![Birkbeck, University of London logo]

BIROn - Birkbeck Institutional Research Online

Zivony, Alon and Allon, A.S. and Luria, R. and Lamy, D. (2018) Dissociating between the N2pc and attentional shifting: an attentional blink study. Neuropsychologia 121 , pp. 153-163. ISSN 0028-3932.

Dissociating between the N2pc and attentional shifting: an attentional blink study

Neuropsychologia, 121, 153-163 (2018)

Alon Zivony[1], Ayala S. Allon[2], Roy Luria[1,3] and Dominique Lamy[1,3]

1. School of Psychological Sciences, Tel Aviv University

2. Department of Psychology, The Ohio State University

3. Sagol Shool of Neuroscience, Tel Aviv University

Please address correspondence to

Alon Zivony

Email: alonzivony@gmail.com

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.

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 & Hillyard, 1994). Several studies attempted to clarify which aspects of spatial attention are indexed by the N2pc (e.g., Foster, Bsales & Awh, 2018; Kiss, van Velzen & Eimer, 2008; van Velzen & 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.'s (2008) 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, Horstmann & Worschech, 2010; Buodo, Sarlo & Munafò, 2009; Burra & Kerzel, 2013; Burra, Barras, Coll & Kerzel, 2016; Dell'Acqua, Sessa, Jolicoeur, & Robitaille, 2006; Eimer & Kiss, 2008; Eimer & Kiss, 2010; Hilimire & Corballis, 2014; Holguín, Doallo, Vizoso & Cadaveira 2009; Ikeda, Sugiura & Hasegawa, 2013; Jiao et al., 2013; Jolicoeur, Sessa, Dell'Acqua, and Robitaille, 2006a; Jolicoeur, Sessa, Dell'Acqua, & Robitaille, 2006b; Kiss, Grubert, Petersen & Eimer, 2012; Kiss, Jolicœur, Dell'Acqua & Eimer 2008; Lien, Gemperle & Ruthruff, 2011; Liu, Lan, Teng, Guo & Yao, 2017; Lorenzo-López, Amenedo & Cadaveira, 2008; Schubö & Müller, 2009; Woodman & Luck, 1999; Wu et al., 2013 ; Wykowska & 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 necessarily entails that the information at that location is further processed (e.g., Goldfarb & Treisman, 2010; Posner, Rueda & Kanske 2008; 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 & 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., 2008; Forester 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.

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 200-500ms after the first target (T1).

Many studies have shown that the N2pc is suppressed during the AB (Akyürek, Leszczyński & Schubö, 2010; Dell'Acqua et al., 2006; Jolicoeur et al., 2006a; Jolicoeur et al., 2006b; Robitaille, Jolicœur, Dell'Acqua, & Sessa, 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 at 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; Jolicoeur 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, Jung & Han, 2018; Ghorashi, Spalek, Enns, & Di Lollo, 2009a; Ghorashi, Enns, Klein, & Di Lollo, 2010; Ghorashi, Enns, Spalek, & Di Lollo, 2009b; Zivony & 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, Leber & Egeth, 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, Remington & Johnston, 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, Suero & Barriopedro, 2001; Vul, Nieuwenstein, & Kanwisher, 2008) when the cue appeared inside than outside the blink. In line with contemporary theories of the AB (Nieuwenstein, Chun, van der Lubbe & Hooge, 2005; Olivers & Meeter, 2008; Wyble, Bowman, & Nieuwenstein, 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, Ester & Troemel, 2009; Nieuwenstein et al., 2005; Posner et al., 2008) 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; Jolicoeur 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 & 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.

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 & Di Lollo, 1998; Vogel & Luck, 2002; Zuvic, Visser & Di Lollo, 2000, but see Jannati, Spalek & Di Lollo, 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 & 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, 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[1] (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.

---

[1] Note that in our previous accuracy-based AB paradigm (Zivony & 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.

Method

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.

Apparatus

Displays were presented in a dimly lit room on a 23" LED screen, using 1920X1280

resolution graphics mode and 120Hz refresh rate. Responses were collected via the

computer keyboard. Viewing distance was set at 50 cm from the monitor.

Stimuli and design

The sequence of events is presented in Figure 1. Each trial began with the

presentation of a fixation display, a gray 0.2°x 0.2° 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°

in height), each enclosed in an outline square (3-pixel thick, 1.5° in side) and appearing at

