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OBSERVATION

Eye Movements Blink the Attentional Blink

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When presented with a sequence of visual stimuli in rapid succession, participants often fail to detect a second salient target, a phenomenon referred as the attentional blink (AB; Raymond, Shapiro, & Arnell, 1992; Shapiro, Raymond, & Arnell, 1997). On the basis of a vast corpus of experiments, several cognitive theories suggest that the blink results from a discrete structuring of attention, sampling information from temporal episodes during which several items can access encoding process (Wyble, Bowman, & Nieuwenstein, 2009; Wyble, Potter, Bowman, & Nieuwenstein, 2011). The objective of this work is to explore the AB when multiple items are presented at the fovea during ocular movements. The authors reasoned that each fixation may cohesively form an episode and hence expected that the blink may vanish within a single fixation. In turn, they expected saccades to accentuate episodic borders and hence shorten the regime of interference when 2 targets are presented fovealy in successive fixations. Evidence is provided in favor of this hypothesis, showing that the blink vanishes when both targets are presented in the core of a single fixation (far from the saccadic boundaries) and that it recovers more rapidly in successive fixations. These studies support current views that episodes should have an effect on the AB and provide evidence that eye movements play an important role in the formation of episodes.

Keywords: attentional blink, eye movements, episodes, attention, saccades, bottleneck, RSVP, natural vision

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When presented with a sequence of visual stimuli in rapid succession at the same spatial location on a screen, participants often fail to detect a second salient target (T2) occurring in succession if it is presented between 200 and 500 ms after the first one (T1), a phenomenon referred to as the attentional blink (AB; Raymond et al., 1992; Shapiro et al., 1997).

A notable exception to the blink is that T2 can be easily seen if it is presented immediately after T1, an effect called *Lag 1 sparing*. Sparing may also occur even if a distractor item is presented between them (Bowman & Wyble, 2007; Nieuwenhuis, Gilzenrat, Holmes, & Cohen, 2005; Potter, Staub, & O'Connor, 2002). Identification accuracy for trailing targets also remains unimpaired at later *lags*—positions in the sequence of stimuli—if preceded by another target (Kawahara, Kumada, & Di Lollo, 2006), and the blink vanishes when participants report all of the items in a *rapid sequential visual presentation* (RSVP) instead of some of them (whole-report superiority effect; Nieuwenstein & Potter, 2006; Potter, Nieuwenstein, & Strohminger, 2008). These results suggest that the blink does not result from a resource depletion but, instead, from temporal sequencing of attention. The window of attention might be affected by task instructions; observers who had to report some combination of T1 and T2, thus having one single goal to accomplish, presented a strongly reduced AB effect compared with observers who had to report T1 and T2 (two separate goals; Ferlazzo, Fagioli, Di Nocera, & Sdoia, 2008; Ferlazzo, Lucido, Di Nocera, Fagioli, & Sdoia, 2007). Shapiro and collaborators showed that the blink is strongly attenuated when the two targets can be perceived as the same "object" (Kellie & Shapiro, 2004; Raymond, 2003), incorporating notions of gestalt continuity to the formation of episodes and suggesting that targets sharing an "object file" might form shared episodic representations (Kahneman, Treisman, & Gibbs, 1992).

These features of the phenomenology of the blink have been taken as converging evidence of the formation of constrained windows of attentional enhancement, referred as events or episodes, deployed in response to detected relevant stimuli (Bowman & Wyble, 2007; Wyble et al., 2009, 2011). These notions have

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been incorporated to models that posit that visual attention samples information from temporal episodes, formally defined as temporal intervals during which attention remains strongly engaged, allowing one or more targets to enter the encoding process (Wyble et al., 2009, 2011). The engagement in such episodes affects visibility and conscious access of concurrent items not merged in the episode.

