

# Dissociating between the N2pc and attentional shifting: An attentional blink study

Alon Zivony<sup>a,\*</sup>, Ayala S. Allon<sup>b</sup>, Roy Luria<sup>a,c</sup>, Dominique Lamy<sup>a,c</sup>

<sup>a</sup> School of Psychological Sciences, Tel Aviv University, Israel

<sup>b</sup> Department of Psychology, The Ohio State University, United States

<sup>c</sup> Sagol School of Neuroscience, Tel Aviv University, Israel

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## ABSTRACT

The N2pc is routinely used as an electrophysiological index of attentional shifting. Its absence is thus taken as evidence that no shift of attention occurred. We provide evidence in contrast to this notion using a variant of the attentional blink (AB) paradigm. Two target letters, embedded in two streams of distractor letters and defined by their color, were separated by either 300 or 800 ms. The second target was preceded by a distractor frame of the same color (cue). As expected, identification of the second target was poorer at the short than at the long lag (the AB effect). The AB did not affect attentional capture by the cue, but suppressed and delayed the N2pc associated with it. This result suggests that the N2pc does not reflect attentional shifting. Instead, we conclude that the N2pc indexes the transient enhancement that occurs at the spatial focus of attention and promotes high-level processing such as identification. This conclusion calls for a reinterpretation of findings from the attentional capture literature that relied on the N2pc as an index of attentional shifting. Our results also inform contemporary models of the AB.

## 1. Introduction

Visual attention refers to the mechanisms that help resolve the capacity limitations inherent to our visual system by selectively enhancing the processing of certain stimuli at the expense of others. Space plays an important role in such selection: a stimulus that appears at an attended location is more likely to undergo extensive processing than a stimulus at an unattended location.

An increasingly popular measure of spatial attention is the N2pc (N2-posterior-contralateral) component of the event-related potential (ERP), a negative-going deflection of the EEG waveform with a maximum over visual (posterior) areas contralateral to the location of an attended stimulus (e.g., Eimer, 1996; Luck and Hillyard, 1994). Several studies attempted to clarify which aspects of spatial attention are indexed by the N2pc (e.g., Foster et al., 2018; Kiss et al., 2008a, 2008b; Van Velzen and Eimer, 2003). In particular, they examined the relationship between the N2pc and attentional shifting, which is the focus of the present paper. For instance, in Kiss et al. (2008a, 2008b) study, informative cues indicated the side of upcoming targets in some blocks, whereas cues were spatially uninformative in other blocks. Performance was better following informative cues, indicating that attention was shifted towards the target's location before the target appeared. Yet, the

target-locked N2pc was similar following informative and uninformative cues. Since informative cues eliminated the need for an attentional shift towards the target, this finding suggests that the N2pc can emerge in the absence of an attentional shift and that this component reflects processes that occur downstream from attentional shifting (see also Foster et al., 2018).

Nevertheless, the presence of an N2pc is routinely taken as evidence that attention was shifted to the location contralateral to the component peak, and conversely, its absence is taken as evidence that no such shift has occurred (Ansorge et al., 2010; Buodo et al., 2009; Burra and Kerzel, 2013; Burra et al., 2016; Dell'Acqua et al., 2006; Eimer and Kiss, 2008, 2010; Hilimire and Corballis, 2014; Holguín et al., 2009; Ikeda et al., 2013; Jiao et al., 2013; Jolicœur et al., 2006a, 2006b; Kiss et al., 2012, 2008a, 2008b; Lien et al., 2011; Liu et al., 2017; Lorenzo-López et al., 2008; Schubö and Müller, 2009; Woodman and Luck, 1999; Wu et al., 2013; Wykowska and Schubö, 2011).

Finding an N2pc provides unambiguous evidence that an attentional shift occurred, because it is unanimously agreed that this component indexes lateralized attentional processing. However, does its absence necessarily entail that attention did not shift? It is often assumed to be the case. This inference is based on the assumption made by most models of spatial attention that shifting attention towards a stimulus

\* Correspondence to: The School of Psychological Sciences, Tel Aviv University, Ramat Aviv 69978 POB 39040, Aviv, Israel.

E-mail address: [alonzivo@post.tau.ac.il](mailto:alonzivo@post.tau.ac.il) (A. Zivony).

necessarily entails that the information at that location is further processed (e.g., Goldfarb and Treisman, 2010; Posner et al., 2007; Wolfe, 2007). If the N2pc reflects processing stages that are a mandatory consequence of attentional shifting, then it is legitimate to take the absence of an N2pc as evidence that no shift of attention occurred. However, while this assumption naturally holds when attention is voluntarily moved for the purpose of extracting information from the prioritized location, it can break down when attention is captured involuntarily. In two recent studies, we showed that a distractor can summon attention to its location with no further processing, such as stimulus identification, at that location (Zivony and Lamy, 2016, 2018). Thus, at least under certain circumstances, finding no N2pc associated with a stimulus does not suffice to conclude that attention did not shift towards that stimulus.

To summarize, while there is previous evidence showing that the N2pc can occur in the absence of an attentional shift (e.g., Kiss et al., 2008a, 2008b; Foster et al., 2018), evidence that a shift of attention can occur in the absence of an N2pc is lacking. The objective of the present study was to fill this gap. We relied on a variant of the attentional blink paradigm as a manipulation that disrupts the N2pc while leaving attentional shifting intact. We thus provide direct evidence that the N2pc cannot be used as an analog of attentional shifting.

### 1.1. The attentional blink

The attentional blink (AB) is one of the most widely used paradigms for the study of the temporal limitations of our perceptual system. 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 impaired when this target appears within 200–500 ms after the first target (T1).

Many studies have shown that the N2pc is suppressed during the AB (Akyürek et al., 2010; Dell'Acqua et al., 2006; Jolicœur et al., 2006a, 2006b; Robitaille et al., 2007; Verleger et al., 2009). For example, Jolicœur et al. (2006a) had participants identify two colored digits, T1 and T2 in a stream of letter distractors, with T1 presented in the center of the screen and T2 presented laterally. The amplitude of the N2pc elicited by T2 was clearly attenuated when T2 appeared 200 ms after T1 (i.e., at the short lag, or inside the blink period) relative to when it appeared 800 ms after T2 (i.e., at the long lag, or outside the blink period). Jolicœur et al. (2006a) concluded that the AB impairs the deployment of attention and that the allocation of spatial attention “freezes” during the blink period (see also Dell'Acqua et al., 2006; Jolicœur et al., 2006b; Robitaille et al., 2007). In other words, they concluded that attentional shifts are prevented during the blink. Note, however, that none of these studies used an independent measure of spatial attention allocation: the N2pc was only assumed to index spatial attention.

In direct contradiction with the conclusion of the foregoing studies, recent findings suggest that attentional capture (i.e., attentional shifting) is unaffected by the blink (Bae et al., 2018; Ghorashi, Spalek, Enns, & Di Lollo, 2009a; Ghorashi et al., 2010; Ghorashi et al., 2009b; Zivony and Lamy, 2014, 2016). For instance, in Zivony and Lamy (2016, Exp.3), participants searched for two targets (T1 and T2), defined by their color (e.g., red) and embedded in two RSVP streams. Immediately prior to T2, a colored outline square distractor (henceforth, the cue) appeared either in the same stream as T2 or in the alternative stream. As this cue shared the targets' color, it was expected to capture attention (e.g., Folk et al., 2002). Critically, the cue appeared either during the blink period (at lag 2 from T1) or outside the blink (at lag 7 from T1). As is customary in cueing paradigms, we measured attentional capture towards the cue as the improvement in performance when the target appeared at the cued location relative to when it appeared at the alternative location (henceforth, location benefit; e.g., Posner, 1980; Folk et al., 1992). We found a location benefit of equal magnitude whether the cue appeared inside or outside the blink period,

suggesting that spatial attention was not “frozen” during the blink.

By contrast, we found identification of the letter at the cued location to be impaired during the blink. Specifically, observers were less likely to erroneously report the distractor letter inside the cue instead of the target (i.e., there were fewer distractor intrusions, Botella et al., 2001; Vul et al., 2008) when the cue appeared inside than outside the blink. In line with contemporary theories of the AB (Nieuwenstein et al., 2005; Olivers and Meeter, 2008a, 2008b; Wyble et al., 2009), we interpreted this finding as indicating that the AB disrupts the transient attentional enhancement or “attentional engagement” that follows attentional capture (see Discussion). Attentional engagement (e.g., Folk et al., 2009; Nieuwenstein et al., 2005; Posner et al., 2007) is typically defined as a process that promotes feature binding and stimulus identification at the spatial locus of attention, and gates the consolidation of bound stimuli into working memory. Thus, Zivony and Lamy's (2016) results suggest that the AB disrupts attentional processes that occur downstream to attentional shifting, which itself is unaffected by the blink.

