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Temporal cues and the attentional blink: A further examination of the role of expectancy in sequential object perception

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Abstract Although perception is typically constrained by limits in available processing resources, these constraints can be overcome if information about environmental properties, such as the spatial location or expected onset time of an object, can be used to direct resources to particular sensory inputs. In this work, we examined these temporal expectancy effects in greater detail in the context of the attentional blink (AB), in which identification of the second of two targets is impaired when the targets are separated by less than about half a second. We replicated previous results showing that presenting information about the expected onset time of the second target can overcome the AB. Uniquely, we also showed that information about expected onset (a) reduces susceptibility to distraction, (b) can be derived from salient temporal consistencies in intertarget intervals across exposures, and (c) is more effective when presented consistently rather than intermittently, along with trials that do not contain expectancy information. These results imply that temporal expectancy can benefit object processing at perceptual and postperceptual stages, and that participants are capable of flexibly encoding consistent timing information about environmental events in order to aid perception.

Keywords Divided attention · Inattention · Attentional blink · Precuing

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Perception depends upon a complex interplay between the innate tuning of our brains to certain object properties, ongoing demands on the processing resources of the observer, and strategic expectations about when and where the object is likely to appear and what it is likely to be. For example, it is well known that objects with a unique color or shape "pop out" of the environment, leading to faster and more accurate perception (Treisman & Gelade, 1980). With respect to processing demands, the attentional blink (AB) task shows that processing resources engaged by the detection of an initial target (T1) result in reduced identification of a subsequent target (T2) presented within about 500 ms (Raymond, Shapiro, & Arnell, 1992; see Dux & Marois, 2009, and Martens & Wyble, 2010, for reviews). Finally, with regard to expectations, much research has shown that spatial cues (see Theeuwes, 2010, for a review), cues that share target features (Folk, Remington, & Johnston, 1992), and temporal cues (e.g., Correa, Lupiáñez, Milliken, & Tudela, 2004; Coull & Nobre, 1998; Niemi & Näätänen, 1981; Nobre, Correa, & Coull, 2007) all can aid the processing of subsequent targets.

The present work focused on the interaction between temporal cues and the resource depletion that normally accompanies first target detection in the AB task. The specific goal was to better understand the conditions under which temporal cues can ameliorate the perceptual deficits arising from target detection. Our focus on the AB was motivated by theoretical accounts that have broadly ascribed the T2 deficits to T1 processing, either directly, through a "central bottleneck" that both targets must pass (e.g., Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998), or indirectly, because of task switching inherent in processing both T1 and T2 (e.g., Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Olivers & Meeter, 2008; Shapiro, Raymond, & Arnell, 1994). These accounts are consistent with abundant evidence that processing T1 reduces resource availability for T2 (e.g., Dell'Acqua, Sessa, Jolicœur, & Robitaille, 2006; Vogel, Luck, & Shapiro, 1998;

Williams, Visser, Cunnington, & Mattingley, 2008), resulting in delayed T2 processing (Zuvic, Visser, & Di Lollo, 2000) and decreased perceptibility (e.g., Enns, Visser, Kawahara, & Di Lollo, 2001; Giesbrecht & Di Lollo, 1998).

Previous studies have suggested that advance knowledge about when T2 will occur can significantly improve accuracy, similar to the ways that personally relevant target material (Fox, Russo, & Georgiou, 2005; Maratos, Mogg, & Bradley, 2008; Shapiro, Caldwell, & Sorensen, 1997), individual differences in immunity to distraction (Arnell & Stubitz, 2010; Martens, Munneke, Smid, & Johnson, 2006), and even task-irrelevant stimuli can improve accuracy (Arend, Johnston, & Shapiro, 2006). For example, Nieuwenstein, Chun, van der Lubbe, and Hooge (2005, Exp. 1) found that identification of a red T2 was facilitated when it was preceded by red rather than black distractors, suggesting that the presence of a target-defining feature (red) in the distractors immediately prior to T2 facilitated target processing. Similarly, Hilkenmeier and Scharlau (2010) found that the AB was reduced when the identity of T1 indicated the most likely intertarget interval (lag).