This vast experimental corpus has been acquired in fixed-gaze experiments. However, in normal vision, information is sampled in a discrete sequence of fixations with characteristic time constants (~300 ms) shorter than the window of the blink (Henderson, 2003; Otero-Millan, Troncoso, Macknik, Serrano-Pedraza, & Martinez-Conde, 2008; Rayner, 1998). Does a single fixation in natural vision constitute a single episode? If so, are targets in RSVP occurring during a single fixation during natural eye movements spared from the blink? Might a saccade abruptly close an attentional episode, preventing targets in a successive fixation from being blinked? In this article, we set to investigate these questions by quantifying visibility in RSVPs occurring in a saccade–fixation–saccade complex.

Method

Participants (N = 22; 12 male, 10 female, M_{age} = 23.7 years, age range = 20–31 years) made two rapid saccades to the left, to the center, and then to the right side of the screen (see Figure 1). The distance between the left and right fixation squares was 19.2 degrees. Two RSVP of letters (size = 0.8 degrees of visual angle) updated every 70 ms (stimulus duration = 60 ms) were presented in the central and right positions of the screen. A first target (T1, the letter *X*) was always presented in the central RSVP. A second target (T2, the letter *Y*) was presented immediately after T1 (Lag 1) or after 1 to 4 distractors after T1 (Lags 2 to 5), in either the central or right RSVP—or fixations. Participant's reported whether they saw the targets.

Eye movements were recorded with a video-based eye tracker Eyelink 1000 (http://www.sr-research.com/). Observers' left eyes were tracked at a sample rate of 1000 Hz. All experiments were implemented in MATLAB (Mathworks, Natick, MA) using psychophysics toolbox (Brainard, 1997).

All trials in which the distance of the fixation to the center of the RSVP exceeded 0.4 degrees or in which participants made more than one fixation within the central RSVP were rejected. We also excluded from analysis trials in which, due to the specific sequence of eye movement of the participant (which was not under the experimenter's control) T1 or T2 were not presented at participants gaze. Three participants were excluded from analysis because less than 50 trials passed the trial rejection criterion. The rejection procedure was very strict and resulted in the rejection of a high fraction of the trials (60%, range: [27%, 73%]). This required collecting more than 800 trials per participant in several experimental sessions.

In a controls experiment, eight participants maintained fixation in the center of the screen during the trial seeing a single RSVP as in a "classic" blink experiment. All stimulus properties were identical to the main experiment. T1 distribution within the RSVP and the T2–T1 lag were matched to the main experiment. T2 was absent in 50% of the trials.

Data Analysis

The experiment has three main variables: The presentation of T1 and T2 within the same fixation or across different fixations, the lag between T1 and T2, and the stimulus to saccade asynchrony (SSA). The SSA was measured at half-duration of stimulus occurrence (30 ms after the onset and 30 ms before the offset) and the