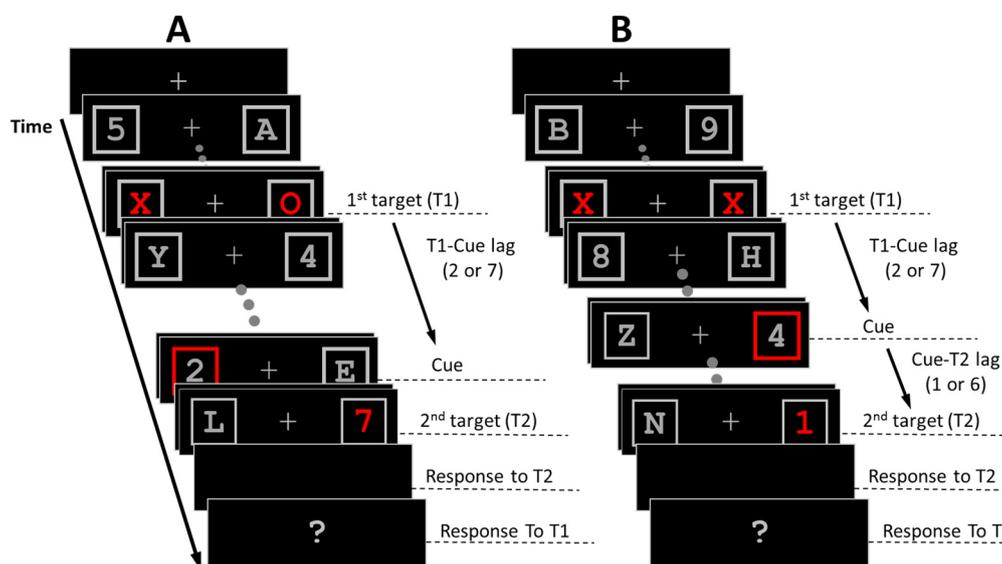
To summarize, electrophysiological findings show that the N2pc is suppressed during the blink (e.g., Dell'Acqua et al., 2006; Jolicœur et al., 2006a) and behavioral findings show that attentional shifts are intact during the blink (e.g., Bae et al., 2018; Ghorashi et al., 2009a; Zivony and Lamy, 2016). Taken together, these findings strongly suggest that the N2pc does not index attentional shifts, but processes that occur downstream to attentional shifting. However, the findings supporting this conclusion were observed in different experiments. The objective of the present study was to investigate whether the AB can be shown to suppress the N2pc, while leaving attentional shifting unaffected, under the same experimental conditions. Such findings would not only indicate that the N2pc reflects processes arising downstream from attentional shifting, but also that this component is not a mandatory consequence of attentional shifting.

## 2. Experiment 1

Reaction times are the standard dependent measure in studies of the N2pc, whereas accuracy rates are the standard measure in AB experiments. However, there have been previous reports of an AB with RTs as the dependent measure. In these studies, T2 was not masked by a subsequent distractor, and responses to T2 were slower with short than with long T1-T2 lags (Giesbrecht and Di Lollo, 1998; Vogel and Luck, 2002; Zuvic et al., 2000, but see Jannati et al., 2011). In order to maximize the number of usable trials in our ERP experiment (i.e., the trials associated with a correct response) we used RTs rather than accuracy as the dependent measure. Thus, before conducting the ERP experiment, we performed a behavioral experiment, the objective of which was to replicate Zivony and Lamy's (2016) main findings, namely, intact attentional capture and impaired identification during the blink, using an RT-based attentional blink paradigm.

Participants searched for two red targets embedded in two RSVP streams of gray distractors. The first target (T1) consisted of a pair of red letters that appeared simultaneously in the two streams. Participants had to determine whether these letters were the same or different, without time pressure. The second target (T2) was a red digit that participants had to classify as smaller or larger than 5, as fast as possible. Immediately prior to T2, a red cue appeared either in the same stream as T2 or in the alternative stream. This cue enclosed a gray distractor digit, also either smaller or larger than 5. Thus, the digit inside the cue associated with either the same response as T2 (compatible trials) or with the alternative response (incompatible trials). Identification of the cued digit should lead to the preparation of the response associated with it, and therefore result in poorer performance on incompatible- relative to compatible-response trials (Eriksen and Eriksen, 1974). The cue (as well as T2) appeared either at a short or at a long lag from T1 (i.e., inside or outside the blink).

If a blink occurred in our experiment, identification at the locations of both T2 and the cue preceding it should be disrupted. Accordingly,



**Fig. 1.** Illustration of the stimulus sequence in Experiment 1 (Panel A) and 2 (Panel B). In Experiment 1, the second target (T2) appeared at positions 14, 16, or 18. The cue preceded the target by exactly one frame, and the first target (T1) preceded the cue by either two or seven frames. Accordingly, T1-T2 lag was either 3 or 8. This example corresponds to the different-location cue condition and when the digit inside the cue was incompatible with the target. In Experiment 2, T2 appeared at positions 16, 18, or 20. The cue preceded T2 by either one or six frames, and T1 preceded the cue by either two or seven frames. Accordingly, T1-T2 lag was 3, 8, or 13. This example corresponds to the same-location cue condition and when the digit inside the cue was compatible with the target.

responses to T2 should be slower when T2 appeared within vs. outside the blink, and the effect of the compatibility between the cued digit and the target digit, which is diagnostic of processing at the cued location, should be smaller inside than outside the blink<sup>1</sup> (see Peressotti, Pesciarelli, Mulatti & Dell'Acqua, 2012, for a similar rationale). Crucially, we expected no effect of the blink on attentional capture. Specifically, reaction times to T2 should be faster when the cue appeared at the same location as the target than at the alternative location and this location benefit should be of equal magnitude whether the cue appeared inside or outside the blink.

### 3. Method

#### 3.1. Participants

Participants were 15 (13 women) Tel-Aviv University undergraduate students ( $M$  age = 23.91,  $SD$  = 4.55) who participated for course credit. All reported normal or corrected-to-normal visual acuity and color vision.

#### 3.2. Apparatus

Displays were presented in a dimly lit room on a 23" LED screen, using  $1920 \times 1280$  resolution graphics mode and 120 Hz refresh rate. Responses were collected via the computer keyboard. Viewing distance was set at 50 cm from the monitor.

#### 3.3. Stimuli and design

The sequence of events is presented in Fig. 1. Each trial began with the presentation of a fixation display, a gray  $0.2^\circ \times 0.2^\circ$  plus sign at the center of the screen. Then, after 500 ms, two RSVP streams appeared as the succession of 14, 16 or 18 frames along with the fixation sign. Each frame consisted of two alphanumeric characters ( $1.3^\circ$  in height), each enclosed in an outline square (3-pixel thick,  $1.5^\circ$  in side)

<sup>1</sup> Note that in our previous accuracy-based AB paradigm (Zivony and Lamy, 2016), we used intrusions from the cued distractor (i.e., erroneous reports of the distractor letter inside the cue instead of the target) in order to measure of processing at the cued location. Here, because we relied on RTs, accuracy was expected to be at ceiling, and intrusions to be extremely rare. We therefore manipulated the compatibility between the cued digit and the target to achieve the same goal.

and appearing at a center-to-center distance of  $4.5^\circ$  to the left and right of fixation.

The two targets (T1 and T2) were red. The first target (T1) was a pair of letters (either "X" or "O") that appeared in the same frame and were unpredictably either identical (e.g. "X" and "X") or different (e.g. "X" and "O"). T2 could be any digit between 1 and 9 except for 5. T2 appeared randomly in the 14th, 16th or 18th positions and was followed by a blank screen. T1 appeared either 3 or 8 frames prior to T2 (i.e., T1-T2 lag was either 3 or 8). Participants were asked to report first whether the red digit (T2) was larger or smaller than 5 and then whether the two red letters (T1) were identical or different. The T2 task was speeded and the trial was terminated if no response was given after 1500 ms. The T1 task not speeded. A new trial began immediately after the participant made the second response.