But other results have been less decisive. Martens and Johnson (2005) systematically compared the effects of various temporal cueing procedures on T2 identification at shorter (300 ms) and longer (800 ms) intertarget lags. In their first experiment, observers were given separate blocks of trials in which T2 always followed T1 by either 300 or 800 ms, thus allowing them to potentially make use of the temporal regularity across trials to predict the onset of T2. Despite this possibility, the results showed no performance benefits relative to a control group who received an unpredictable mix of trials at both lags. In their second experiment, the central fixation cue was varied prior to each trial to indicate the upcoming intertarget lag. Under these conditions, T2 accuracy was improved at the shorter lag, relative to a second group of observers who received no temporal cues. However, cueing did not affect accuracy at the longer lag. This result was replicated in their third experiment, which compared the same observers across separate blocks of trials that did or did not use temporal cues.

Martens and Johnson (2005) interpreted their results as supporting two key theoretical ideas about the relationship between temporal cues and the AB. First, because temporal cues enhanced T2 identification only at the short lag, Martens and Johnson proposed that cues provide a unique advantage specifically for T2 in the competition for resources between targets (Shapiro et al., 1994). In their view, this allowed temporal cues to be effective at the shorter, 300-ms lag, where competition among targets for common resources is maximal, but not at the longer, 800-ms lag, where competition is minimal. Second, because temporal cues were only effective when presented on a trial-by-trial basis, it implied that observers had to keep the informational content of the cue active in working memory. When blocks of trials were presented, observers were either unable or unwilling to engage working memory in order to use this information to predict T2 onset.

In the present study, we investigated these two hypotheses in greater detail. First, whereas there is solid evidence that temporal cues benefit the competitive strength of T2, it is notable that the stimulus streams in Martens and Johnson (2005) contained distractors (digits) that possessed significant similarity with the targets (letters). Previous work has shown that high levels of target–distractor similarity increase the magnitude of the AB deficit (e.g., Chun & Potter, 1995; Maki & Padmanabhan, 1994; Raymond et al., 1992; Visser, Bischof, & Di Lollo, 2004). This effect has been explained by positing that observers establish a template (or perceptual filter) based on target attributes to govern the access of perceptual inputs to cognitive resources, resulting in inadvertent distractor processing (Visser et al., 2004) or a loss of control over perceptual filtering (Di Lollo et al., 2005) under conditions of high target–distractor similarity. On the basis of these explanations, we hypothesized that temporal cues might also reduce the AB by allowing perceptual processing to be optimized around the expected time of target presentation, thereby reducing the likelihood that distractors would pass the perceptual filter. We tested this prediction in Experiment 1 by examining whether target–distractor similarity interacts with temporal cueing benefits. According to our hypothesis, we would expect temporal cueing to be more beneficial when target–distractor similarity is high, reflecting the proportionally greater benefit of avoiding similar distractors that magnify the AB.

Another notable finding from Martens and Johnson (2005) was the absence of benefits arising from repeated trials at a constant lag. Although this pattern is consistent with results from spatial-cueing studies (Posner, Snyder, & Davidson, 1980), it seems somewhat at odds with effects found elsewhere. For example, Zahn and Rosenthal (1966) showed that increasing the proportion of trials at a given foreperiod reduced response times. Badcock, Badcock, Fletcher, and Hogben (2013) also found that the AB was ameliorated when T1 followed a lengthy and predictable foreperiod, suggesting that adequate preparation for the appearance of both targets facilitated superior processing. Shen and Alain (2010) found that instructing participants at the beginning of a block of trials to focus attention at a specific time interval following T1 strongly benefited T2 accuracy when it appeared at that interval. Finally, Choi, Chang, Shibata, Sasaki, and Watanabe (2012) and Tang, Badcock, and Visser (2014) both demonstrated that exposure to repeated trials with a consistent, brief, and salient intertarget lag reduced the size of the AB on a subsequent task that contained a mix of both short- and long-lag trials. These results imply that exposure to temporal regularity can ameliorate the AB, if these regularities are sufficiently salient. To test this prediction, in Experiment 2 we replicated the first experiment of Martens and Johnson, together with explicit instruction to the observers to use this regularity to improve target accuracy.

A final goal of the present work was to examine the effectiveness of temporal cueing when cued and uncued trials are intermixed, as compared to when these trials are presented in separate blocks, as in Martens and Johnson (2005). If the only requirement for effective temporal cueing is that the cues be actively processed in working memory, then it seems unlikely that simply mixing cued and uncued trials would lead to results substantially different from those obtained when the two types of trials are presented in separate blocks. On the other hand, if the effectiveness of temporal cueing also depends on being able to anticipate that such cues will be present across trials, as is the case when cued and uncued trials are presented in separate blocks, then this would imply that the benefits of temporal cueing are modulated by other factors. For example, the necessity of switching strategies between trials with and without temporal cues might lead to costs, such as reducing the ability of temporal cues to engage working memory. To investigate this possibility, in Experiment 3 we directly compared the results from mixed and blocked manipulations of temporal cueing.