a center-to-center distance of 4.5° 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 1500ms. 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 cd/m^2) for red and (128, 128, 128; 26.93 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. All conditions were randomly intermixed within the blocks.
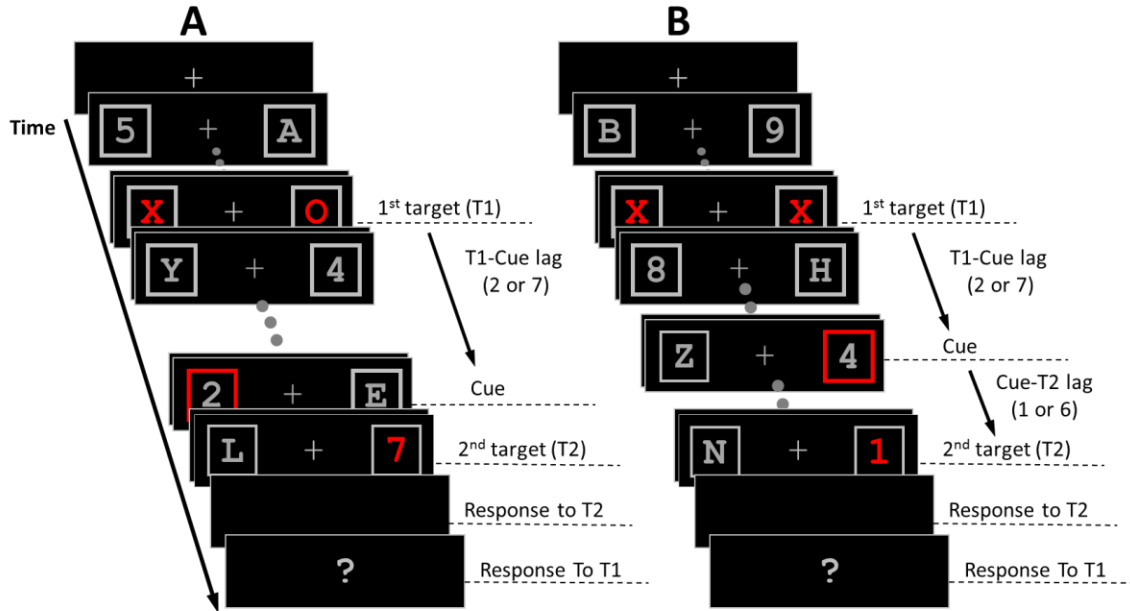
Figure 1. Illustration of the stimulus sequence in Experiment 1 (Panel A) and 2 (Panel B). In Experiment 1, the second target (T2) appeared at positions 14, 16, or 18. The cue preceded the target by exactly one frame, and the first target (T1) preceded the cue by either two or seven frames. Accordingly, 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.

Statistical analysis

   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-specific intercepts as a random factor[2], 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

---

[2] Preliminary analyses showed that the maximum model (Barr, Levy, Scheepers, & Tily, 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.

package (version 1.1-13; Bates, Maechler, Bolker, & Walker, 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).

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 & Lamy, 2018; Kinoshita & 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 & 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 the data in the 50% fastest trials in each

condition.

Bayesian analyses. Similar to Zivony & 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 & 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 only the main effects.

Following Dienes and Mclatchie (2017) we consider a BF_{10} to provide evidence for H0 if

it is smaller than 0.33 (i.e., $BF_{01} > 3$).

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.

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

Cue-T2 compatibility effect. As is clear from Figure 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 *Statistical analyses* section). Mean RTs are presented in Figure

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

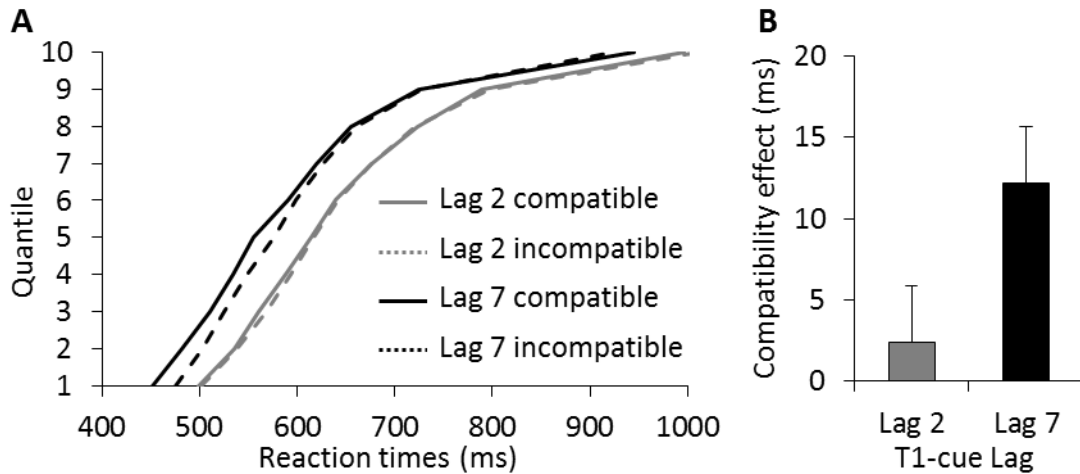cue appeared inside the blink (lag 2), $M = 1.7$ ms, $F < 1$.

Figure 2. Compatibility effects in Experiment 1. Left panel (A): Vincentized 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).

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 Figure 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[3],
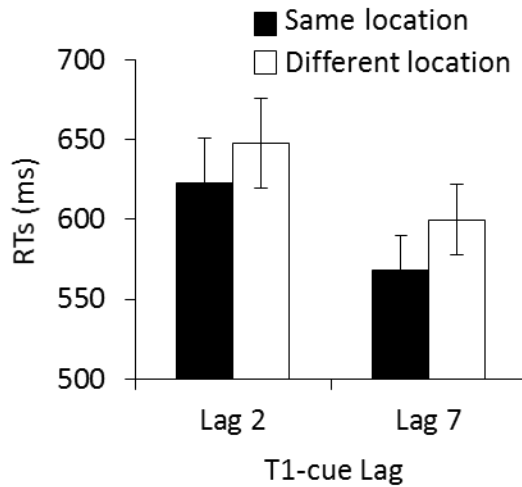
BF01 = 13.19.

Figure 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).

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,

---

[3] 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 (BF01 = 4.29 and BF01 = 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 $ps > .20$, that is, the location effect was of the same magnitude inside and outside the blink on both fast and slow trials.