On 80% of the trials, all the outline squares were gray, except for one square (the cue) that was red and appeared immediately prior to T2. The cue and T2 appeared unpredictably and independently in either the left or the right stream. Thus, they were equally likely to appear at the same location or at different locations. On the remaining 20% of the trials (cue-absent trials) all frames were gray.

All the distractors were gray. Each distractor frame contained one letter randomly selected from a 23-letter set (all English alphabet letters, excluding I, X and O) and one digit randomly selected between 1 and 9 but different from 5. Each frame contained a letter on one side and a digit on the other side, except for the T1 frame (which contained two letters). The distractor within the cue was always a digit and was equally likely to be compatible or incompatible with the response associated with the target digit (T2). T2 as well as the digit within the cue could appear only once per trial. The other digits and letters could repeat, but not in two consecutive frames. The RGB values were (180, 180, 40;  $15.93 \text{ cd/m}^2$ ) for red and (128, 128, 128;  $26.93 \text{ cd/m}^2$ ) for gray. All alphanumeric stimuli were drawn in bold "Courier New" font.

The experiment included 10 practice trials followed by 480 experimental trials divided into 60-trial blocks. Four participants did not complete all experimental trials but were still included in the analysis, with missing data ranging from 12 to 150 trials. All conditions were randomly intermixed within the blocks.

#### 3.4. Statistical analysis

##### 3.4.1. Mixed-effects models

Reaction times were analyzed using linear mixed-effects model (LMM) and accuracy rates were analyzed with generalized linear mixed-effects model (GLMM). These analyses were conducted with subject-

**Table 1**

Mean accuracy rates (in percentage) and reaction times (in milliseconds) for T1 and T2 responses on cue-absent trials as a function of T1-T2 lag. Standard errors appear in parentheses. In both experiments, there was a significant Attentional Blink effect (i.e., poorer T2 identification performance at lag 3 relative to lag 8) on both accuracy rates and RTs.

		Accuracy rates			Reaction times		
		T1-T2 lag 3	T1-T2 lag 8	Lag effect	T1-T2 lag 3	T1-T2 lag 8	Lag effect
Experiment 1	T1	80.0% (3.3%)	74.9% (3.9%)	5.1%, p = .002	–	–	–
	T2	96.7% (1.1%)	98.1% (0.7%)	– 1.4%, p = .06	641.0 (24.7)	570.2 (24.8)	70.8, p < .001
Experiment 2	T1	96.9% (10%)	95.6% (1.4%)	1.3%, p = .04	–	–	–
	T2	98.1% (0.8%)	99.5% (0.3%)	– 1.4%, p = .008	713.0 (24.6)	620.4 (24.6)	92.3, p < .001

specific intercepts as a random factor,<sup>2</sup> and were carried out using the R statistical software (R Core Team, 2015). For RT analyses, effects were tested in a type III ANOVA, using the lmer function of the lme4 package (version 1.1–13; Bates et al., 2015). The p-values of the effects were determined using Satterthwaite approximations to degrees of freedom, as implemented in the ANOVA function from the stats4 package (version 3.4.1). For accuracy analyses, a GLMM for binary data was fitted by using the glme function and a logit link function (Jaeger, 2008).

### 3.4.2. Cue-T2 compatibility effects

Compatibility effects are measured as the RT difference between trials where the cued digit is associated with a different response than the target (incompatible trials) and trials where it is associated with the same response (compatible trials). Previous studies (e.g., Avneon and Lamy, 2018; Kinoshita and Hunt, 2008) suggested that taking the RT distribution into account when analyzing compatibility effects is important because these effects are strong on fast trials and tend to disappear on slow trials. We thus examined the compatibility effect across the RT distribution. To this end, we used a vincentization procedure (Ratcliff, 1979): quantiles of RT distributions were computed for each participant, each summarizing 10% of the cumulative RT distribution, and were then averaged to produce the group distribution (Rouder and Speckman, 2004). This procedure was applied separately for compatible and incompatible trials and for T1-cue lag 2 and T1-cue lag 7, thus yielding estimates of the compatibility effect for each bin and condition. Because there were not enough trials per condition to conduct a meaningful statistical analysis of the vincentized data with 10 bins, the compatibility effects were measured for the aggregated data in the 50% fastest trials in each condition.

### 3.4.3. Bayesian analyses

Similar to Zivony and Lamy (2016), we expected to find no modulation of the location benefit by the attentional blink. In order to provide positive support for the null hypothesis, in this and the following experiment, we conducted Bayesian analyses using the anovaBF function from the BayesFactor package in R (Morey and Rouder, 2015) with default priors ( $r = 0.5$ ), and with participant intercepts as random effects. Evidence for the lack of the two-way interaction was evaluated by comparing the model including all effects to the model including

<sup>2</sup> Preliminary analyses showed that the maximum model (Barr et al., 2013), which includes random slopes for the independent variables and their interactions, produced the same results. We report the random intercept model in order to be consistent with the model used for the Bayesian analyses. Note that for both experiments, all the reported results were fully replicated when we used a repeated-measures ANOVA.

only the main effects. Following Dienes and Mclatchie (2018) we consider a  $BF_{10}$  to provide evidence for H0 if it is smaller than 0.33 (i.e.,  $BF_{01} > 3$ ).

## 4. Results

Trials with a reaction time below 200 ms were excluded from all RT analyses as anticipatory responses. Trials with an RT deviating from the median RT of each cell by more than 2.5 median absolute deviations were also excluded (2.34% of trials in Experiment 1 and 2.26% of trials in Experiment 2). Accuracy rates and RTs for T1 and T2 responses on cue-absent trials are presented in Table 1. All other analyses included trials in which the cue was present and both T1 and T2 responses were accurate.<sup>3</sup>

### 4.1. Cue-T2 compatibility effect

As is clear from Fig. 2A, for the long lag, the compatibility effect was present in the early part of the RT distribution and entirely vanished in the later part. In contrast, for the short lag, the compatibility effect was absent throughout the RT distribution. We used a model including T1-cue lag (2 vs. 7) and cued distractor compatibility (compatible vs. incompatible) as fixed factors and subject-specific intercepts as a random factor. This analysis included only the 50% fastest trials in each condition (see the Section 3.4). Mean RTs are presented in Fig. 2B.

Reaction times were faster for the long than for the short lag,  $F(1,1950) = 367.7$ ,  $p < .001$ , and when the cued distractor was compatible with T2 than when it was incompatible with it,  $F(1,1950) = 8.79$ ,  $p = .003$ . The interaction between lag and cued distractor compatibility was significant,  $F(1,1950) = 3.93$ ,  $p = .048$ . Follow-up analyses indicated that the compatibility effect was significant when the cue appeared outside the blink (lag 7),  $M = 12.8$  ms,  $F(1, 963) = 15.36$ ,  $p < .001$ , but was entirely absent when the cue appeared inside the blink (lag 2),  $M = 1.7$  ms,  $F < 1$ .

### 4.2. Location benefits

The model included T1-cue lag (2 vs. 7) and cue location relative to the target (same vs. different) as fixed factors and subject-specific intercepts as a random factor. Mean RTs to T2 as a function of T1-cue lag and cue location are presented in Fig. 3.

Reaction times were faster for the long than for the short lag,  $F(1,3460) = 176.9$ ,  $p < .001$ , and when the cue appeared in the target's location than in the alternative location,  $F(1,3460) = 48.04$ ,  $p < .001$ . The interaction between lag and cue location was not significant,  $F < 1$ . The Bayesian analysis provided strong support for the null hypothesis, according to which the location effect is of equal magnitude inside and outside the blink,<sup>4</sup>  $BF_{01} = 13.19$ .

<sup>3</sup> Behavioral data from both experiments is available at figshare (<https://doi.org/10.6084/m9.figshare.7325696>).

<sup>4</sup> Overall RTs were longer within than outside the blink, which raises the possibility that attentional shifting is disrupted during the blink, but this effect is obscured due to scaling effects. We conducted two control analyses to test this alternative account. First, we conducted the same analyses on log-transformed RTs and obtained the same results, with the Bayesian analysis again provided substantial support for the null hypothesis ( $BF_{01} = 4.29$  and  $BF_{01} = 6.80$ , for Experiments 1 and 2, respectively). Second, we examined a prediction deriving from this alternative account, namely, that longer RTs should also be associated with larger location effects. We applied the same vincentization procedure for location effects as we did for compatibility effects and compared the location effects on the fastest vs. the slowest trials (i.e., RTs faster vs. slower than the median RT), for the short and the long lag. None of these analyses showed a significant difference, in either Experiment 1 or 2, all  $ps > 0.20$ , that is, the location effect was of the same magnitude inside and outside the blink on both fast and slow trials.