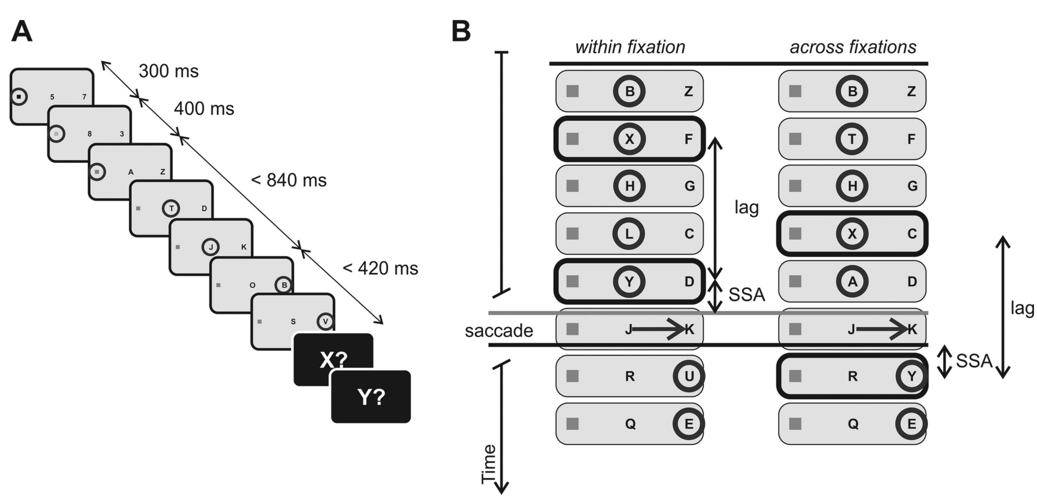

Figure 1. Experimental design. A: In the beginning of each trial, participants fixate on a square in the left of the screen along the horizontal meridian. When the color of the dot changes to green (after 700 ms), they make two successive saccades, first to a rapid sequential visual presentation (RSVP) in the center and then to an RSVP in the right of the screen. Each panel indicates a frame of the sequence for a representative trial. The position of the eye is indicated with a black circle. B: In different trials targets were presented either in the same or in different RSVPs. Representative examples of two LAG 3 trials; within fixation (left panels) or across fixation (right panel). The horizontal black lines indicate the onset of the fixations and the horizontal gray line, the onset of the saccade.

onset (offset) of the saccade for the within (across) fixation conditions and averaged across nonoverlapping bins of 70 ms. For each lag, data from an SSA bin were considered for the analysis only if there were at least 35 trials in this category.

Results

Participants moved their eyes rapidly from a fixation square in the left of the screen to an RSVP in the center and then rapidly made a second saccade to an RSVP in the right portion of the screen. The mean fixation duration in the central RSVP was (363 ± 97) and was weakly determined by the onset of T1 [correlation coefficient of T1 and saccade onset: *R*(T1 SEEN, within fixation) = 0.31; *R*(T1 UNSEEN, within fixation) = 0.05; *R*(T1 SEEN, across fixation) = 0.39; *R*(T1 UNSEEN, across fixation) = 0.02; supplementary Figure 1 and supplementary Table 1].

We analyzed separately cases in which both targets were presented in the same RSVP (referred as within-fixation condition) or in different RSVPs (referred as across-fixations condition). Performance on T1 was overall greater for the within-fixation condition ($M \pm SEM$) for Lag 2 to 4: (0.70 ± 0.02) and (0.61 ± 0.02) for within- and across-fixations conditions, respectively; $p < .0001$, $t = 4.00$. The conditional probability of seeing T2 given that T1 was seen P(T2|T1)– showed a monotonic decrease with lag for the within-fixation condition [Figure 2, black solid line; analysis of variance (ANOVA) with lag as main factor and participants as random factor revealed a significant effect, $F(3) = 6.53$, $p < .0005$]. The effect of lag was significantly less pronounced than in the control experiment in which the RSVP was presented while participants maintained their gaze fixed [slope between Lag 1 to Lag 4 for within-fixation condition = (−0.30 ± 0.07) and for control experiment = (−0.64 ± 0.05); see Table 1]. P(T2|T1) also showed a significant effect of lag for the across-fixations condition [ANOVA with lag as main factor and participants as random factor, $F(3) = 7.34$, $p < .0001$] but showing an opposite pattern; the likelihood of seeing T2 increased for larger lags (see Figure 2A, black dashed lines). This was confirmed by a regression analysis of P(T2|T1) with lag that revealed a positive slope [slope between Lag 2 to Lag 5 for across-fixations condition = (0.38 ± 0.08); see Table 1].