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 appear in close succession (e.g., Eimer & Grubert, 2014). In Experiment 2 we nevertheless added a condition in which T2 appeared 600ms 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)[4]. 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[5].

Method

Participants

Twenty-eight participants went through a screening experiment for 10 minutes 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

---

[4] 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., 2006; Zivony & 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.

[5] 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.

one of the conditions. Therefore, the final sample included 15 (7 female) participants (mean age = 25.03, SD = 3.66).

Apparatus, stimuli, design and procedure

The apparatus, stimuli and design were similar to those of Experiment 1 except for the following changes. Participants completed 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 & Vogel, 2009; Luck & Vogel, 1997; Vogel, Woodman & Luck, 2001) designed to estimate their visual working memory capacity. A memory array consisting of either four or eight colored squares ($1.24^o \times 1.24^o$ of visual angle each) was presented for 150 ms against a grey background within a $16.6^o \times 16.6^o$ region, with the constraint that two adjacent squares were separated by a center-to-center distance of at least 2° 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)[6].

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.

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

---

[6] 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), $r(13) = -.64$, $p = .017$, indicating that
participants with a larger WM capacity showed a smaller blink. This finding is in line with previous reports
(Colzato, Spapé, Pannebakker & Hommel, 2007, but see Martens & Johnson, 2009).

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 Toolbox

(Delorme & Makeig, 2004), ERPLAB Toolbox (Lopez-Calderon & 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 μV 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.

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.

Behavioral results

   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, $F(1,1431) = 3.50$, $p =$

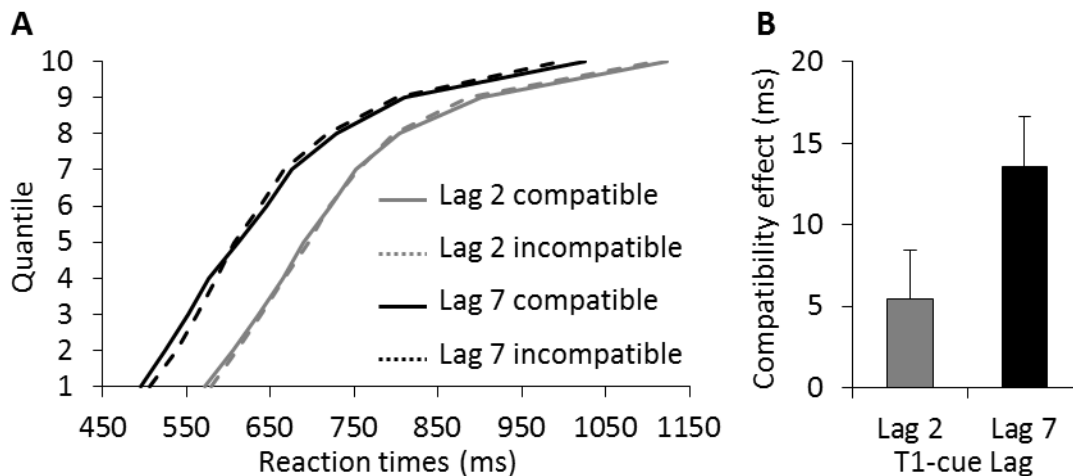.06. Vincenticized and mean RTs are presented in Figure 4A and Figure 4B, respectively.

Figure 4. Compatibility effects in Experiment 2. Left panel (A): Vincentized 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).

   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 Figure 5.
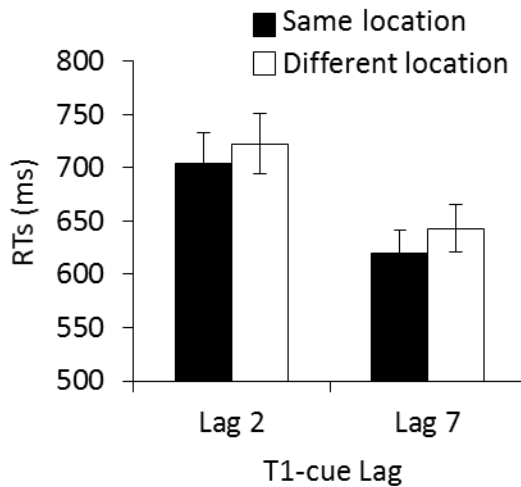

Figure 5. T2 reaction times in Experiment 2 as a function of T1-cue lag (lag 2 vs. lag 7) and cue location relative to the target (same vs. different).

ERP results

   Cue-locked N2pc. Figure 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. Figure 7 shows the difference wave obtained by subtracting ipsilateral from contralateral ERPs. The N2pc is typically observed between 150 and 300ms 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, Grubert, Spalek, Di Lollo & Eimer, 2015), we first measured the N2pc's onset, defined as the 15% fractional peak latency of the negative deflection in the 150-350ms

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 of cue-T2 lag and the interaction between the two factors were not significant, both ps $> .20$.

Based on the previous analysis, we quantified the cue-locked N2pc as the mean amplitude of the ipsi-contra difference in two different 100ms time windows, starting approximately 15ms 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[7]. 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 ($M = -0.66\mu v$, $SE = 0.36$ vs. $M = -1.51\mu v$, $SE = 0.52$). 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.