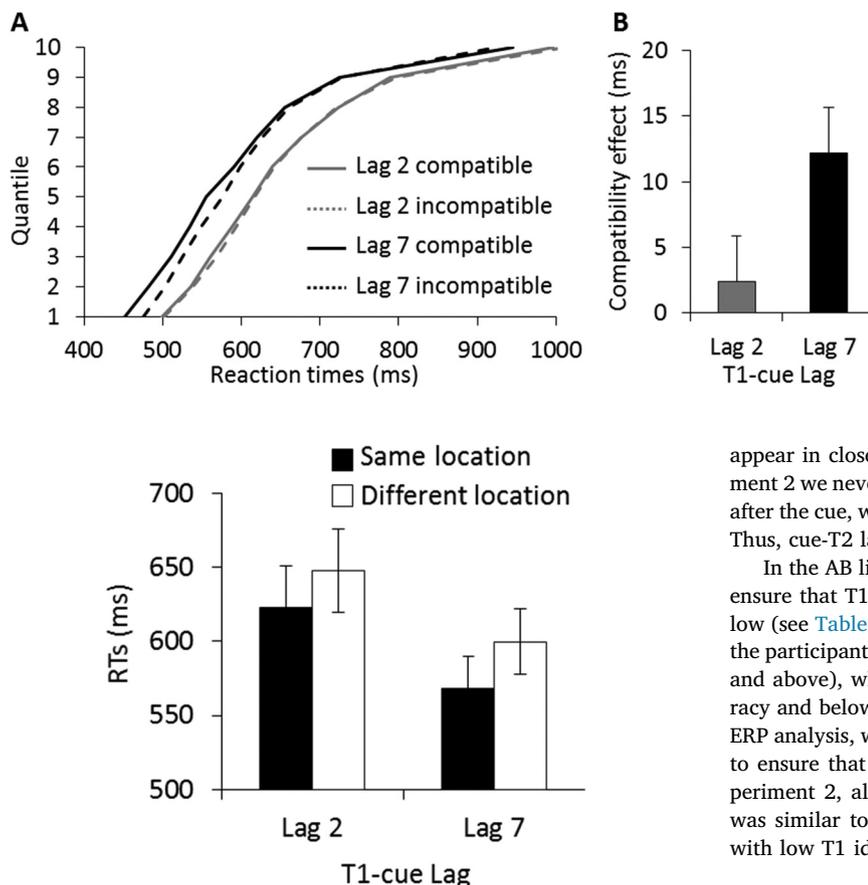


Fig. 3. T2 reaction times in Experiment 1 as a function of T1-cue lag (lag 2 vs. lag 7) and cue location relative to the target (same vs. different).

## 5. Experiment 2

Experiment 1 yielded two main findings. On the one hand, we observed an attentional blink following the selection of T1: T2 responses were slower and less accurate inside than outside the blink. In addition the cued distractor compatibility effect was smaller during the blink, suggesting that the blink disrupted attentional engagement. On the other hand, we observed a location benefit of equal magnitude inside and outside the blink, indicating that attentional capture was unaffected by the blink. The findings of Zivony and Lamy (2016), see also Bae et al. (2018); Ghorashi et al. (2009a, 2009b, 2010) were thus fully replicated.

In Experiment 2 we turned to examine the cue-locked N2pc. Our main prediction was that the amplitude of the cue-locked N2pc would be smaller during the blink than outside the blink (e.g., Dell'Acqua et al., 2006; Jolicoeur et al., 2006a). This result, together with the finding that the AB does not affect attentional capture, would indicate that the N2pc does not reflect attentional shifting. Although our main hypothesis concerned the cue-locked N2pc, we also examined the effect of the AB on the T2-locked N2pc. Note that unlike most studies that examined the effect of the AB on the T2-locked N2pc (e.g., Dell'Acqua et al., 2006; Jolicoeur et al., 2006a), T2 in our study was the last item in the RSVP stream and was therefore not masked. We return to this point in the Discussion. We did not analyze the T1-locked N2pc because T1 was not lateralized: it consisted of two stimuli flanking the fixation point.

Besides collecting electrophysiological data, two changes were introduced in this experiment relative to the previous one. When two stimuli appear in close succession, the waveforms elicited by the two stimuli might overlap (e.g., Woodman, 2010), although recent studies showed that two events can be successfully isolated even when they

Fig. 2. Compatibility effects in Experiment 1. Left panel (A): Vincitized reaction time distributions on compatible and incompatible cued-distractor trials for T1-cue lag 2 and T1-cue lag 7. Right panel (B): Mean compatibility effect (incompatible minus compatible) for the 50% fastest trials in each condition as a function of T1-cue lag (lag 2 vs. lag 7).

appear in close succession (e.g., Eimer and Grubert, 2014). In Experiment 2 we nevertheless added a condition in which T2 appeared 600 ms after the cue, which ensured that the cue-locked N2pc could be isolated. Thus, cue-T2 lag was either 1 (as in Experiment 1) or 6.

In the AB literature, only accurate T1 trials are included in order to ensure that T1 was selected. In Experiment 1, T1 accuracy was rather low (see Table 1). Inspection of individual means revealed that 60% of the participants performed the T1 task with relative ease (80% accuracy and above), whereas the rest found the task very difficult (65% accuracy and below).<sup>5</sup> In order to collect enough trials per condition in the ERP analysis, while remaining consistent with the AB literature, we had to ensure that participants could easily identify T1. Therefore, in Experiment 2, all the participants went through a screening phase that was similar to Experiment 1 and designed to screen out participants with low T1 identification rates.<sup>6</sup>

## 6. Method

### 6.1. Participants

Twenty-eight participants went through a screening experiment for 10 min and completed between 60 and 100 trials (based on their individual pace), after which their average T1 accuracy was calculated. Twelve participants whose T1 accuracy was lower than 80% were not included in Experiment 2. The remaining sample included 16 Tel-Aviv University undergraduate students who participated for either course credit or a payment of 140 NIS (approximately 35\$). All reported normal or corrected-to-normal visual acuity and color vision. The data from one participant was excluded from the analyses because of more than 25% rejection rate due to eye-blinks or eye-movements in one of the conditions. Therefore, the final sample included 15 (7 female) participants (mean age = 25.03,  $SD = 3.66$ ).

### 6.2. Apparatus, stimuli, design and procedure

The apparatus, stimuli and design were similar to those of Experiment 1 except for the following changes. Participants completed

<sup>5</sup> Note that the findings from Experiment 1 were entirely replicated when inaccurate T1 responses were included in the analyses. Previous reports show that the AB occurs when T1 is replaced with an irrelevant frame sharing T2's defining color (Folk et al., 2002; Jolicoeur et al., 2008; Zivony and Lamy, 2016). These findings suggest that detection of the target color suffices for the blink and can explain why the blink occurred in Experiment 1 even when T1 was not correctly identified: while T1 was difficult to identify, it was easy to detect, based on its color.

<sup>6</sup> It is unlikely that the screening had any impact on our results. First, Experiment 2 fully replicated the results of Experiment 1, which did not include this screening procedure. Second, the finding that the N2pc is disrupted by the blink has been replicated many times, and is therefore unlikely to result from the screening procedure.

10 practice trials, followed by 960 experimental trials divided into 16 blocks of 60 trials each. Out of these trials, 20% were no-cue trials (192 trials). The lag between the cue and T2 was randomly set at either 1 or 6. All the conditions (T1-cue lag, cue-T2 lag, cue-T2 location, distractor compatibility) were equiprobable and intermixed within the blocks. Note that only two factors were relevant for the analyses of the cue-locked N2pc, namely, T1-cue lag and cue-T2 lag. For these analyses, the number of experimental trials per cell was 192.