The lag between T1 and T2 correlated with the delay between the presentation of T2 and the onset of the saccade henceforth referred as stimulus to saccade asynchrony (SSA; see sketch in Figure 2B). For instance, in the within-fixation condition, longer lags increased the probability that T2 is presented just before the saccade. Similarly, in the across-fixations condition, short lags increased the likelihood that T2 was presented just after the saccade. Since the window of visibility during a fixation might not be homogeneous, we reasoned that this factor may affect the P(T2|T1) pattern reported above. To identify the relative contributions of these effects we submitted P(T2|T1) to independent ANOVAs for the within- and across-fixations conditions, with lag and SSA as main factors. These ANOVAs showed that only the SSA had a significant effect for within-fixation condition: lag, $F(3) = 2.03$, $p = .11$, and SSA, $F(2) = 6.90$, $p < .005$. In the across-fixations condition, both lag and SSA showed significant effects: LAG, $F(3) = 3.93$, $p < .01$, and SSA, $F(2) = 23.13$, $p < 10^{-6}$. In this ANOVA, we did not include the interactions due to the lack of sufficient statistical power exacerbated by some degree of colinearity between the two main regressors. To investigate this interaction, we follow the ANOVA with a logistic regression (Hosmer & Lemeshow, 2000; see Table 2). For the within-fixation condition this analysis revealed an effect of lag, typical of the blink, only for the shorter SSA values where T2 is presented just a few milliseconds before the onset of the saccade. When T2 was presented far from the saccades—both onset and offset of fixation—the blink effect vanished (see Figure 2B, left panels; and Table 2). For the across fixation, we observed that, only for intermediate SSA values, the AB carries over from the first fixation to the second one and then recovers abnormally quickly (see Figure 2B, right panels; and Table 2), reaching a plateau over the 70% at Lag 3: *t* test for the across-fixation condition at SSA between 30 and 100 ms, comparing between Lag 3 and Lag 4, $t = 0.34$, $p = .73$; and between Lag 3 and Lag 4, $t = 3.40$, $p < .001$. When SSA was very short, implying that T2 is presented just after the saccade, the visibility is very poor regardless of the lag (see Figure 2B, right panels; and Table 2). When SSA is very long, T2 visibility is very high (higher than for all other conditions) and remains stable for all lag values, revealing the absence of a blink effect (see Figure 2B, right panels; and Table 2).

Discussion

These results are highly consistent with an “episodic” origin of the blink (Bowman & Wyble, 2007; Wyble et al., 2009, 2011) and suggest that (a) targets in a single fixation are more likely to be grouped within an episode, hence resulting in a very modest blink effect in the within-fixation condition; and (b) saccades, in turn, may mark episodic boundaries, disengaging from an episode and hence removing the blink effect when T2 is presented (independent of lag) more than 100 ms after the saccade.

Table 1
Main Effects of Lag on P(T1|T2)

	Logistic regression					
Condition	Weights	p	Deviance	χ^2	*df*	$p\ (X > \chi^2)$
Fixed gaze	(−0.64 ± 0.05)	$<10^{-5}$	1841 (1663)	0.19	32	1.00
Within fixation	(−0.30 ± 0.07)	$<10^{-5}$	1212 (933)	0.90	42	1.00
Across fixations	(0.38 ± 0.08)	$<10^{-5}$	924 (737)	0.81	41	1.00

Logistic regression of P(T2|T1), using lag and participants as factors were performed for each individual condition: within fixation, between fixation, and fixed-gaze experiment. The estimated and measured values did not differ significantly as shown by the Hosmer-Lemeshow test (see Method section).