---

[7] In this and the following analysis the results were fully replicated when we used standard time windows (180-280ms; e.g., Eimer & Kiss, 2010, or 200-300ms; e.g., Woodman & Luck, 1999) for both lag conditions.

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 reanalyzed the data using individual N2pc time windows, determined separately for each participant and condition, instead of a uniform window based on the average N2pc latency. We set the 100-ms N2pc time window for a given participant and condition from 15ms 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 ($M = -0.59\mu v$, $SE = 0.27$ vs. $M = -1.33\mu v$, $SE = 0.41$). 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, $t(14) = 2.08$, $p = .056$.
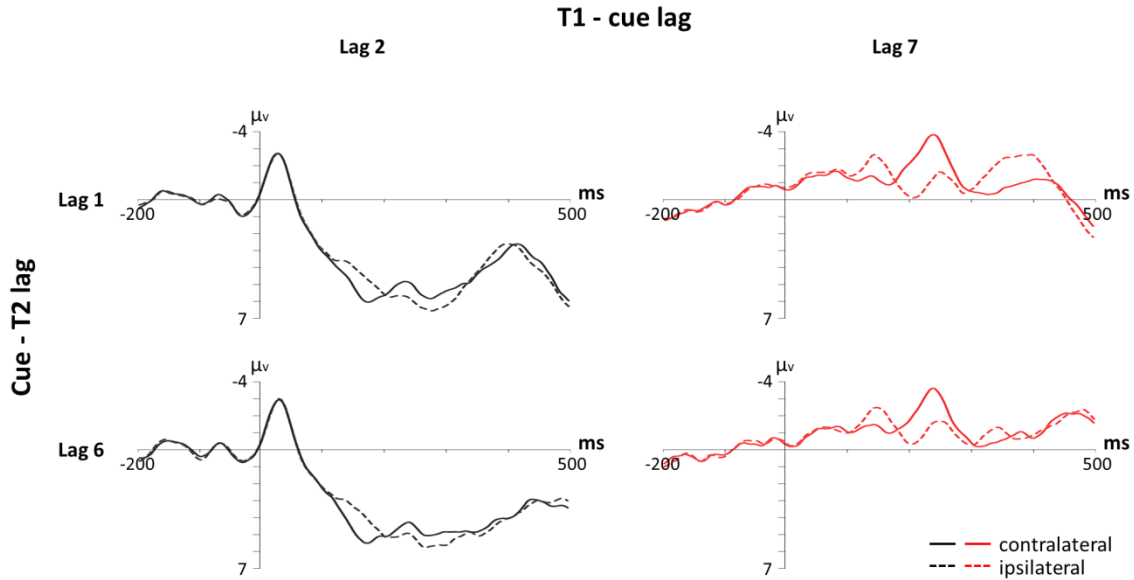
Figure 6. Grand-average event-related potentials (ERPs) waveforms time-locked to the cue at electrodes PO7/PO8 on contralateral and ipsilateral electrodes relative to the cue as a function of T1-cue lag and cue-T2 lag.
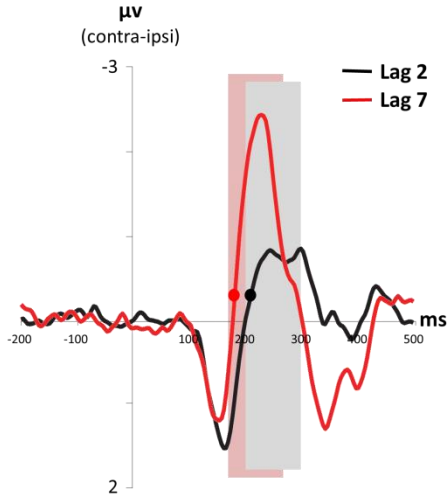

Figure 7. Difference waveforms time-locked to the cue obtained by subtracting ipsilateral from contralateral waveforms as a function of cue-T1 lag. The dots depict the N2pc onset, defined as the 15% fractional peak latency of the negative deflection in the 150-350ms time window. The N2pc inside the AB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

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, Moffat, Dell'Acqua, McDonald, & Jolicœur, 2012; Leblanc, Prime, & Jolicœur, 2008), which emerges approximately 100ms 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 & Kerzel, 2014; Hilimire, Mounts, Parks, & Corballis, 2010; Sawaki, Geng & Luck, 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, $M = 0.73\mu v$, $SE = 0.15$, $t(14) = 4.42$, $p < .001$, and inside the blink, $M = 0.91\mu v$, $SE = 0.17$, $t(14) = 5.05$, $p < .001$. 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.

