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SHORT REPORT

First target timing influences the attentional blink under low, but not high working memory load

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Abstract
A growing literature posits attention as a core component of working memory (Baddeley, *European Psychologist, 7*(2), 85-97, 2002), yet research exploring this relationship is scarce in the temporal attention domain. The present research provided further evidence that the magnitude of the attentional blink (AB) can be influenced by working memory load (WML; Akyürek et al., *Memory & Cognition 35*, 621–627, 2007). Additionally, we behaviorally tested Akyürek and colleagues' (*Psychophysiology, 47*(6), 1134-1141, 2010) conclusion that working memory influences attention at an early stage by systematically manipulating the timing of the first target in relation to the stimuli preceding and following it. In two experiments, we demonstrated that the AB effect increases as the temporal interval between the first target and the stimulus following it decreases. Importantly, this effect was observed only when WML was low, indicating that WM influences attending to a second target at an early stage of attentional processing.

Keywords Attentional blink · Working memory · Attention and executive control

Introduction

Observed limitations in attending to multiple target stimuli in a Rapid Serial Visual Presentation (RSVP) task (Lawrence, 1971) have fueled theories describing the sub-second operations of attentional processes (e.g., Chun & Potter, 1995; Di Lollo et al., 2005; Olivers & Meeter, 2008; Olivers & Nieuwenhuis, 2006; Wyble et al., 2009; for a review, see Dux & Marois, 2009). These theories were based on conditions necessary to elicit the attentional blink (AB) effect – a deficit in responding to a second target (T2) when T2 appears approximately 200–500 ms after a first target (T1) (Broadbent & Broadbent, 1987; Raymond et al., 1992). Contemporary theorizing considers attention to be a core component of working memory (WM; e.g., Baddeley, 2002; Barrouillet et al., 2004), yet accounts of the AB fail to consider how WM influences the AB. The potential interactions between attention and memory processes warrant examination of how people attend in time under different WM loads (WML).

While the *spatial* attention literature generally supports the notion that, at minimum, attention and WM processes interact functionally or, at maximum, are intertwined mechanistically (e.g., Awh & Jonides, 2001; Awh et al., 2006; Fougnie, 2008; Manohar et al., 2019; Theeuwes et al., 2011), the *temporal* attention literature is more divided. Indeed, some correlational research highlights relationships between executive WM processes and performance during the AB (e.g., Arnell & Stubitz, 2010; Colzato et al., 2007; Martens & Johnson, 2009; Willems & Martens, 2016). However, experimental explorations are limited and provide mixed evidence; some research demonstrates a direct influence of WML, but not short-term storage load, on the AB (Akyürek et al., 2007, 2010; Hommel & Akyürek, 2005), while other evidence suggests parallel and distinct processes (Glennon et al., 2016). Still other research has found no impact of WM on temporal attention (Zanto et al., 2020). More data examining temporal attention in the context of different WM conditions is needed before strong integrative theories of attention and WM can be developed.

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The current research adds to the existing literature by replicating and extending the work of Akyürek et al. (2007) examining the magnitude of the AB under different WML conditions. In their research, participants indicated whether T1 had appeared in a memory set of varying sizes presented at the beginning of each trial. Participants then identified T2. The magnitude of the AB increased as WML (i.e., the memory set size) increased. In the present research, we tested whether WML influences temporal attention at an *early* stage of attentional processing by manipulating a putatively early attentional process, attentional entrainment. Attentional entrainment is a process by which temporal expectations are trained with periodic presentations of auditory (Jones, 1976; Large & Jones, 1999; McAuley, 1995) or visual (Kizuk & Mathewson, 2017; Kranczioch, 2017; Mathewson et al., 2010) stimuli. We disrupted attentional entrainment by manipulating the timing of T1 relative to the stimuli preceding and following it systematically across two experiments. If WML interacts with this T1 timing manipulation, then WM can be assumed to interact with temporal attention at an early stage of processing.

Experiment 1

If WML disrupts temporal attention at an early stage of processing, then increasing WML should decrease the influence of T1 Timing on the AB. That is, under low WML the magnitude of the AB should be different when T1 appears on time than when T1 appears early or late, and this difference should be greater than when WML is high.