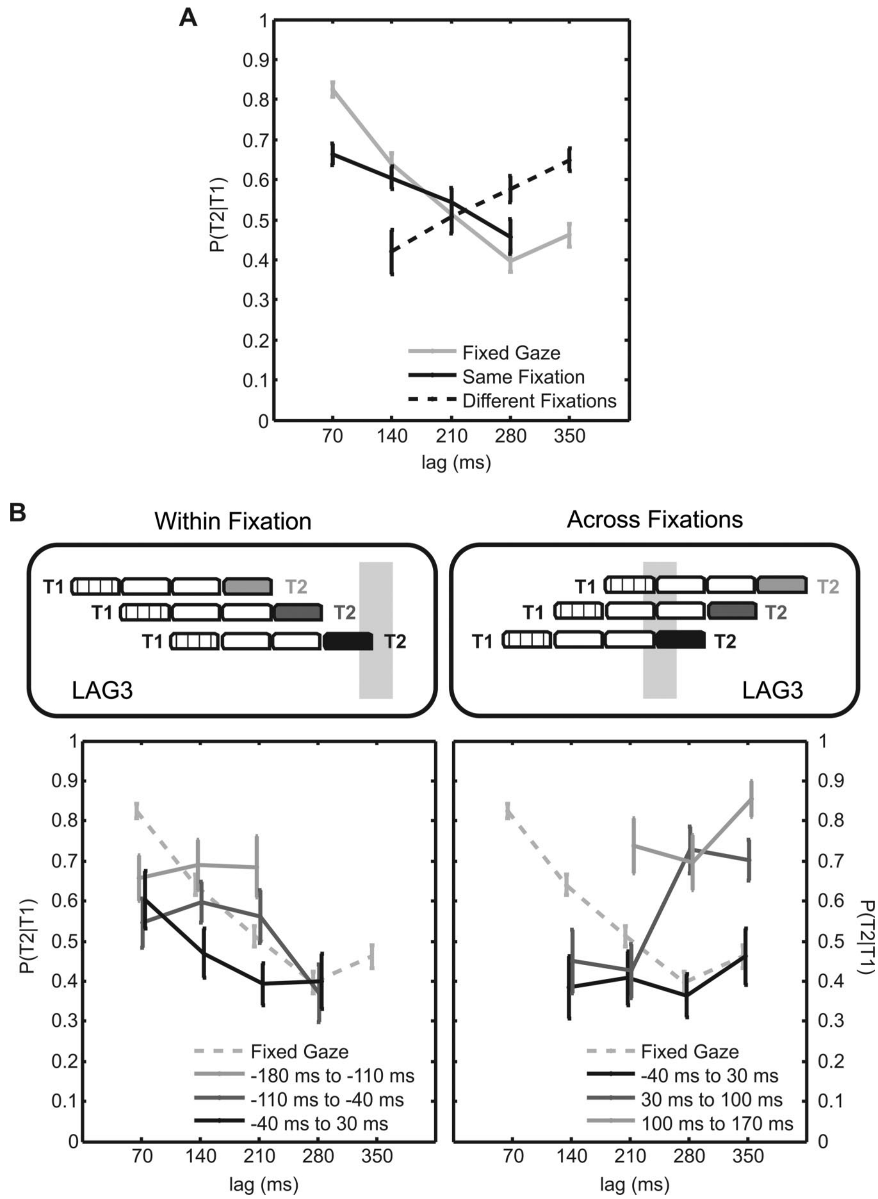

Figure 2. Blinking the attentional blink across and within saccades. A: P(T2|T1) as a function of lag showed a typical dependence with lag for a "classic blink" control experiment in which participants sustained fixation and atypical patterns within and across fixations in the eye-movement experiment. In the within, Condition P(T2|T1) showed only a moderate decrease as a function of lag. In the across condition it showed a monotonic increase with lag. B: Performance for within (left) and across (right) conditions as a function of the relative timing between the onset of T2 and the saccades (SSA). In the schema for LAG 3 at different SSA, each box represents a stimulus. The striped box is T1, the white boxes are distractors, and the filled boxes are T2 at different SSA. Gray shading represents the saccade.

This is, to our knowledge, the first report of an AB during eye movements and, thus, at this stage, we cannot discard other possible mechanisms that also explained the observations. For instance, the AB is strongly reduced or abolished when participants are engaged in distracting tasks such as music or task-irrelevant visual motion (Arend, Johnston, & Shapiro, 2006; Olivers, van der Stigchel, & Hulleman, 2007). It is then likely that eye movement planning might accrue a cost which removes attention from T1 diminishing the effect of the blink. However, dual-task cost cannot explain the differences observed between the within- and across-fixations conditions, and in the relative timing of stimulus and saccade onset. The intricate pattern of interactions indicates that more is at play than simply distraction by a concurrent task.

