to rate its visibility. Thus, a distractor can trigger a blink under conditions in which participants have nothing to gain by encoding it in VSTM. However, in these studies, the distractor matched the target-defining feature and was thus likely to capture attention. Schmidt et al. (2002) suggested that the representations of stimuli that benefit from spatial attention are automatically encoded in visual working memory. If so, it might still be the case that in these studies, the blink elicited by a to-be-ignored distractor that captured attention may have resulted from encoding this distractor in VSTM.

Schmidt et al.'s (2002) used a change detection paradigm in which a spatially uninformative cue appeared at the location of one of the objects subsequently presented in the memory array. They found better change detection performance when the probe following the memory array appeared at the cued than at a non-cued location. They concluded that the information at the cued location was automatically transferred in VSTM. Note, however, that since observers had to remember all the objects in the memory array, preferentially encoding the object at the cued location in VSTM incurred no cost. By contrast, in AB studies (e.g., Folk et al., 2002) encoding the distractor in working memory would serve no purpose at all and would, therefore, unnecessarily burden VSTM.

Although the idea that conscious perception of the distractor triggered the blink in these studies provides a parsimonious account for the blink, it remains possible that conscious perception is not sufficient for the blink to occur and that encoding of the cue in WM is also necessary. We are currently addressing this question more directly by investigating the impact of the report in our paradigm. In light of the foregoing discussion, we thus conclude that the current results establish that spatial attention is neither necessary nor sufficient for the blink and that instead, conscious perception is necessary, although encoding in WM may also be required.

Spatial shifts of attention, attentional engagement and conscious perception

In typical AB studies all items, including the targets, appear at fixation. Thus, the task involves no spatial uncertainty and attentional selection is purely temporal. It could be argued that while we showed that spatial attention is not necessary for the AB, non-spatial attentional selection may, in fact, be crucial. In other words, one could claim that the cue-triggered attentional amplification locked to the time of its appearance but spatially diffuse, and that such transient amplification occurred only when the cue was consciously perceived. However, according to this definition, attentional amplification is indistinguishable from conscious perception. In addition, it is widely agreed that transient attentional enhancement is mediated by spatial attention even in tasks in which selection is temporal (e.g., Chun, Golomb & Turk-Browne 2011; Wyble et al., 2009).[6] Thus, we take the finding that the cue was not spatially attended in Experiments 1 and 2 to indicate that it did not benefit from any attentional enhancement.

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[6] McKay and Juola (2007) showed that spatial and temporal cues are associated with independent cueing benefits. However, this finding only entails that observers can take advantage of two separate sources of knowledge and that these have additive effects on performance. McKay and Juola's (2007) finding does not entail that spatial selection and temporal attentional selection per se, operate independently of each other.

Our finding that spatial attention is not necessary for the blink to occur entails that observing a blink when a distractor is presented shortly before a target does not necessarily imply that this distractor captured attention. It thus invalidates the inference made by previous studies (e.g., Folk et al., 2002; Leblanc & Jolicoeur, 2005; Wyble, Folk & Potter, 2013, Oriet, Panday & Kawahara, 2017, Meijs et al., 2018) and promotes an alternative account, according to which objects that capture attention (either because they belong to a special class of stimuli such as faces or because they match a given task set) are more likely to be consciously perceived than objects not capturing attention (see Lamy et al., 2015; Most et al., 2005 for findings supporting this claim; see also Fei–Fei et al., 2005 for evidence that the meaning of peripheral natural images can be consciously perceived even when spatial attention is focused on the center of the screen).

Reports of an "unconscious blink"

Recent reports that an attentional blink can be elicited by a stimulus that is not consciously perceived are inconsistent with our claim (as well as Nieuwenstein et al.'s, 2009) that conscious perception of the first event is required for an AB to occur. For instance, Oriet et al. (2017) had participants identify a target letter embedded in an RSVP stream, in which unbeknownst to them, a schematic face was briefly presented at critical lags prior to the letter target. Awareness of the faces was probed at the end of the experiment, and even participants who reported no conscious experience of the faces were found to suffer from a blink when the face shared the target-defining color. The authors concluded that the blink reflected involuntary attentional capture by the faces and could occur in the absence of any conscious perception of the face. Note, however, that while only 15% of the participants were aware that there had been a face in the stream, 90% of the participants noted something unusual. The authors underscored that the remaining 10% of participants, who reported no awareness of any kind, also showed an AB. However, given that the procedure promoted a very high proportion of (albeit minimal) conscious perception and that participants were asked to report detection of anything unusual only at the end of the experiment, it is reasonable to suggest that the measure used to assess awareness in that study might simply not have been sensitive enough to capture fleeting conscious experience of an unidentified and task-irrelevant stimulus.

In a recent study, Meijs, Slagter, de Lange and van Gaal (2018, Experiment 3) also reported an unconscious blink, as an incidental finding. The authors' objective was to determine how T1-based predictions influence T2 detection during the blink. Two targets, defined as one of two possible letters, appeared in a single RSVP stream of distractor letters.