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. Figures 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 Figure 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, $M = 213ms$, $SE = 10$ vs. $M = 178ms$, $SE = 4$, $t(14) = 3.18$, $p = .006$. 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: 170-270ms post-T2 for T1-T2 lag 8 and 200-300ms post-cue for T1-T2 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, $M = -2.05\mu v$, $SE = 0.55$ vs. $M = -2.60\mu v$, $SE = 0.54$, $t(14) = 3.41$, $p = .004$. Follow-up analysis indicated that the N2pc was reliable at both lags, both $ps < .01$.
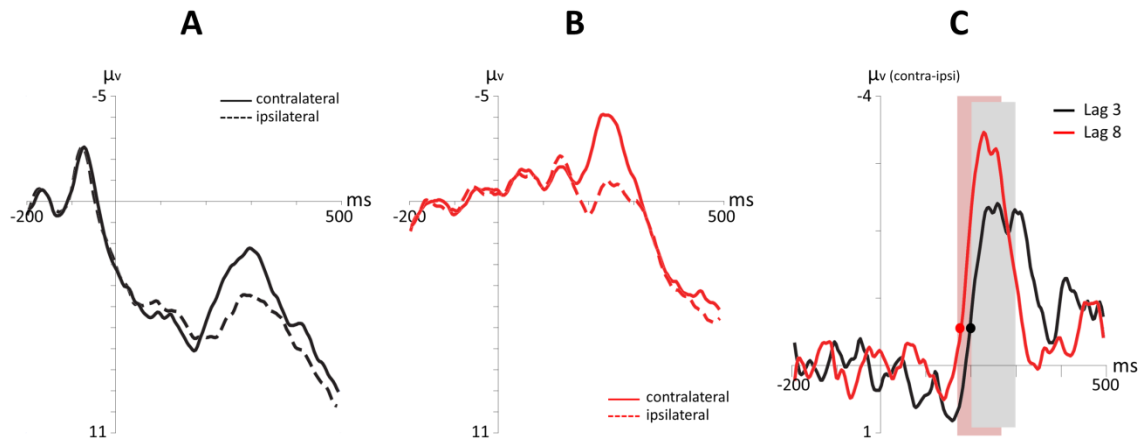

Figure 8. Grand-average event-related potentials (ERPs) time-locked to T2 on absent cue T2 trials at electrodes PO7/PO8 contralateral and ipsilateral to the target in (A) T1-T2 lag 3 and (B) T1-T2 lag 8. (C) N2pc difference waveforms time-locked to T2 obtained by subtracting ipsilateral from contralateral 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 150-350ms time window. The N2pc inside the AB (lag 3) was delayed and attenuated relative to the N2pc outside the AB (lag 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 & Kerzel, 2013; Kiss et al., 2012; Woodman & 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 & 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; Jolicoeur 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., 2008).

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.

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[8]. Attentional engagement differs from attentional shifting in several important respects. Shifting attention is a relatively resource-free operation (Lamy, Alon, Carmel & Shalev, 2015; Zivony & Lamy, 2016) that occurs following the rapid extraction of basic features (such as location or color) during feed-forward processing (Lamme & Roelfsema, 2000; Töllner, Rangelov, & Müller, 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 & 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 & 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; Jolicoeur et al., 2006a; Jolicoeur et al.,

---

[8] 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.

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 & Hillyard, 1994; Luck, Girelli, McDermott and Ford, 1997) or the enhancement of targets (e.g., Eimer, 1996; Mazza, Turatto & Caramazza, 2009). Despite this disagreement, the major and most contemporary accounts of the N2pc (Callahan-Flintoft, Chen & Wyble, 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 & Wyble, 2015), they also suggest that the amplitude of the N2pc and it 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, Turatto, Umiltà and Eimer (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.

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, Kawahara, Ghorashi, & Enns, 2005; Kawahara, Kumada & Di Lollo, 2006; Olivers, Van der Stigchel & Hulleman, 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 & Meeter, 2008) 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), 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 & Meeter, 2008; 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 20-30ms, 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 & 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, Luria, Verleger & Dell'Acqua, 2007; Vogel & 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[9]. 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 & Luck, 2002).

It could be usefully tested in future studies designed so as to isolate both the N2pc and

the P3 components.

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 & Kiss, 2008; Lien, et al., 2017). 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

---

[9] 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, Figure 2) yielded insufficient power to test this effect.

(Folk & Remington, 2015; Gaspelin, Ruthruff & Lien, 2016), but do not result in attentional engagement (Zivony & 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.

References

Akyürek, E. G., Leszczyński, M., & Schubö, A. (2010). The temporal locus of the interaction between working memory consolidation and the attentional blink. *Psychophysiology*, *47*(6), 1134-1141.

Ansorge, U., Horstmann, G., & Worschech, F. (2010). Attentional capture by masked colour singletons. *Vision Research*, *50*(19), 2015-2027.

Avneon, M., & Lamy, D. (2018). Reexamining unconscious response priming: A liminal-prime paradigm. *Consciousness and cognition*, *59*, 87-103.

Bae, E., Jung, S., & Han, S. W. (2018). The perceptual enhancement by spatial attention is impaired during the attentional blink. *Acta psychologica, 190*, 150-158.

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of memory and language*, *68*(3), 255-278.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). lme4: Linear mixed-effects models using Eigen and S4. R package version 1.1–7. 2014.

Botella, J., Barriopedro, M., & Suero, M. (2001). A model of the formation of illusory conjunctions in the time domain. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(6), 1452- 1467.

Buodo, G., Sarlo, M., & Munafò, M. (2009). The neural correlates of attentional bias in blood phobia as revealed by the N2pc. *Social Cognitive and Affective Neuroscience*, *5*(1), 29-38.

Burra, N., & Kerzel, D. (2013). Attentional capture during visual search is attenuated by target predictability: evidence from the N2pc, Pd, and topographic segmentation. *Psychophysiology*, *50*(5), 422-430.

Burra, N., & Kerzel, D. (2014). The distractor positivity (Pd) signals lowering of attentional priority: Evidence from event-related potentials and individual differences. *Psychophysiology*, *51*(7), 685-696.

Burra, N., Barras, C., Coll, S. Y., & Kerzel, D. (2016). Electrophysiological evidence for attentional capture by irrelevant angry facial expressions. *Biological psychology*, *120*, 69-80.