Another relevant element that may play a role in the impact of eye movements in the blink is that attention is directed to the

Table 2
Effects of Lag on P(T1|T2) for Different Stimulus to Saccade Asynchrony (SSA)

Logistic regression							
Condition	SSA (ms)	Weights	p	Deviance	χ^2	df	p ($X > \chi^2$)
Within fixation	−180 to −110	(−0.20 ± 0.28)	0.4855	169 (143)	1.21	21	1.00
Within fixation	−110 to −40	(−0.26 ± 0.15)	0.0924	283 (241)	1.17	22	1.00
Within fixation	−40 to 30	(−0.31 ± 0.14)	<0.05	316 (233)	1.74	22	1.00
Across fixations	−40 to 30	(−0.02 ± 0.17)	0.9174	248 (202)	0.60	22	1.00
Across fixations	30 to 100	(0.55 ± 0.14)	$<10^{-4}$	266 (217)	0.78	22	1.00
Across fixations	100 to 170	(0.52 ± 0.30)	0.0782	119 (130)	0.74	19	1.00

Note. Logistic regression of P(T2|T1), using lag and participants as factors were performed for each condition: within fixation and between fixation, and SSA bin. The estimated and measured values did not differ significantly as shown by the Hosmer-Lemeshow test (see Method section). SSA was measured between the middle of the stimulus and the onset (offset) of the saccade for the within fixation (across fixations) condition, and averaged across no overlapping bins of 70 ms.

saccade location prior to the eye movement (Berman & Colby, 2009; Caspi, Beutter, & Eckstein, 2004; Dore-Mazars, Pouget, & Beauvillain, 2004; Duhamel, Colby, & Goldberg, 1992; Melcher & Colby, 2008; Posner, Cohen, & Rafal, 1982). However, this predicts high T2 performance in the across fixations because the saccade should direct, in anticipation, attention to the second RSVP, boosting perceptual performance. Instead, we observe that T2 performance is very poor, only achieving normal levels when the time between the saccade and T2 onset is greater than 100 ms (see Figure 2B, right panel). This shows that our findings cannot be explained solely by eye-movement triggered redirection of attention (Berman & Colby, 2009; Caspi et al., 2004; Dore-Mazars et al., 2004; Duhamel et al., 1992; Melcher & Colby, 2008; Posner et al., 1982). However, it is possible that eye movements play a role in resetting an episode online, with phase-resetting mechanism in neuronal oscillatory activity locked to the onset of saccades (Maldonado et al., 2008; Rajkai et al., 2008; Schroeder & Lakatos, 2009).

An important question is how to reconcile our observation that there is no blink with a fixation, with the vast experimental corpus demonstrating an AB if fixed-gaze experiments. We see two complementary solutions to this puzzle. First, episodes are likely to have a typical time scale (Wyble et al., 2011); an episode may halt either with goal termination (Ferlazzo et al., 2007), with an eye-movement, as we described, or after a time limit (of around 500 ms), which might establish a typical duration of episodes in natural vision. A second related and interesting alternative is that even during "fixed-gaze" participants make microsaccades, which have been shown to play a role in perceptual (Martinez-Conde, Macknik, Troncoso, & Dyar, 2006) and attentional (Engbert & Kliegl, 2003; Hafed & Clark, 2002; Laubrock, Engbert, & Kliegl, 2005) transitions in several experimental paradigms (Rolfs, 2009). For instance, they may trigger perceptual alternations during multistable vision (Laubrock, Engbert, & Kliegl, 2008; Troncoso, Macknik, & Martinez-Conde, 2008; Troncoso, Macknik, Otero-Milian, & Martinez-Conde, 2008). It is interesting to note that the temporal dependency of the blink and the distribution of microsaccades locked to a stimulus, have comparable timescales (Dimigen, Valsecchi, Sommer, & Kliegl, 2009; Engbert & Kliegl, 2003; Otero-Millan et al., 2008; Rolfs, 2009). A prediction of our study, which might motivate future studies, is that the formation of episodes (as revealed by the blink) might be related to the occurrence of microsaccades.

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