Method

Fifty-eight undergraduates participated for course credit. Figure 1 depicts the procedure for the experiment. A memory set of one, two, or four letters appeared in the center of the screen for 2,000 ms (WML) followed by a fixation cross displayed for 300 ms. Then, an RSVP sequence of 19 letters followed. All letters were white except for two blue target letters separated by zero, two, or six letters (T1-T2 Lag: Lag-1, Lag-3, Lag-7). Each letter was displayed for 16 ms with a stimulus onset asynchrony (SOA) of 96 ms. However, T1 appeared 32 ms early on 25% of the trials and 32 ms late on 25% of the trials (T1 Timing manipulation). Each WML condition was blocked and counterbalanced across participants. The Lag and T1 Timing variables were randomly assigned on each trial with the constraint that proportion of trials within each block equaled the probabilities described above. Participants indicated whether the first blue letter was present in the memory set and then reported the identity of the second blue letter.

Results

T1 proportion correct is summarized in Table 1. Accuracy decreased as WML increased, $F(2,114) = 42.30$, $p < .001$, $\eta_p^2 = .42$, and as the temporal interval between T1 and the T1+1 stimulus decreased, $F(1.62,92.39) = 111.12$, $p < .001$, $\eta_p^2 = .66$. Additionally, there was a main effect of lag, $F(2,144) = 28.37$, $p < .001$, $\eta_p^2 = .33$, such that T1 proportion correct was lower when T2 appeared in lag-1 than lags-3 and -7. Finally, a two-way interaction between Lag and Jitter, $F(4,228) = 2.46$, $p = .046$, $\eta_p^2 = .04$, was observed such that the reduction in T1 proportion correct when T1 appeared late was greater when T2 appeared at Lag-1 than at Lags-3 or -7.

For results concerning T2, we analyzed only the cases in which participants responded correctly to the first target task (T2|T1; second target given a correct response for the first target). Additionally, because T2|T1 performance at lag-1 is generally independent of performance during the AB (Olivers

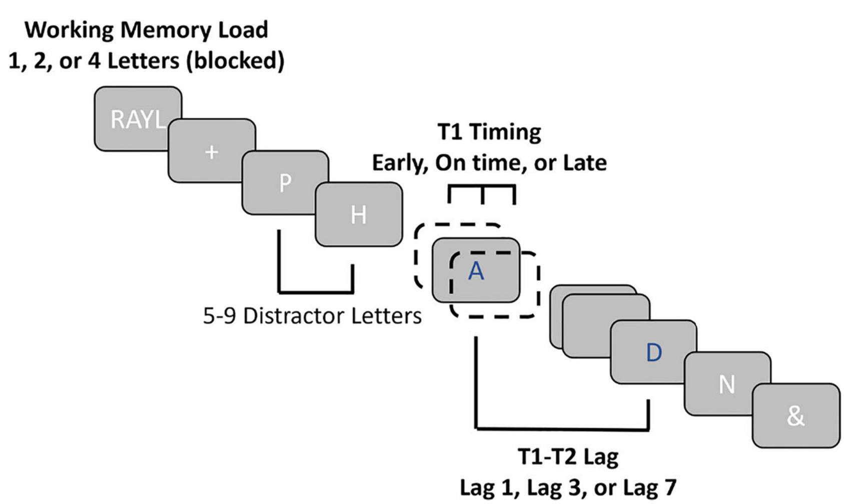

Fig. 1 Diagram of the procedure employed in the present experiments. One, two or four letters appeared in the memory set (WML). T1 appeared 32 ms early, on time, or 32 ms late (T1 Timing). T2 was presented at lag 1, 3, or 7 (T1-T2 lag)

Table 1 Means and standard deviations of T1 proportion correction by lag, timing, and working memory load (WML) conditions

	Lag 1			Lag 3			Lag 7		
	Early	On Time	Late	Early	On Time	Late	Early	On Time	Late
Experiment 1									
Low WML	.91 (.13)	.89 (.10)	.74 (.20)	.93 (.11)	.94 (.08)	.83 (.19)	.93 (.12)	.93 (.10)	.86 (.18)
Medium WML	.86 (.19)	.82 (.13)	.72 (.21)	.90 (.16)	.87 (.13)	.78 (.22)	.92 (.12)	.90 (.13)	.77 (.21)
High WML	.84 (.19)	.76 (.17)	.60 (.23)	.84 (.17)	.80 (.17)	.71 (.22)	.85 (.21	.84 (.15)	.71 (.25)
Experiment 2									
Low WML	.83 (.17)	.83 (.14)	.86 (.23)	.91 (.16)	.88 (.19)	.88 (.17)	.93 (.10)	.90 (.16)	.90 (.17)
Medium WML	.73 (.24)	.79 (.16)	.81 (.21)	.81 (.19)	.82 (.17)	.84 (.18)	.85 (.19)	.86 (.15)	.85 (.20)
High WML	.73 (.21)	.76 (.20)	.75 (.23)	.81 (.21)	.79 (.19)	.77 (.23)	.83 (.19)	.83 (.20)	.82 (.20)

& Meeter, 2008; Wyble et al., 2009), results concerning T2|T1 at lag-1 were analyzed separately from lags-3 and -7. All pairwise comparisons were Bonferroni adjusted. Greenhouse-Geisser adjusted degrees of freedom were used when data violated the sphericity assumption. Proportion correct for T2|T1 is shown in Fig. 2 for Experiment 1 and in Fig. 3 for Experiment 2.