T1 was presented liminally and its identity predicted the identity of T2 on most trials. At the end of each trial, participants were asked to type in any target letters they had seen. The authors found valid T1-based predictions to facilitate T2 detection only when T1 was seen (i.e., correctly identified) yet, crucially, an unidentified T1 elicited a blink. The 'liminal' T1 was presented at fixation for a median duration of 125 ms and participants were able to identify it with 75% accuracy. Under these viewing conditions, it is reasonable to assume that participants were at least partially aware of T1 on the trials in which they failed to report its identity. By contrast, here, a trial was classified as an unaware-cue trial only if participants reported the cue as being absent. In other words, the categorization of T1 as "not consciously perceived" was considerably more liberal in that study than in ours: unconscious-T1 trials were those in which T1 was not fully identified in Meijs et al.'s study and those in which T1 was not detected (i.e., indistinguishable from a blank) in ours. In this sense, Meijs et al.'s finding does not constitute strong evidence for the existence of an "unconscious blink".

A perceptual-grouping account of Lag-1 sparing

Our study is the first to disentangle the roles of spatial attention and conscious perception in lag 1 sparing, by directly manipulating spatial attention to T1 while monitoring its conscious perception. Our results indicate that spatial attention is neither necessary (Experiment 2) nor sufficient (Experiment 3) for lag 1 sparing to occur and that conscious perception of T1 is the crucial condition. Thus, they invalidate the widespread notion that lag-1 sparing occurs because the transient attentional enhancement triggered by T1 also accrues to T2 (e.g., Bowman & Wyble, 2007; Chua, 2015; Nieuwenstein et al., 2005; Nieuwenstein et al., 2009; Olivers & Meeter, 2008; Shih, 2008). Note that these findings appear to be at odds with Nieuwenstein et al.'s (2009) report of a lag 1 sparing associated with a missed T1. However, considering that unlike the typical effect, their lag 1 sparing was not followed by an attentional blink, the two sets of findings can be readily reconciled if one interprets the performance benefit these authors reported at lag 1 vs. lag 3 on missed-T1 trials as unconscious attentional capture by T1, rather than as lag 1 sparing.

What mechanism might account for lag-1 sparing that occurs only when the target appears at the location of a consciously perceived cue, but the location of which is not attended? We suggest that lag-1 sparing occurs when T1 and T2 (which correspond to the cue and target here) are perceived as belonging to the same consciously perceived event. Building on Akyurek, et al.'s (2012) suggestion that lag 1 sparing is linked to a mechanism of temporal integration (see also Hommel & Akyurek, 2005; Akyurek & Hommel, 2005), we further propose that the binding of T1 and

T2 into a single conscious event is more likely to occur when T1 and T2 can be grouped into a unified representation, and especially when they occupy the same location and are contiguous in time (but see Jefferies, Enns & Di Lollo, 2014, for an argument against the location specificity of lag 1 sparing).

This T1-T2 grouping account of lag-1 sparing thus strongly links lag-1 sparing to observers' subjective conscious experience. It provides a framework that can accommodate many disparate findings in the literature relative to lag-1 sparing (e.g., Akyurek et al., 2012; Dell'Acqua, Jolicoeur, Pascali & Pluchino, 2007; Dux & Harris, 2007; Harris, Benito, & Dux, 2010; Livesey & Harris, 2011; Wyble, Bowman, Potter & Nieuwenstein, 2011) as well as to other forms of sparing, such as 3-target sparing (e.g., Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Kawahara, Kumada, & Di Lollo, 2006; Nieuwenstein & Potter, 2006; Olivers, Van der Stigchel, & Hulleman, 2007). For instance, Livesey and Harris (2011) showed that lag-1 sparing occurs when letters or digits are used as stimuli but is virtually eliminated when using line drawings of familiar objects. According to the proposed framework, such stimulus dependence of lag-1 sparing may reflect that letters and digits are easily combined into unitized letter strings and multiple-digit numbers, whereas grouping is less likely between successive objects. Furthermore, Akyurek et al. (2012) provided direct support for a T1-T2 grouping account of lag-1 sparing by showing that when the conjunction of T1 and T2 formed a possible target stimulus, observers frequently reported seeing only a single merged target stimulus when targets appeared at lag 1.

Conclusions

The present study demonstrates that focused spatial attention is neither necessary nor sufficient for eliciting the AB. This finding implies that attentional episodes can be initiated successively without a perceptual cost or a refractory period (see Zivony & Lamy, 2014; 2016 for converging evidence). Instead, we showed that conscious perception of an event (when reported) induces a robust cost on the processing of a subsequent event—which we call the cost of awareness (CoA) and that this cost exhibits all the defining characteristics of the attentional blink. We thus conclude that the AB and the CoA reflect the operation of the same mechanism. Framing the AB as a cost of awareness opens new perspectives for our understanding of this phenomenon. In particular, it suggests novel directions for future research by highlighting the potential role of factors influencing subjective conscious experience, such as perceptual grouping, in shaping our performance when we interact with successive events. However, whether conscious perception per se or reported conscious perception (which entails encoding in

VSTM) is critical for the blink, remains to be clarified in further research.

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