Callahan-Flintoft, C., Chen, H., & Wyble, B. (2018). A hierarchical model of visual processing simulates neural mechanisms underlying reflexive attention. *Journal of Experimental Psychology: General, 147*(9), 1273.

Colzato, L. S., Spapé, M. M., Pannebakker, M. M., & Hommel, B. (2007). Working memory and the attentional blink: Blink size is predicted by individual differences in operation span. *Psychonomic Bulletin & Review, 14*(6), 1051-1057.

Cowan, N. (2001). Metatheory of storage capacity limits. *Behavioral and brain sciences*, *24*(1), 154-176.

Dell'Acqua, R., Sessa, P., Jolicœur, P., & Robitaille, N. (2006). Spatial attention freezes during the attention blink. *Psychophysiology*, *43*(4), 394-400.

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of neuroscience methods*, *134*(1), 9-21.

Di Lollo, V., Kawahara, J.I., Ghorashi, S.S., & Enns, J.T. (2005). The attentional blink: Resource depletion or temporary loss of control? *Psychological research*, *69*(3), 191-200.

Dienes, Z., & Mclatchie, N. (2018). Four reasons to prefer Bayesian analyses over significance testing. *Psychonomic bulletin & review*, *25*(1), 207-218.

Donchin, E., & Coles, M. G. (1988). Is the P300 component a manifestation of context updating?. *Behavioral and brain sciences*, *11*(3), 357-374.

Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalography and clinical neurophysiology*, *99*(3), 225-234.

Eimer, M., & Kiss, M. (2008). Involuntary attentional capture is determined by task set: Evidence from event-related brain potentials. *Journal of cognitive neuroscience*, *20*(8), 1423-1433.

Eimer, M., & Kiss, M. (2010). Top-down search strategies determine attentional capture in visual search: Behavioral and electrophysiological evidence. *Attention, Perception, & Psychophysics*, *72*(4), 951-962.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & psychophysics, 16*(1), 143-149.

Folk, C. L., & Remington, R. W. (2015). Unexpected abrupt onsets can override a top-down set for color. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(4), 1153- 1165.

Folk, C. L., Leber, A. B., & Egeth, H. E. (2002). Made you blink! Contingent attentional capture produces a spatial blink. *Perception & psychophysics*, *64*(5), 741-753.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human perception and performance*, *18*(4), 1030-1044.

Fortier-Gauthier, U., Moffat, N., Dell'Acqua, R., McDonald, J. J., & Jolicœur, P. (2012). Contralateral cortical organisation of information in visual short-term memory: Evidence from lateralized brain activity during retrieval. *Neuropsychologia*, *50*(8), 1748-1758.

Foster, J., Bsales, E., & Awh, E. (2018). The N2pc does not reflect a shift of covert spatial attention. Presented at the annual meeting of the Visual Sciences Society, St. Pete Beach, Florida.

Fukuda, K., & Vogel, E. K. (2009). Human variation in overriding attentional capture. *Journal of Neuroscience*, *29*(27), 8726-8733.

Gaspelin, N., Ruthruff, E., & Lien, M. C. (2016). The problem of latent attentional capture: Easy visual search conceals capture by task-irrelevant abrupt onsets. *Journal of Experimental Psychology: Human Perception and Performance*, *42*(8), 1104-1120.

Ghorashi, S., Enns, J. T., Klein, R. M., & Di Lollo, V. (2010). Spatial selection and target identification are separable processes in visual search. *Journal of Vision, 10*(3), 1-12.

Ghorashi, S., Enns, J. T., Spalek, T. M., & Di Lollo, V. (2009a). Spatial cuing does not affect the magnitude of the attentional blink. *Attention, Perception, & Psychophysics*, *71*(5), 989-993.

Ghorashi, S., Spalek, T. M., Enns, J. T., & Di Lollo, V. (2009b). Are spatial selection and identity extraction separable when attention is controlled endogenously?. *Attention, Perception, & Psychophysics*, *71*(6), 1233-1240.

Giesbrecht, B., & Di Lollo, V. (1998). Beyond the attentional blink: visual masking by object substitution. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(5), 1454-1466.

Hilimire, M. R., & Corballis, P. M. (2014). Event-related potentials reveal the effect of prior knowledge on competition for representation and attentional capture. *Psychophysiology*, *51*(1), 22-35.

Hilimire, M. R., Mounts, J. R., Parks, N. A., & Corballis, P. M. (2010). Event-related potentials dissociate effects of salience and space in biased competition for visual representation. *PloS one*, *5*(9), e12677.

Holguín, S. R., Doallo, S., Vizoso, C., & Cadaveira, F. (2009). N2pc and attentional capture by colour and orientation-singletons in pure and mixed visual search tasks. *International Journal of Psychophysiology*, *73*(3), 279-286.

Ikeda, K., Sugiura, A., & Hasegawa, T. (2013). Fearful faces grab attention in the absence of late affective cortical responses. *Psychophysiology*, *50*(1), 60-69.

Jaeger, T. F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. *Journal of memory and language*, *59*(4), 434-446.

Jannati, A., Spalek, T. M., & Di Lollo, V. (2011). Neither backward masking of T2 nor task switching is necessary for the attentional blink. *Psychonomic Bulletin & Review*, *18*(1), 70-75.