Before the ERP session participants performed a change-detection task (e.g., Fukuda and Vogel, 2009; Luck and Vogel, 1997; Vogel, Woodman and Luck, 2001) designed to estimate their visual working memory capacity. A memory array consisting of either four or eight colored squares ( $1.24^\circ \times 1.24^\circ$  of visual angle each) was presented for 150 ms against a gray background within a  $16.6^\circ \times 16.6^\circ$  region, with the constraint that two adjacent squares were separated by a center-to-center distance of at least  $2^\circ$  of visual angle. The color of each square was randomly selected (without replacement) from a set of nine colors: black, blue, brown, cyan, green, orange, pink, red, and yellow. The memory array disappeared for 900 ms (retention interval), and then, a colored square (the test probe) appeared at one of the previous locations of the items in the memory array. Participants made an unspeeded *same vs. different* response via button press (“Z” and “/” on the computer keyboard, counterbalanced across participants) to indicate whether or not the test item had the same color as the square that had appeared at the same location in the memory array. Same- and different-color test probes were equally probable. Sixty trials were presented for each array size in one intermixed block. The accuracy for each individual was transformed into a K estimate (separately for each set-size) following standard formula (Cowan, 2001; Pashler, 1988). The formula is  $K = S \times (H - F)$ , where K is the memory capacity, S is the size of the memory array, H is the observed hit rate, and F is the false alarm rate. These two values were averaged to form a single visual working memory capacity estimate (K).<sup>7</sup>

### 6.2.1. Statistical analyses of behavioral results

The statistical analyses of the behavioral results were similar to those reported in Experiment 1. Accordingly, they did not include trials in which T2 appeared at lag 6 from the cue because these were not informative for the behavioral analyses but only for the ERP analyses.

### 6.3. Electroencephalography recordings

The EEG was recorded inside a shielded Faraday cage using a Biosemi Active Two EEG recording system (Biosemi B.V., Amsterdam, The Netherlands). Data was recorded from 32 scalp-electrodes at a subset of locations out of the extended 10–20 system, including mostly occipital and parietal sites (in which the N2pc is most pronounced): Fp1, Fp2, AF3, AF4, F3, F4, F7, F8, Fz, FCz, C3, C4, Cz, T7, T8, P1, P2, P3, P4, P5, P6, P7, P8, Pz, PO3, PO4, PO7, PO8, POz, O1, O2, and Oz. In addition, the horizontal electrooculogram (EOG) was recorded from electrodes placed 1 cm to the left and right of the external canthi to detect horizontal eye movement, and the vertical EOG was recorded from an electrode beneath the left eye to detect blinks and vertical eye movements. The single-ended voltage was recorded between each electrode site and a common mode sense electrode (CMS/DRL). Data was digitized at 256 Hz.

Offline signal processing and analysis was performed using EEGLAB

<sup>7</sup> This task was administered for purposes irrelevant to the current study and will therefore not be discussed further. We found a significant correlation between WM capacity and the AB effect (measured as the mean RT at the T1-T2 lag 8 minus the mean RT at the T1-T2 lag 3),  $r(13) = -0.64$ ,  $p = .017$ , indicating that participants with a larger WM capacity showed a smaller blink. This finding is in line with previous reports (Colzato et al., 2007, but see Martens and Johnson, 2009).

Toolbox (Delorme and Makeig, 2004), ERPLAB Toolbox (Lopez-Calderon and Luck, 2014), and custom MATLAB (The Mathworks, Inc.) scripts. All electrodes were referenced offline to the average of the left and right mastoids. For analysis of the cue-locked N2pc and T2-locked N2pc, the continuous data were segmented into epochs from  $-200$  to  $+500$  ms relative to the onset of the locked stimulus, and were normalized relative to a 200 ms window before stimulus onset. Artifact detection was performed using a pick-to-pick analysis, based on a sliding window of 200 ms wide with a step of 100 ms. Threshold activity for rejecting trials was 80 and 100  $\mu\text{V}$  at the EOG electrodes and at the analyzed electrodes (PO7 and PO8). This procedure resulted in a mean rejection rate of 1.49% ( $SD = 1.55\%$ ). The epoched data was then averaged and low-pass filtered using a non-causal Butterworth filter (12 dB/oct) with a half-amplitude cutoff at 30 Hz. Only trials where both T1 and T2 responses were accurate were included in the analysis.

## 7. Results

Following the same RT outlier rejection procedure as in Experiment 1, 2.26% of the trials were excluded. Accuracy rates and RTs for T1 and T2 responses on cue-absent trials are presented in Table 1.

### 7.1. Behavioral results

#### 7.1.1. Cue-T2 compatibility effect

For this analysis we included only the 50% fastest trials in each condition (see the *Statistical analyses* section). Reaction times were faster for the long than for the short lag,  $F(1,2857) = 341.7$ ,  $p < .001$ , and when the cued distractor was compatible with T2 than when it was incompatible with it,  $F(1,2857) = 19.36$ ,  $p < .001$ . The interaction between lag and cued distractor compatibility approached significance,  $F(1,2857) = 3.53$ ,  $p = .06$ , suggesting that the compatibility effect tended to be larger when the cue appeared outside the blink (lag 7),  $M = 13.3$  ms,  $F(1,1412) = 23.89$ ,  $p < .001$ , than when it appeared inside the blink (lag 2),  $M = 6.5$  ms,  $F(1,1431) = 3.50$ ,  $p = .06$ . Vincitized and mean RTs are presented in Fig. 4A and Fig. 4B, respectively.

#### 7.1.2. Location benefit

Reaction times were faster for the long than for the short lag,  $F(1,4974) = 486.7$ ,  $p < .001$ , and when the cue appeared in the target's location than in the alternative location,  $F(1,4974) = 32.31$ ,  $p < .001$ . Importantly, the interaction between lag and cue location was not significant,  $F < 1$ , indicating that the location effect was of equal magnitude inside and outside the blink, with the Bayesian analysis providing strong support for the null,  $BF_{01} = 18.59$ . Mean RTs as a function of T1-cue lag and cue location are presented in Fig. 5.

#### 7.1.3. ERP results

**7.1.3.1. Cue-locked N2pc.** Fig. 6 shows the cue-locked ERP waveforms recorded from electrodes PO7 and PO8 as a function of T1-cue lag and cue-T2 lag, contralateral and ipsilateral to the cue. Fig. 7 shows the difference wave obtained by subtracting ipsilateral from contralateral ERPs. The N2pc is typically observed between 150 and 300 ms post-stimulus (see Luck, 2012, for review), with different time windows used in different studies. In order to define the appropriate time window in this study, while taking into account for the possibility that the AB may delay the onset of the N2pc (Lagroix et al., 2015), we first measured the N2pc's onset, defined as the 15% fractional peak latency of the negative deflection in the 150–350 ms time window, for each combination of T1-cue and cue-T2 lag for each participant. We then conducted an ANOVA with T1-cue lag (lag 2 vs. lag 7) and cue-T2 lag (lag 1 vs. lag 6) as independent variables and N2pc onset as the dependent variable. The main effect of T1-cue lag was significant,  $F(1,14) = 26.19$ ,  $p < .001$ ,  $\eta_p^2 = .65$ , with a later N2pc onset for the short than for the long lag ( $M = 216$  ms,  $SE = 8$  vs.  $M = 182$  ms,  $SE = 4$ , respectively). The main effect

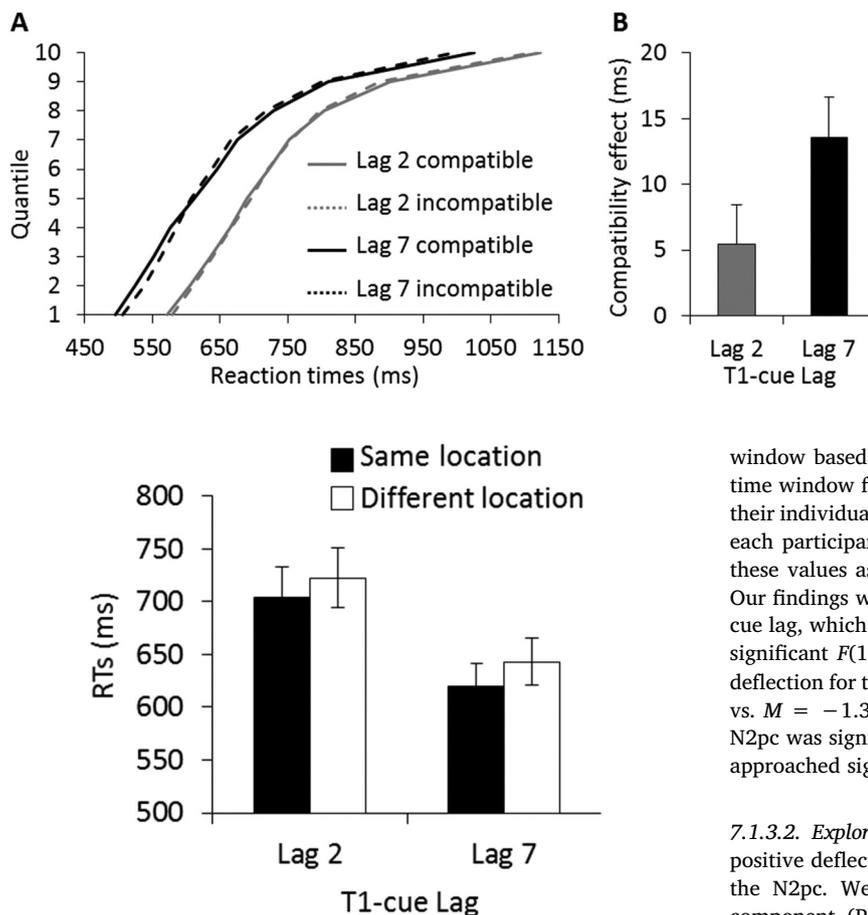


Fig. 5. T2 reaction times in Experiment 2 as a function of T1-cue lag (lag 2 vs. lag 7) and cue location relative to the target (same vs. different).

of cue-T2 lag and the interaction between the two factors were not significant, both  $p$ s > 0.20.