Experiment 1

Method

Participants A group of 20 undergraduate students (11 female, nine male; mean age 19.10 years, range = 17–23) were recruited in exchange for partial credit toward course completion. All provided informed consent prior to participating, had normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

Apparatus and stimuli The stimuli were presented on a 19-in. (viewing size: 18 in.) Dell M992 monitor running at a refresh rate of 100 Hz, attached to a Pentium computer running Presentation software (Version 16.20; Neurobehavioral Systems), located in a dimly lit room. The software also recorded response times and accuracy from a computer keyboard.

All stimuli subtended a visual angle of approximately 1° at a viewing distance of 60 cm and were shown in light gray (C.I.E.: $u' = .184$, $v' = .456$). The targets consisted of all letters of the English alphabet except I, O, Q, and Z, which were omitted due to their structural similarity to the digits 1, 0, 2, and 7. The masking items presented immediately after T1 and T2 consisted of the digits 1–9. The low-similarity distractors consisted of five keyboard symbols (@, #, %, &, ?) that shared some geometric features with the target letters. Targets, masks, and low-similarity distractors were presented in 28-point Arial font. The high-similarity distractors consisted of ten "pseudoletter" geometric shapes formed from rearranging letter segments. Although these distractors shared features with target letters, they were not confusable with any English letter (see Visser, 2007, for further details).

Procedure The procedure was based on that of Martens and Johnson (2005). Each participant viewed two blocks of trials in counterbalanced order. In the "uncued" block, trials began with a central fixation consisting of a "+" that did not predict the intertarget interval. In the "cued" block, trials began with a fixation that consisted of "-" on trials with a short intertarget interval (lag 3), or "—" on trials with a long intertarget interval (lag 8). Each block consisted of 400 trials, equally divided amongst short and long lags and low- or high-similarity distractors.

On each trial, participants were instructed to focus their gaze on the fixation and press the space bar to begin the trial. This initiated an rapid serial visual presentation (RSVP) stream at fixation. Each item in the stream was presented for 20 ms and followed by a blank screen for 80 ms. After six distractors, T1 was presented, followed by a trailing digit mask, and then one (lag 3) or six (lag 8) additional distractors. Finally, T2 was presented, followed by a digit mask that completed the RSVP stream. The distractors, targets, and masks were chosen pseudorandomly with replacement, with the provisos that identical items could not appear consecutively and that targets must be different. When the RSVP stream finished, participants were prompted to identify the two target letters by typing them into the keyboard. Prior to the experiment, participants were instructed to guess if they were uncertain about target identity, and that responses did not have to be made in the order that targets were presented. Following these responses, the fixation reappeared, indicating the next trial was ready to begin. Progress through the experiment was self-paced and took approximately 50 min.

Results

The chief finding was that temporal cueing was more effective when target–distractor similarity was high than when it was low. This conclusion was based on the following analyses. Mean target accuracy was first calculated separately for each lag, distractor type, and block of trials. As is customary in analyses of AB performance, second-target accuracy was calculated only on trials in which T1 had been identified correctly in an effort to ensure that the first target had been attended (Raymond et al., 1992). Preliminary examination of the data showed that one participant in the cued condition had a mean T2 identification accuracy more than 2.5 standard deviations below the group average. The data from this individual were omitted from further analysis.

T1 accuracy Mean T1 accuracy scores can be seen in Fig. 1, and were submitted to a 2 (Cue: Present vs. Absent) × 2 (Lag: 3 vs. 8) × 2 (Similarity: high vs. low) within-subjects analysis of variance (ANOVA). This analysis revealed a significant main effect of similarity, $F(1, 18) = 22.71$, $p < .001$, $\eta^2 = .56$, with greater overall accuracy when target–distractor similarity was low than when it was high. This replicated the results of Visser et al. (2004), who showed an impact of target–distractor similarity on both T1 and T2 accuracy.