Jiao, J., Zhao, G., Wang, Q., Zhang, K., Li, H., Sun, H. J., & Liu, Q. (2013). Contingent capture can occur at specific feature values: Behavioral and electrophysiological evidence. *Biological psychology*, *92*(2), 125-134.

Jolicœur, P., Brisson, B., & Robitaille, N. (2008). Dissociation of the N2pc and sustained posterior contralateral negativity in a choice response task. *Brain Research*, 1215, 160–172.

Jolicœur, P., Sessa, P., Dell'Acqua, R., & Robitaille, N. (2006). On the control of visual spatial attention: Evidence from human electrophysiology. *Psychological research*, *70*(6), 414-424.

Jolicœur, P., Sessa, P., Dell'Acqua, R., & Robitaille, N. (2006). Attentional control and capture in the attentional blink paradigm: Evidence from human electrophysiology. *European Journal of Cognitive Psychology*, *18*(4), 560-578.

Kawahara, J. I., Kumada, T., & Di Lollo, V. (2006). The attentional blink is governed by a temporary loss of control. *Psychonomic Bulletin & Review*, *13*(5), 886-890.

Kinoshita, S., & Hunt, L. (2008). RT distribution analysis of category congruence effects with masked primes. *Memory & Cognition*, *36*(7), 1324-1334.

Kiss, M., Grubert, A., Petersen, A., & Eimer, M. (2012). Attentional capture by salient distractors during visual search is determined by temporal task demands. *Journal of cognitive neuroscience*, *24*(3), 749-759.

Kiss, M., Jolicœur, P., Dell'Acqua, R., & Eimer, M. (2008). Attentional capture by visual

singletons is mediated by top-down task set: New evidence from the N2pc

component. *Psychophysiology*, *45*(6), 1013-1024.

Kiss, M., Van Velzen, J., & Eimer, M. (2008). The N2pc component and its links to

attention shifts and spatially selective visual processing. *Psychophysiology*, *45*(2),

240-249.

Lagroix, H. E., Grubert, A., Spalek, T. M., Di Lollo, V., & Eimer, M. (2015). Visual

search is postponed during the period of the AB: An event-related potential

study. *Psychophysiology*, *52*(8), 1031-1038.

Lamme, V. A., & Roelfsema, P. R. (2000). The distinct modes of vision offered by

feedforward and recurrent processing. *Trends in neurosciences, 23*(11), 571-579.

Lamy, D., Alon, L., Carmel, T. & Shalev, N. (2015). The role of conscious perception in

attentional capture and object-file updating. *Psychological Science*, *26*(1), 48-57.

Leblanc, É., Prime, D. J., & Jolicoeur, P. (2008). Tracking the location of visuospatial

attention in a contingent capture paradigm. *Journal of cognitive neuroscience*, *20*(4),

657-671.

Lien, M. C., Gemperle, A., & Ruthruff, E. (2011). Aging and involuntary attention

capture: electrophysiological evidence for preserved attentional control with advanced

age. *Psychology and aging*, *26*(1), 188-202.

Liu, Y., Lan, H., Teng, Z., Guo, C., & Yao, D. (2017). Facilitation or disengagement?

Attention bias in facial affect processing after short-term violent video game exposure.

PloS one, 12(3), e0172940.

Lorenzo-López, L., Amenedo, E., & Cadaveira, F. (2008). Feature processing during visual search in normal aging: electrophysiological evidence. *Neurobiology of Aging*, *29*(7), 1101-1110.

Luck, S. J. (2012). Electrophysiological correlates of the focusing of attention within complex visual scenes: N2pc and related ERP components. *The Oxford handbook of event-related potential components*, 329-360.

Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(5), 1000-1014.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*(6657), 279-281.

Luck, S. J., Girelli, M., McDermott, M. T., & Ford, M. A. (1997). Bridging the gap between monkey neurophysiology and human perception: An ambiguity resolution theory of visual selective attention. *Cognitive psychology, 33*(1), 64-87.

Lopez-Calderon, J., & Luck, S.J. (2014). ERPLAB: an open-source toolbox for the analysis of event-related potentials. *Frontiers in Human Neuroscience, 8*, 1–14.

Martens, S., & Johnson, A. (2009). Working memory capacity, intelligence, and the magnitude of the attentional blink revisited. *Experimental Brain Research, 192*(1), 43-52.

Mazza, V., & Caramazza, A. (2011). Temporal brain dynamics of multiple object processing: the flexibility of individuation. *PloS one*, *6*(2), e17453.

Mazza, V., Turatto, M., & Caramazza, A. (2009). Attention selection, distractor suppression and N2pc. *cortex, 45*(7), 879-890.

Mazza, V., Turatto, M., Umiltà, C., & Eimer, M. (2007). Attentional selection and identification of visual objects are reflected by distinct electrophysiological responses. *Experimental Brain Research*, *181*(3), 531-536.

Morey, R. D., & Rouder, J. N. (2015). BayesFactor 0.9. 12-2. Comprehensive R Archive Network.

Nieuwenstein, M. R. (2006). Top-down controlled, delayed selection in the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(4), 973-985.

Nieuwenstein, M. R. (2006). Top-down controlled, delayed selection in the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(4), 973-985.

Nieuwenstein, M. R., Chun, M. M., van der Lubbe, R. H., & Hooge, I.T. (2005). Delayed attentional engagement in the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *31*(6), 1463-1475.