Based on the previous analysis, we quantified the cue-locked N2pc as the mean amplitude of the ipsi-contra difference in two different 100 ms time windows, starting approximately 15 ms prior to the N2pc's onset: 170–270 post-cue for T1-T2 lag 7 and 200–300 post-cue for T1-T2 lag 2.<sup>8</sup> In order to examine the effects of the AB on the cue-locked N2pc, we conducted an ANOVA with T1-cue lag (lag 2 vs. lag 7) and cue-T2 lag (lag 1 vs. lag 6) as independent variables and N2pc mean amplitude as the dependent variable. The main effect of T1-cue lag was significant,  $F(1,14) = 14.13$ ,  $p = .002$ ,  $\eta_p^2 = .50$ , with a less negative deflection for the short than for the long lag ( $M = -0.66 \mu\text{v}$ ,  $SE = 0.36$  vs.  $M = -1.51 \mu\text{v}$ ,  $SE = 0.52$ ). Follow-up analyses revealed that the N2pc was significantly larger than 0 (i.e. the contralateral waveform was significantly more negative than the ipsilateral waveform) for the long lag but not for the short lag,  $t(14) = 2.92$ ,  $p = .01$ , and  $t(14) = 1.44$ ,  $p = .17$ , respectively. The main effect of cue-T2 lag and the interaction between T1-cue lag and cue-T2 lag were not significant,  $F(1,14) = 2.97$ ,  $p = .10$ ,  $\eta_p^2 = .18$ , and  $F(1,14) = 2.08$ ,  $p = .17$ ,  $\eta_p^2 = .13$ , respectively.

The reduction of the N2pc during the blink may reflect increased jittering of the component's latency during the blink rather than suppression of the N2pc. To examine this alternative account, we re-analyzed the data using individual N2pc time windows, determined separately for each participant and condition, instead of a uniform

<sup>8</sup> In this and the following analysis the results were fully replicated when we used standard time windows (180–280 ms; e.g., Eimer and Kiss, 2010, or 200–300 ms; e.g., Woodman and Luck, 1999) for both lag conditions.

Fig. 4. Compatibility effects in Experiment 2. Left panel (A): Vincitized reaction time distributions on compatible and incompatible cued distractor trials for T1-cue lag 2 and T1-cue lag 7. Right panel (B): Mean reaction times for the 50% fastest trials in each condition as a function of T1-cue lag (lag 2 vs. lag 7) and cued distractor compatibility (compatible vs. incompatible).

window based on the average N2pc latency. We set the 100-ms N2pc time window for a given participant and condition from 15 ms prior to their individual N2pc onset. We then measured the mean amplitudes for each participant based on their respective time window, and entered these values as the dependent variable into the same ANOVA model. Our findings were fully replicated. In particular, the main effect of T1-cue lag, which reflects the effect of the AB on the N2pc amplitude, was significant  $F(1,14) = 13.57$ ,  $p = .002$ ,  $\eta_p^2 = .49$ , with a less negative deflection for the short than for the long lag ( $M = -0.59 \mu\text{v}$ ,  $SE = 0.27$  vs.  $M = -1.33 \mu\text{v}$ ,  $SE = 0.41$ ). Follow-up analyses revealed that the N2pc was significant for the long lag,  $t(14) = 3.03$ ,  $p = .008$ , and only approached significance for the short lag,  $t(14) = 2.08$ ,  $p = .056$ .

**7.1.3.2. Exploratory cue-locked ERP analyses (Ppc and Pd).** We observed positive deflections in the difference wave both prior to and following the N2pc. We speculate that the early deflection reflects the Ppc component (Positivity, posterior contralateral; e.g., Fortier-Gauthier et al., 2012; Leblanc et al., 2008), which emerges approximately 100 ms after the stimulus and is tied to low-level sensory processing. We also speculate that the late deflection reflects the late Pd component (distractor positivity; e.g., Burra and Kerzel, 2014; Hilimire et al., 2010; Sawaki et al., 2012), which is thought to reflect the withdrawal of attentional resources. In line with this literature, we measured the Ppc in the 100–170 ms time window and the Pd in the 300–350 ms time window. Post-hoc analyses revealed that the Ppc was not significantly modulated by the blink,  $F(1,14) = 2.19$ ,  $p = .16$ ,  $\eta_p^2 = .14$ , and was reliable both outside the blink,  $M = 0.73 \mu\text{v}$ ,  $SE = 0.15$ ,  $t(14) = 4.42$ ,  $p < .001$ , and inside the blink,  $M = 0.91 \mu\text{v}$ ,  $SE = 0.17$ ,  $t(14) = 5.05$ ,  $p < .001$ . In contrast, the Pd component was significantly modulated by the blink,  $F(1,14) = 12.49$ ,  $p = .003$ ,  $\eta_p^2 = .47$ . It was significant outside the blink,  $M = 0.87$ ,  $SE = 0.28$ ,  $t(14) = 2.84$ ,  $p = .013$ , and was absent inside the blink,  $M = -0.31$ ,  $SE = 0.25$ ,  $t(14) = -0.94$ ,  $p = .35$ . As noted, these analyses were exploratory and further experiments are required to assess the reliability of the resulting findings.

**7.1.3.3. T2-locked N2pc.** To avoid any contamination of the T2-locked N2pc from overlapping cue-related activity, we included only trials in which the cue was absent in these analyses. Figs. 8A and 8B show the cue-locked ERP waveforms recorded from electrodes PO7 and PO8 as a function of T1-T2 lag (lag 3 vs. lag 8). The rightmost panel of Fig. 8 shows the difference wave obtained by subtracting ipsilateral from contralateral ERPs. We first defined the T2-locked N2pc onset using the same procedures as for the cue-locked N2pc analyses described above. A dependent-sample  $t$ -test on the T2-locked N2pc onset revealed that the N2pc was significantly delayed at the short lag relative to the long lag,  $M = 213$  ms,  $SE = 10$  vs.  $M = 178$  ms,  $SE = 4$ ,  $t(14) = 3.18$ ,  $p = .006$ . We thus defined the effect of the AB on the T2-locked N2pc as the mean amplitude of the difference in two different time windows: 170–270 ms post-T2 for T1-T2 lag 8 and 200–300 ms post-cue for T1-T2