T2 accuracy Mean T2 accuracy scores can also be seen in Fig. 1, and were also submitted to a 2 (Cue) × 2 (Lag) × 2 (Similarity) within-subjects ANOVA. This analysis revealed main effects of cue, $F(1, 18) = 13.06$, $p = .002$, $\eta^2 = .42$, lag, $F(1, 18) = 73.36$, $p < .001$, $\eta^2 = .80$, and similarity, $F(1, 18) = 6.58$, $p = .019$, $\eta^2 = .27$, as well as Cue × Lag, $F(1, 18) = 7.06$, $p = .016$, $\eta^2 = .28$, Lag × Similarity, $F(1, 18) = 19.82$, $p < .001$, $\eta^2 = .52$, and, critically, Cue × Lag × Similarity, $F(1, 18) = 9.98$, $p = .005$, $\eta^2 = .36$, interactions. Examination of Fig. 1 shows clear evidence for a significant AB and a greater effect of similarity at the nadir of the AB (i.e., at lag 3) for uncued trials. For cued trials, on the other hand, the interaction between similarity and the AB was not present. To confirm this impression, we conducted separate Lag × Similarity ANOVAs for cued and uncued trials. As is suggested by Fig. 1, the Similarity × Lag interaction was significant for the uncued trials, $F(1, 18) = 27.45$, $p < .001$, $\eta^2 = .80$, along with a marginal main effect of similarity, $F(1, 18) = 3.01$, $p = .099$, $\eta^2 = .14$, and a main effect of lag, $F(1, 18) = 27.45$, $p < .001$, $\eta^2 = .60$. In contrast, for the cued trials, we observed a main effect of similarity, $F(1, 18) = 9.49$, $p = .006$, $\eta^2 = .34$, and lag, $F(1, 18) = 51.73$, $p < .001$, $\eta^2 = .74$, but no Similarity × Lag interaction, $F(1, 18) = 1.08$, $p = .313$, $\eta^2 = .06$.

These results imply that temporal cues benefit the AB by allowing more effective perceptual filtering. Following the logic of the filtering account advanced by Visser et al. (2004), we suggest that temporal cues allow the filter to be optimally tuned to the time of T2's expected arrival. This temporal information thus provides an additional dimension to the filter, over and above the geometric features of shape and color, which allows distractors to be more effectively excluded. This hypothesis not only explains the extant data, but is also consistent with recent findings by Visser (under review) showing that target probability influences the magnitude of extended sparing, as well as studies showing beneficial effects of knowledge about RSVP rate (Akyürek, Riddell, Toffanin, & Hommel, 2007) and the expected availability of processing time (Akyürek, Toffanin, & Hommel, 2008) on T2 accuracy at lag 1. Similarly, recent work by Wierda, van Rijn, Taatgen, and Martens (2012) has suggested that mental effort, as measured by pupil dilation, reliably increases around the expected temporal position of a target in the AB, indicating that observers are able to flexibly target attentional allocation to a cued interval.

In Experiment 2, we turned to the issue of establishing the conditions under which temporal cueing affects the AB. As we noted earlier, the work of Martens and Johnson (2005) had suggested that observers could not use temporal regularities

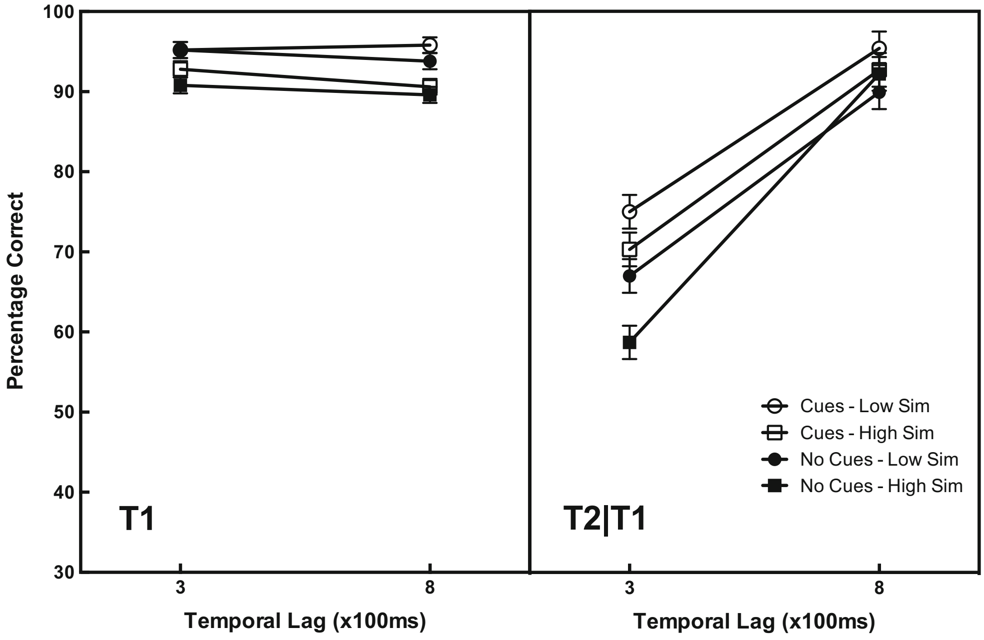

Fig. 1 Percentages of correct target identification, plotted as a function of intertarget lag. Solid symbols depict target accuracy on uncued trials. Open symbols depict target accuracy on cued trials. Circle symbols depict performance with low-similarity distractors, and square symbols depict performance with high-similarity distractors. The left panel depicts T1 performance, and the right panel depicts T2 performance on trials in which T1 was identified correctly. Error bars represent one within-subjects standard error of the mean (Masson & Loftus, 2003).