Olivers, C. N. L., & Meeter, M. (2008). A boost and bounce theory of temporal attention. *Psychological review*, *115*(4), 836-863.

Olivers, C. N. L., Van der Stigchel, S., & Hulleman, J. (2007). Spreading the sparing: Against a limited-capacity account of the attentional blink. *Psychological Research*, *71*, 126–139.

Olivers, C. N., & Meeter, M. (2008). A boost and bounce theory of temporal attention. *Psychological review*, *115*(4), 836- 863.

Pashler, H. (1988). Familiarity and visual change detection. *Perception & psychophysics, 44*(4), 369-378.

Peressotti, F., Pesciarelli, F., Mulatti, C., & Dell'Acqua, R. (2012). Event-related potential evidence for two functionally dissociable sources of semantic effects in the attentional blink. *PloS one*, *7*(11), e49099.

Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical neurophysiology*, *118*(10), 2128-2148.

Posner, M. I. (1980). Orienting of attention. *Quarterly journal of experimental psychology*, *32*(1), 3-25.

Raffone, A., Srinivasan, N., & van Leeuwen, C. (2014). The interplay of attention and consciousness in visual search, attentional blink and working memory consolidation. *Philosophical Transaction of the Royal Society of London B. Biological Sciences*, *369*, 20130215.

Robitaille, N., Jolicœur, P., Dell'Acqua, R., & Sessa, P. (2007). Short-term consolidation of visual patterns interferes with visuo-spatial attention: Converging evidence from human electrophysiology. *Brain research*, *1185*, 158-169.

Rouder, J. N., & Speckman, P. L. (2004). An evaluation of the Vincentizing method of forming group-level response time distributions. *Psychonomic bulletin & review*, *11*(3), 419-427.

Sawaki, R., Geng, J. J., & Luck, S. J. (2012). A common neural mechanism for preventing and terminating the allocation of attention. *Journal of Neuroscience*, *32*(31), 10725-10736.

Schubö, A., & Müller, H. J. (2009). Selecting and ignoring salient objects within and across dimensions in visual search. *Brain Research*, *1283*, 84-101.

Sessa, P., Luria, R., Verleger, R., & Dell'Acqua, R. (2007). P3 latency shifts in the

attentional blink: further evidence for second target processing postponement. *Brain

research*, *1137*, 131-139.

Tan, M., & Wyble, B. (2015). Understanding how visual attention locks on to a location:

Toward a computational model of the N 2pc component. *Psychophysiology, 52*(2),

199-213.

Theeuwes, J. (2010). Top–down and bottom–up control of visual selection. *Acta

psychologica*, *135*(2), 77-99.

Töllner T. Rangelov D. Müller H. J. (2012). How the speed of motor-response decisions,

but not focal-attentional selection, differs as a function of task set and target

prevalence. *Proceedings of the National Academy of Sciences, USA, 109*, E1990–

E1999.

Van Velzen, J., & Eimer, M. (2003). Early posterior ERP components do not reflect the

control of attentional shifts toward expected peripheral

events. *Psychophysiology*, *40*(5), 827-831.

Verleger, R., Sprenger, A., Gebauer, S., Fritzmannova, M., Friedrich, M., Kraft, S., &

Jaśkowski, P. (2009). On why left events are the right ones: Neural mechanisms

underlying the left-hemifield advantage in rapid serial visual presentation. *Journal of

cognitive neuroscience*, *21*(3), 474-488.

Vogel, E. K., & Luck, S. J. (2002). Delayed working memory consolidation during the

attentional blink. *Psychonomic Bulletin & Review*, *9*(4), 739-743.

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(1), 92-114.

Vul, E., Nieuwenstein, M., & Kanwisher, N. (2008). Temporal selection is suppressed, delayed, and diffused during the attentional blink. *Psychological Science*, *19*(1), 55-61.

Woodman, G. F., & Luck, S. J. (1999). Electrophysiological measurement of rapid shifts of attention during visual search. *Nature*, *400*(6747), 867–869.

Wu, R., Scerif, G., Aslin, R. N., Smith, T. J., Nako, R., & Eimer, M. (2013). Searching for something familiar or novel: Top–down attentional selection of specific items or object categories. Journal of Cognitive Neuroscience, 25(5), 719-729.

Wyble, B., Bowman, H., & Nieuwenstein, M. (2009). The attentional blink provides episodic distinctiveness: sparing at a cost. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(3), 787-807.

Wykowska, A., & Schubö, A. (2011). Irrelevant singletons in visual search do not capture attention but can produce nonspatial filtering costs. Journal of Cognitive Neuroscience, 23(3), 645-660.

Zivony, A., & Lamy, D. (2014). Attentional engagement is not sufficient to prevent spatial capture. *Attention, Perception, & Psychophysics*, *76*(1), 19-31.

Zivony, A., & Lamy, D. (2016). Attentional capture and engagement during the attentional blink: A "camera" metaphor of attention. *Journal of experimental psychology: human perception and performance*, *42*(11), 1886-1902.

Zivony, A. & Lamy, D. (2018). Contingent attentional engagement: stimulus- and goal-driven capture have qualitatively different consequences (in press). *Psychological Science*. doi: 10.1177/0956797618799302

Zuvic, S. M., Visser, T. A., & Di Lollo, V. (2000). Direct estimates of processing delays in the attentional blink. *Psychological Research*, *63*(2), 192-198.

Author's note