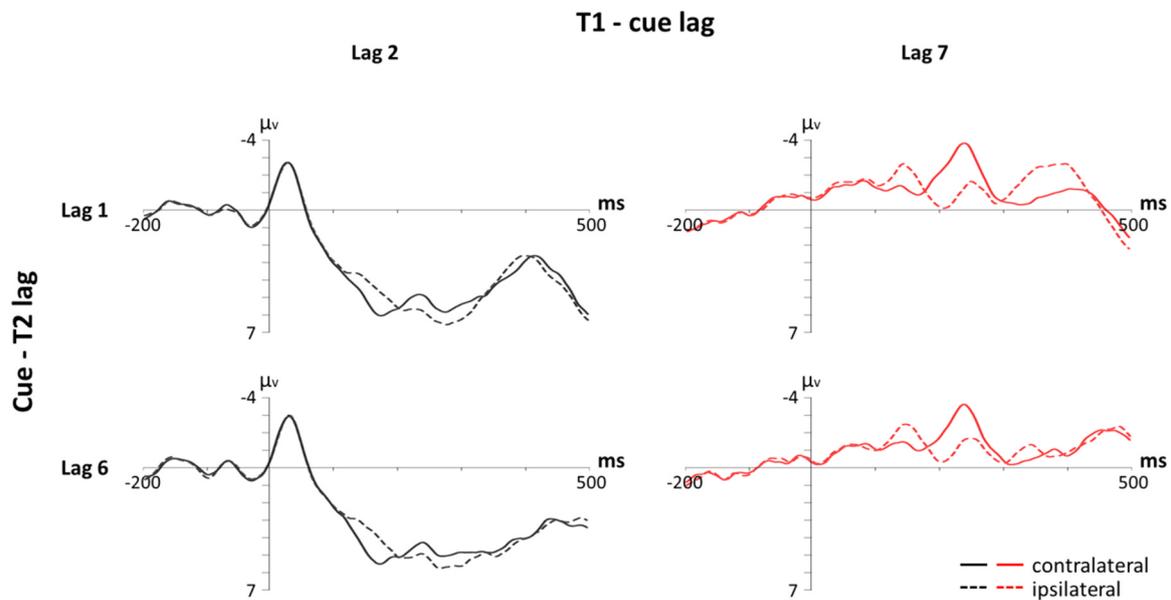


Fig. 6. Grand-average event-related potentials (ERPs) waveforms time-locked to the cue at electrodes PO7/PO8 on contralateral and ipsilateral electrodes relative to the cue as a function of T1-cue lag and cue-T2 lag.

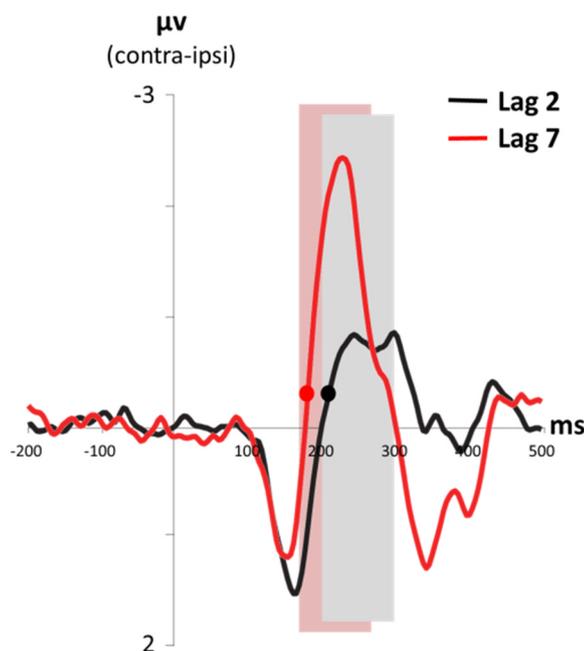


Fig. 7. Difference waveforms time-locked to the cue obtained by subtracting ipsilateral from contralateral waveforms as a function of cue-T1 lag. The dots depict the N2pc onset, defined as the 15% fractional peak latency of the negative deflection in the 150–350 ms time window. The N2pc inside the AB (lag 2) was delayed and attenuated relative to the N2pc outside the AB (lag 7).

lag 3 (see also footnote 7). A dependent sample-test revealed that the N2pc amplitude was significantly smaller at the short relative to the long lag,  $M = -2.05\mu\text{v}$ ,  $SE = 0.55$  vs.  $M = -2.60\mu\text{v}$ ,  $SE = 0.54$ ,  $t(14) = 3.41$ ,  $p = .004$ . Follow-up analysis indicated that the N2pc was reliable at both lags, both  $p$ s < 0.01.

## 8. Discussion

The N2pc component is frequently used as an index of attentional shifting, and its absence is taken as evidence that attention did not shift (e.g., Burra and Kerzel, 2013; Kiss et al., 2012; Woodman and Luck,

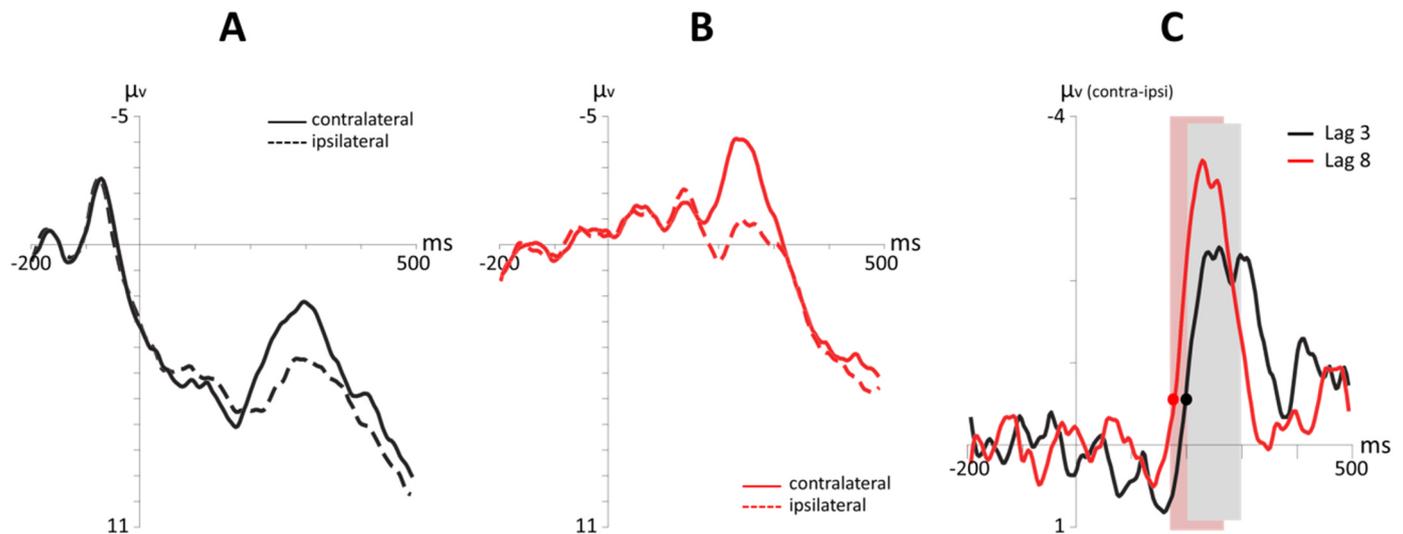
1999). Here, we report findings that challenge this view. On the one hand, we found that the attentional blink did not modulate the location benefit produced by a spatial cue (thus replicating Bae et al., 2018; Ghorashi et al., 2009a, 2009b, 2010; Zivony and Lamy, 2016). On the other hand, we found the AB to reduce the likelihood of identifying the distractor letter inside this cue (as indicated by the smaller response-compatibility effect observed during the blink) and to both delay the onset (see also, Lagroix et al., 2015) and reduce the amplitude (see also, e.g., Dell'Acqua et al., 2006; Joliceur et al., 2006a) of the N2pc component. Taken together, these results demonstrate that the N2pc does not reflect attentional shifting (which, unlike the N2pc, is unaffected by the blink) but processes that occur downstream from attentional shifting (e.g., identification, see also Foster et al., 2018; Kiss et al., 2008a, 2008b).

Note that while the cue-locked and T2-locked N2pc were attenuated during the blink, they were not entirely eliminated (see Dell'Acqua et al., 2006, for similar results). However, the AB is not an all-or-none effect: it typically does not occur on all trials. Thus, the residual N2pc activity during the blink may have stemmed from trials in which the cue or T2 were not blinked (though this cannot be unambiguously established since we had no direct trial-by-trial measure of the attentional blink in the present study). Note however that whether the N2pc was entirely suppressed or simply reduced has no incidence on our main conclusion. Since the AB modulated the N2pc but not attentional capture, the N2pc does not index attentional shifting.

### 8.1. The N2pc as an index of attentional engagement onset

We suggest that the process downstream of attentional shifting that is indexed by the N2pc is the *onset of attentional engagement*, that is, spatially-specific transient attentional enhancement that promotes feature identification, binding and consolidation of the attended stimulus into working memory.<sup>9</sup> Attentional engagement differs from

<sup>9</sup> Note that our incidental finding of cue-locked Pd outside the blink, but not inside the blink can be readily accounted for in the framework of this hypothesis. The Pd is thought to index the withdrawal of attentional resources from a distractor following attentional engagement to that distractor (Sawaki et al., 2012). Here, since attention was engaged to the cue only during the blink, such withdrawal was also required only during the blink.