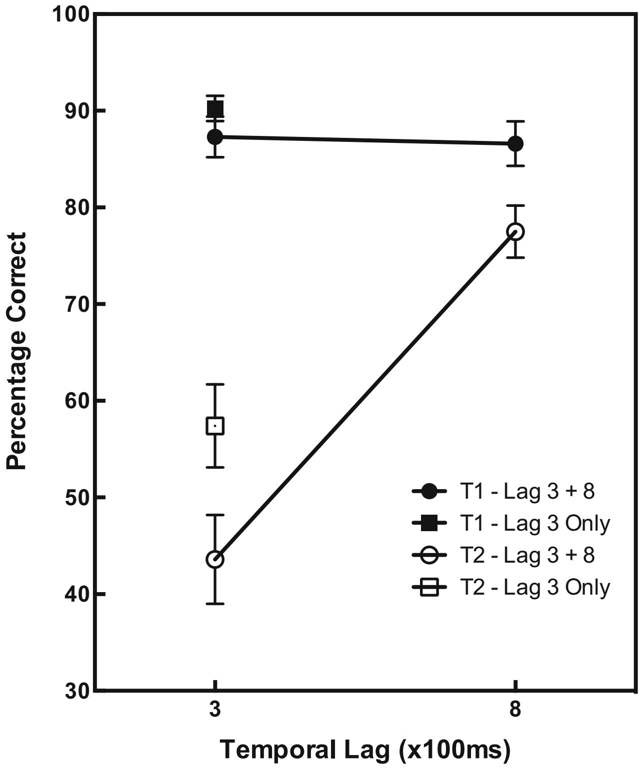

Fig. 2 Percentages of correct target identification, plotted as a function of intertarget lag. Solid symbols represent T1 accuracy, and open symbols represent T2|T1 accuracy. Single points show performance on blocks of trials with an intertarget lag of 3. Error bars represent one standard error of the mean.

across blocks of trials to ameliorate the AB. However, evidence from other studies (e.g., Choi et al., 2012; Tang et al., 2014) has implied that such regularities can be beneficial when they are made salient to observers. This implies a critical strategic component in the effectiveness of using temporal information to influence the perceptual filter. To test this interpretation, we compared performance between two groups: one who viewed trials randomly at lags 3 and 8, and another who viewed trials only at lag 3 and were instructed to use this consistency to improve T2 accuracy.

Experiment 2

Method

Participants A group of 36 new undergraduate students (20 female, 16 male; mean age 19.78 years, range = 17–29) were recruited in exchange for partial credit toward course completion. Half of the participants were randomly assigned to view trials at one intertarget interval, whereas the other half viewed trials at a mix of intertarget intervals. All students provided informed consent prior to participating and had normal or corrected-to-normal vision.

Apparatus and stimuli The apparatus and stimuli were identical to those in Experiment 1.

Procedure The procedure was broadly similar to that used in Experiment 1, except that only high-similarity distractors were used, and all trials began with a “+” fixation that did not predict the inter-target interval on the upcoming trial. Additionally, we created two experimental groups. In the *consistent-interval* group, participants viewed 300 trials presented with an intertarget interval of lag 3. In the *variable-interval* group, participants viewed 600 trials, evenly divided between intertarget intervals of lags 3 and 8. In this group, the two lags were randomly intermixed, and thus the temporal interval on the upcoming trial was unpredictable. Prior to beginning the experiment, participants in the consistent-interval group were informed that there would be a fixed interval between targets on all trials, and they were instructed to use this information to attempt to improve their performance. In the variable-interval group, participants were simply informed that the interval between targets would vary randomly.

Results

The main finding was that T2 accuracy was significantly higher in the *consistent-interval* than in the *variable-interval* group. This conclusion was based on the following analyses. Mean target accuracy was calculated separately for each lag and experimental group, using the parameters outlined in Experiment 1. Preliminary examination of the data showed that one participant in each group had mean T2 identification accuracy more than 2.5 standard deviations below the group average. The data from these individuals were omitted from further analysis.

Following the data-analytic procedure of Martens and Johnson (2005), we used *t*-tests to evaluate performance differences between lags 3 and 8 in the variable-interval group to determine whether an AB occurred. We applied the Holm step-down procedure (Holm, 1979) to control for Type I errors. Confirming the impression given by inspection of the group performance in Fig. 2, we found no difference in T1 accuracy across lags, $t(16) = 1.40$, $p = .180$, but a substantial improvement across lags in T2 accuracy, $t(16) = 9.64$, $p < .001$.

To determine whether presentation of a constant lag across trials improved performance, we then compared performance at lag 3 between the consistent-interval and variable-interval groups. Independent *t*-tests showed no difference between T1 accuracy across these groups, $t(32) = 1.19$, $p = .244$. Critically, however, T2 accuracy was significantly higher in the *consistent-interval* group, $t(32) = 2.19$, $p = .036$.

In contrast to the findings of Martens and Johnson (2005), our results suggest that a series of trials presented at a constant intertarget interval can aid T2 accuracy and reduce the AB deficit. Given that the principal difference between our paradigms was the use of instructions to highlight the constant intertarget interval, it would appear that our findings resolve a key issue arising from Martens and Johnson: It is not that participants cannot use temporal reliability across trials as a cue to upcoming events; rather, they are unable or unwilling to do so, unless this relationship is made salient to them. It is worth noting that another possible explanation for our findings (and for those of Martens & Johnson, 2005) is individual differences between the cued and uncued groups. Although this cannot be definitively ruled out, we note the absence of performance differences between the groups on T1, which is inconsistent with an individual-differences explanation.

In Experiment 3, we examined the potential impact of intermixing cued and uncued trials in a single block, as compared to the between-blocks manipulations of cueing used in previous studies. At issue was whether intermixing trials would lead to any reduction in cueing benefits, and if so, whether this was primarily attributable to differences in performance on cued and uncued trials. Pinpointing whether changes occur on cued and uncued trials would allow us to make some speculations about the differential impact of consistent and inconsistent temporal cues on target processing.

Experiment 3

Method

Participants A group of 21 new undergraduate students (ten female, 11 male; mean age 18.14 years, range = 16–23) were recruited in exchange for partial credit toward course completion. All provided informed consent prior to participating and had normal or corrected-to-normal vision.

Apparatus and stimuli The apparatus and stimuli were identical to those in Experiment 1.

Procedure The procedure was broadly similar to that used in Experiment 1, except that cued and uncued trials were randomly intermixed across the experiment, and only high-similarity distractors were used. A total of 600 trials were evenly divided between lags 3 and 8 and between the presence and absence of a temporal cue.

Results

The main finding was that temporal cues were less effective at improving T2 accuracy when the presented in a single mixed block, especially at the shorter intertarget interval. This conclusion was based on the following analyses. Mean target accuracy was calculated separately for cued and uncued trials at each lag, using the parameters outlined in Experiment 1. Preliminary examination of the data showed that no outliers were present.

T1 accuracy Mean T1 accuracy scores can be seen in Fig. 3, and were submitted to a 2 (Lag) × 2 (Cue: present vs. absent) within-subjects ANOVA. This analysis revealed no significant main effects or interactions (ps> .32, η^2s < .05).

T2 accuracy Mean T2 accuracy scores can be seen in Fig. 3, and were also submitted to a 2 (Lag) × 2 (Cue) within-subjects ANOVA. This analysis revealed a significant main effect of lag, $F(1, 20) = 155.52$, $p < .001$, $\eta^2 = .89$, consistent with the presence of an AB deficit. However, the main effect of cue was only marginally significant, $F(1, 20) = 3.70$, $p < .07$, $\eta^2 = .16$., and the Lag × Cue interaction was not significant, $F(1, 20) = 0.68$, $p = .681$, $\eta^2 = .01$.