**Fig. 8.** Grand-average event-related potentials (ERPs) time-locked to T2 on absent cue T2 trials at electrodes PO7/PO8 contralateral and ipsilateral to the target in (A) T1-T2 lag 3 and (B) T1-T2 lag 8. (C) N2pc difference waveforms time-locked to T2 obtained by subtracting ipsilateral from contralateral ERPs to the target as a function of T1-T2 lags (lag 3 vs. lag 8). The dots depict the N2pc onset, defined as the 15% fractional peak latency of the negative deflection in the 150–350 ms time window. The N2pc inside the AB (lag 3) was delayed and attenuated relative to the N2pc outside the AB (lag 8).

attentional shifting in several important respects. Shifting attention is a relatively resource-free operation (Lamy et al., 2015; Zivony and Lamy, 2016) that occurs following the rapid extraction of basic features (such as location or color) during feed-forward processing (Lamme and Roelfsema, 2000; Töllner et al., 2012). In contrast, attentional engagement allows the transfer of the extracted information to higher-level processing, which requires recurrent activation of neural networks (Töllner et al., 2012). Moreover, the conditions necessary for attentional engagement are more restrictive than the conditions necessary for attentional shifting (Zivony and Lamy, 2018), possibly due to the high cost incurred by engaging attention to an irrelevant object.

The notion that the N2pc is related to attentional engagement follows from the strong parallel that arises from the literature showing that the AB disrupts attentional engagement on the one hand (as indicated by its effect on identity intrusions and compatibility effects, e.g., Peressotti et al., 2012; Vul et al., 2008; Zivony and Lamy, 2016) and from the literature showing that the N2pc is attenuated by the AB on the other hand (Akyürek et al., 2010; Dell'Acqua et al., 2006; Jolicœur et al., 2006a, 2006b; Robitaille et al., 2007; Verleger et al., 2009) – a parallel that we confirmed in the present study.

Early theoretical accounts of the N2pc diverged on whether the N2pc reflects the suppression of distractors (e.g., Luck and Hillyard, 1994; Luck et al., 1997) or the enhancement of targets (e.g., Eimer, 1996; Mazza et al., 2009). Despite this disagreement, the major and most contemporary accounts of the N2pc (Callahan-Flintoft et al., 2018; Mazza and Caramazza, 2011; Luck, 2012) take the N2pc to reflect a process that occurs immediately after an attentional shift and is closely related to feature binding. For example, Mazza and Caramazza (2011) suggested that the N2pc reflects a process that “binds indexes to properties and locations in order to make them available for further cognitive operations” (p. 6). Similarly, Luck (2012) suggested that the N2pc reflects the differentiation between objects of interest and surrounding distractors, which relies on correct feature binding. Lastly, while Callahan-Flintoft et al. (2018) suggest that localization processes trigger the N2pc (see also Tan and Wyble, 2015), they also suggest that the amplitude of the N2pc and its latency reflect the efficacy of the ensuing attentional selection. The hypothesis that the N2pc reflects attentional engagement is therefore aligned with these accounts.

Finally, previous research suggests that the N2pc specifically reflects the onset of attentional enhancement rather than its consequences. Mazza et al. (2007) showed that the N2pc component was

similar when participants had to simply localize a target (left-right hemifield) and when they had to make a difficult discrimination of this target's shape. If the N2pc indexes ongoing attentional processing (as suggested by Theeuwes, 2010), then a task requiring more in-depth analysis should result in a larger N2pc amplitude.

## 9. Implications for the attentional blink literature

One of the earliest theories of the AB suggested that it occurs due to processing capacity limitations. According to this account, the processing of T1 depletes a central resource that is required for WM encoding, leaving no available resources for T2 processing. However, later studies challenged this account by showing that a target can be spared from the blink if it preceded by an additional target (Di Lollo et al., 2005; Kawahara et al., 2006; Olivers et al., 2007) or by a cue that shares T2's defining feature (Nieuwenstein et al., 2005; Nieuwenstein, 2006). If a central processing resource is freed up only after the encoding of T1 is completed, it is difficult to explain why attending to an additional target or a cue should eliminate the AB.

To account for these findings, several theories have proposed that disruption of attentional engagement underlies the attentional blink. The main exemplars of these accounts are the Delayed Engagement Account (DAE; Nieuwenstein et al., 2005), boost-and-bounce model (Olivers and Meeter, 2008a, 2008b) and the episodic simultaneous type serial token (eSTST) model (Wyble et al., 2009). These theories further suggest that attentional engagement is not completely withheld during the AB (as suggested for example by Raffone et al. 2014), but the activation generated by T2 effectively accrues to the stimulus following it. This account readily explains why, for instance, an attention-grabbing object can spare a target that immediately follows it from the AB.

While the three “disrupted-engagement” accounts diverge in several respects (Nieuwenstein et al., 2005; Olivers and Meeter, 2008a, 2008b; Wyble et al., 2009), the most relevant of these for the present study is how the AB affects attentional engagement. According to the DAE, the AB delays the onset of attentional engagement, such that the peak of the transient enhancement of processing occurs later, but is otherwise unaffected during the blink. In contrast, the boost-and-bounce and eSTST models suggest that during the blink, inhibitory processes bring activation below baseline levels, such that the onset of attentional engagement is unaffected, but the maximal enhancement generated by T2 is weaker. Building on our conclusion that the N2pc can be used as a

proxy of attentional engagement, our results support an intermediary position between these accounts: since the onset of the N2pc was delayed and the N2pc amplitude attenuated, we conclude that attentional engagement is both delayed (by approximately 20–30 ms, see also Lagroix et al., 2015) and suppressed during the blink.

Finally, the results of the current study may open the door to new avenues of research into the AB phenomenon. Previous studies have shown that masking modulates the effect of the AB on late ERP components such as the P3, a component often associated with WM updating (Donchin and Coles, 1988; Polich, 2007). They found the amplitude of the T2-locked P3 to be reduced during the blink when T2 was masked but not when it was unmasked (e.g., Sessa et al., 2007; Vogel and Luck, 2002). Here, we measured the effect of the AB on the N2pc when it was locked to a masked stimulus (the cue, which appeared in the middle of the RSVP stream) and when it was locked to an unmasked stimulus (T2, which appeared in the last frame of the RSVP stream). Unlike the P3 results reported in previous studies, we found the N2pc's amplitude to be attenuated during the AB under both masking conditions.<sup>10</sup> Although there were too many differences between the cue and T2 in our study beyond masking, this disparity between the effects of the AB on the N2pc and on the P3 components raises the possibility that the AB may have a different impact on attentional and on WM-related processes. This issue could not be resolved here, because our study was not designed to measure the P3 (which traditionally requires manipulating the frequency of the target, e.g., Vogel and Luck, 2002). It could be usefully tested in future studies designed so as to isolate both the N2pc and the P3 components.

## 10. Implications for the attentional capture literature

Our findings clearly show that while the presence of the N2pc indicates that an attentional shift occurred, one cannot rely on the absence of an N2pc to conclude that attention did not shift. Thus, they call for a reinterpretation of findings from the attentional capture literature, where the N2pc has been abundantly instrumental. In particular, the finding that distractors sharing the target's defining feature are associated with an N2pc, whereas distractors outside the attentional set are not, has been taken as evidence that attentional capture is contingent on a match with the observer's attentional set (e.g., Ansorge et al., 2010; Eimer and Kiss, 2008; Lien, et al., 2011). Our findings raise the possibility that in some of these studies, attention was in fact captured by distractors that did not share the target feature, but was not engaged. Consistent with this conjecture, recent studies show that abrupt onsets outside the attentional set can capture attention (Folk and Remington, 2015; Gaspelin et al., 2016), but do not result in attentional engagement (Zivony and Lamy, 2018). Additional research is required to further distinguish between the boundary conditions of attentional engagement and attentional capture. Such research is crucial for an informed use of the N2pc in attention studies.

## Author's note

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<sup>10</sup> This result departs from those of Lagroix et al. (2015). In their study the T2 task was to detect the presence of a color oddball that appeared in the end of the stream. They found that during the blink the latency of the onset of T2-locked N2pc was delayed, but despite a numerical trend in that direction, the amplitude of the T2-locked N2pc was not significantly reduced. It is possible that the relatively amplitudes small in their study (Lagroix et al., 2015, Fig. 2) yielded insufficient power to test this effect.

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