These results, in tandem with a comparison of Figs. 1 and 3, suggest that presenting cued and uncued trials in a single

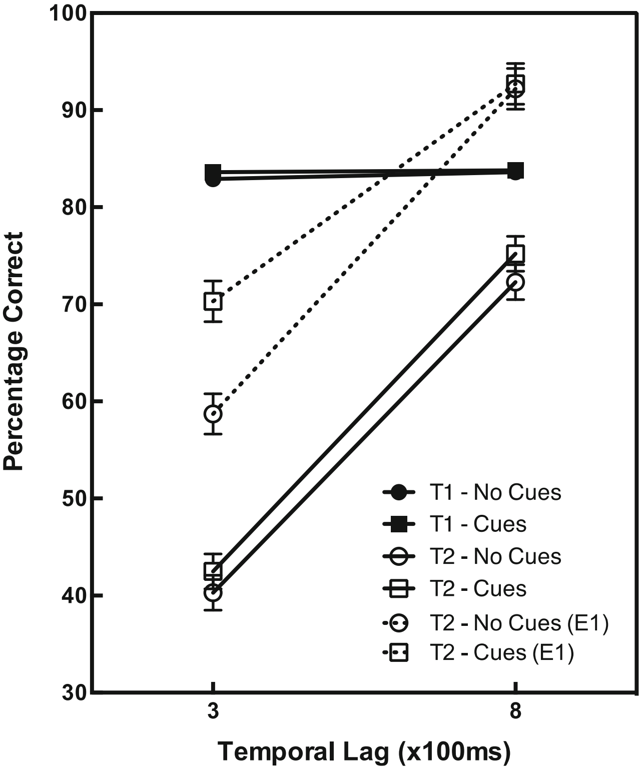

Fig. 3 Percentages of correct target identification, plotted as a function of intertarget lag. Solid symbols depict T1 accuracy. Open symbols depict T2|T1 accuracy. Circle symbols depict performance on trials with no temporal cue, and square symbols depict performance on trials with a temporal cue. For ease of comparison, dotted lines depict the performance on cued and uncued trials from the high-similarity condition in Experiment 1. Error bars represent one within-subjects standard error of the mean (Masson & Loftus, 2003).

mixed block decreased the benefits arising from temporal cueing, particularly at the shorter intertarget interval. To confirm this impression, we conducted a combined analysis incorporating T2 accuracy data from both this experiment and the comparable high-similarity trials from Experiment 1, in which cued and uncued trials were presented in separate blocks. These means were entered into a 2 (Lag) × 2 (Cue) × 2 (Experiment: 1 vs. 3) mixed ANOVA. This analysis revealed significant main effects of experiment, $F(1, 38) = 27.99$, $p < .001$, $\eta^2 = .42$, lag, $F(1, 38) = 242.22$, $p < .001$, $\eta^2 = .86$, and cue, $F(1, 38) = 15.06$, $p < .001$, $\eta^2 = .28$, as well as a Lag × Cue interaction, $F(1, 38) = 8.24$, $p = .007$, $\eta^2 = .18$, and most importantly, a Lag × Cue × Experiment interaction, $F(1, 38) = 10.83$, $p = .002$, $\eta^2 = .22$. The presence of the three-way interaction confirms that the principal impact of mixing cued and uncued trials was to reduce the benefits of temporal cueing when T2 was presented during the nadir of the AB. Moreover, an examination of Fig. 3 clearly suggests that the reduction in cueing benefits stems from a more marked decline in cued T2 accuracy when cued and uncued trials are intermixed relative to uncued T2 accuracy.

General discussion

Thirty years of research on attentional limitations, including the vast literature on the attentional blink, has provided abundant evidence that engaging cognitive resources on one input impairs the processing of subsequent inputs. Although the underlying sources of these limitations are still the subject of much debate (see Dux & Marois, 2009; Martens & Wyble, 2010), much can be learned from studying the ways in which the perceptual costs of cognitive engagement can be reduced by advance information. Past studies have shown that improvements in target performance can be achieved using a variety of methods to cue the onset of upcoming targets (Hilkenmeier & Scharlau, 2010; Martens & Johnson, 2005; Nieuwenstein et al., 2005). These benefits point to characteristics of the attentional system that can be modified through instruction and experience.

The goal of the present work was to investigate the conditions under which such cueing can overcome processing limits. In the first experiment, we showed that temporal cues presented prior to a trial increase observers' ability to form perceptual filters that exclude distractors, thereby improving target accuracy. Notably, this improvement was greater when the target–distractor discrimination task was more difficult, consistent with our hypothesis that temporal cuing adds a dimension to the filter that is over and above the geometric features of shape and color. In the second experiment, we found that repeatedly presenting targets at a constant lag improves performance, as long as participants are aware of this relationship. This points to the critical role of strategic awareness in the effectiveness of temporal cuing. Finally, in the third experiment, we showed that intermixing cued and uncued trials led to significantly less temporal cueing than on comparable trials presented in separate blocks.

The finding that temporal cues can reduce distractor processing suggests that the expected onset of a target can be used as a dimension upon which to base perceptual filtering operations. This implies that expected onset time can be used as a type of object property to form a perceptual input filter, in the same way as color, form, or spatial location can be used. This allows distractors to be effectively excluded on the basis of not appearing at the expected time. Note that the idea is broadly similar to Martens and Johnson's (2005) suggestion that onset time can be used as unique attribute to enhance the competitive strength of T2 when competing for cognitive resources. What is critically different about our proposal, however, is that expected onset time could be used to influence a perceptual selection stage prior to any interitem competition for cognitive resources. It is also worth noting that this apparent ability to select on the basis of expected presentation time may have limited temporal precision, given the rapid rate of stimulus presentation. In the absence of formal studies on this question, the exact precision of temporal cues is unknown. However, some hint may be apparent in Tang et al. (2014), who found that participants who practiced AB trials at lags 2, 4, and 6 did not show additional benefits at lag 2 on subsequent testing, as compared to participants who only practiced AB trials at lag 2. This may suggest some differentiation between temporal intervals beyond at least a 200-ms window.

The notion that a high-level attribute, such as expected onset, could be used as a filter dimension is broadly consistent with Visser et al. (2004) who compared target identification across AB trials with random-dot, digit, pseudoletter, and letter distractors. The results showed that T1 and T2 accuracy declined with increasing target–distractor similarity. More importantly, this decline was much larger between letter and pseudoletter distractors than between digit and pseudoletter distractors, despite similar changes in featural overlap. This suggests that an overlapping higher-order attribute—namely, semantics—contributed to the likelihood that distractors would pass the perceptual filter and interfere with target accuracy. Similarly, Martens, Korucuoglu, Smid, and Nieuwenstein (2010) found that participants who displayed consistently reduced attentional blink deficits (so-called "nonblinkers") were able to filter targets on the basis of alphanumeric category.

As well as pointing to additional ways in which temporal cues may ameliorate perceptual deficits arising from reduced cognitive resources, our work indicates that participants can use temporal regularities across trials to anticipate the time of target onset. Notably, in comparing our paradigm with that of Martens and Johnson (2005), it is clear that this information is only effective when participants are made aware of its existence and motivated to use it. This result not only aligns the temporal cueing results with previous literature on practice effects in the AB (Choi et al., 2012; Tang et al., 2014), but also with literature on the impact of repeating target spatial location. For example, Maljkovic and Nakayama (1996) showed that participants benefited from repeated presentations of a pop-out target at a given spatial location. Importantly, being a pop-out target, it is likely that this increased salience helped to highlight the spatial regularities across trials.

A final aspect of the present results to consider is the finding that intermixing cued and uncued trials led to significantly smaller cueing benefits, as well as a general reduction in T2 accuracy. It is possible that some of this difference, particularly the large overall reduction in accuracy, was due to variability between groups of participants. We think that this is unlikely, because no performance differences emerged between groups on T1, which is inconsistent with an individual-differences explanation. Another option is that task switching (see Kiesel et al., 2010, and Monsell, 2003, for reviews) played a deleterious role, since participants were required to unpredictably shift between cued and uncued trials, and hence continuously reconfigure cognitive and perceptual resources. It seems that this also cannot directly explain our results, since a post-hoc comparison between “switch” and “no-switch” trials, created by separately analyzing trials on the basis of whether the preceding trial had the same or different cues (i.e., valid cue vs. no cue), revealed no effect of the preceding trial type on cueing magnitude ($p > .14$, $\eta^2 < .06$). A third option is that the additional load imposed by unpredictable perceptual and cognitive reconfigurations interfered with the formation of an effective perceptual filter (Di Lollo et al., 2005), thereby eliminating the cueing benefit. This account is consistent both with the broad decline in performance seen in Experiment 3 and with this decline being larger for cued than for uncued trials. This is the proposal that we favor, but it warrants further investigation.

In conclusion, the present results show that information about the expected onset of a stimulus can robustly counteract the negative consequences arising from reduced availability of cognitive resources. This seems partly due to an increase in target salience that comes from predictable temporal regularity, as demonstrated by Martens and Johnson (2005), but that is also due to an enhanced ability to filter out unwanted distractions. In addition, our data show that benefits can occur both when information about expected onset is presented prior to each trial, and when target onset is primed by repeated occurrences across trials. It remains for future research to build upon this work by examining the temporal specificity of cueing benefits, the interaction between temporal and spatial cues in overcoming resource limits, and the overlap between temporal cueing and potentially related phenomena such as temporal contextual cueing (Olson & Chun, 2001).

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