Lags-3 and 7

To determine how WML interacted with T1 Timing to influence the AB, we conducted a series of ANOVAs. First, a 3 (WML) × 2 (Lag: Lags-3 and -7) × 3 (T1 Timing) repeated-measures ANOVA was performed on T2|T1 accuracy. A main effect of WML, $F(2,110) = 11.64$, $p < .001$, $\eta_p^2 = .17$, revealed that T2|T1 accuracy was higher for the low WML condition ($M = .67$, $SD = .17$) than the medium ($M = .59$, $SD = .19$; $p = .001$), or high ($M = .58$, $SD = .18$; $p < .001$) WML conditions, but no difference was observed between the medium and high WML conditions. A main effect of Lag, $F(1,55) = 447.42$, $p < .001$, $\eta_p^2 = .89$, revealed that accuracy was higher when T2|T1 appeared at Lag-7 ($M = .81$, $SD = .15$) than at Lag-3 ($M = .42$, $SD = .19$), reflecting the typical AB effect. A main effect of T1 Timing, $F(1.75,96.48) = 32.34$, $p_{adj} < .001$, $\eta_p^2 = .37$, revealed that T2|T1 accuracy was higher when T1 appeared earlier than expected ($M = .67$, $SD = .16$) than when T1 appeared on time ($M = .62$, $SD = .16$; $p_{adj} = .001$) or later than expected ($M = .54$, $SD = .19$; $p_{adj} < .001$), and accuracy was higher when T1 appeared on time than when it appeared later than expected ($p_{adj} < .001$). Importantly, a significant three-way interaction, $F(4,220) = 3.55$, $p = .008$, $\eta_p^2 = .06$, revealed that T1 Timing influenced the magnitude of the AB in only the low WML condition, $F(2,144) = 7.18$, $p = .001$, $\eta_p^2 = .11$, but not the medium or high WML conditions, $F\text{s} < 2$, $p\text{s} > .2$.

We investigated why the present experiment did not find that increasing working memory load results in an increased AB magnitude (Akyürek et al., 2007). Because Akyürek et al.'s (2007) study did not include a T1 Timing manipulation, our results may not be directly comparable. Therefore, we performed a 3 (WML) × 2 (Lag: Lags-3 and -7) repeated-measures ANOVA on only cases in which T1 appeared on time. In this case, as in their study, T2|T1 accuracy decreased with increasing WML more at Lag-3 than at Lag-7, $F(2,114) = 3.08$, $p = .050$, $\eta_p^2 = .05$.

Lag-1

Next, we performed a 3 (WML) × 3 (T1 Timing) repeated-measures ANOVA on T2|T1 accuracy at Lag-1. An effect of WML, $F(2,114) = 15.16$, $p < .001$, $\eta_p^2 = .21$, was observed such that accuracy was higher for the low WML ($M = .62$, $SD = .16$) than the medium ($M = .52$, $SD = .22$; $p = .001$) and high ($M = .48$, $SD = .21$; $p < .001$) WML conditions, but not different between medium and high WML conditions. An effect of T1 Timing, $F(2,114) = 13.34$, $p < .001$, $\eta_p^2 = .19$ was also observed such that T2|T1 accuracy was higher when T1 appeared later than expected ($M = .62$, $SD = .21$) than when T1 appeared earlier than expected ($M = .48$, $SD = .20$; $p < .001$) or on time ($M = .52$, $SD = .21$; $p = .001$), but not different between when T1 appeared earlier than expected or on time, ($p = .320$). Finally, the interaction did not reach significance, $F(4,228) = 1.05$, $p = .380$, $\eta_p^2 = .01$.

Discussion

The most notable result from Experiment 1 was that T1 Timing had a larger effect on the magnitude of the AB under low than under high WML. This interaction is consistent with the hypothesis that WM influences an early stage of temporal attention. Interestingly, the smallest AB effect was observed when T1 appeared earlier than expected, with the AB effect increasing as T1 appeared closer in temporal proximity to the T1+1 stimulus. We explore this finding further in Experiment 2.

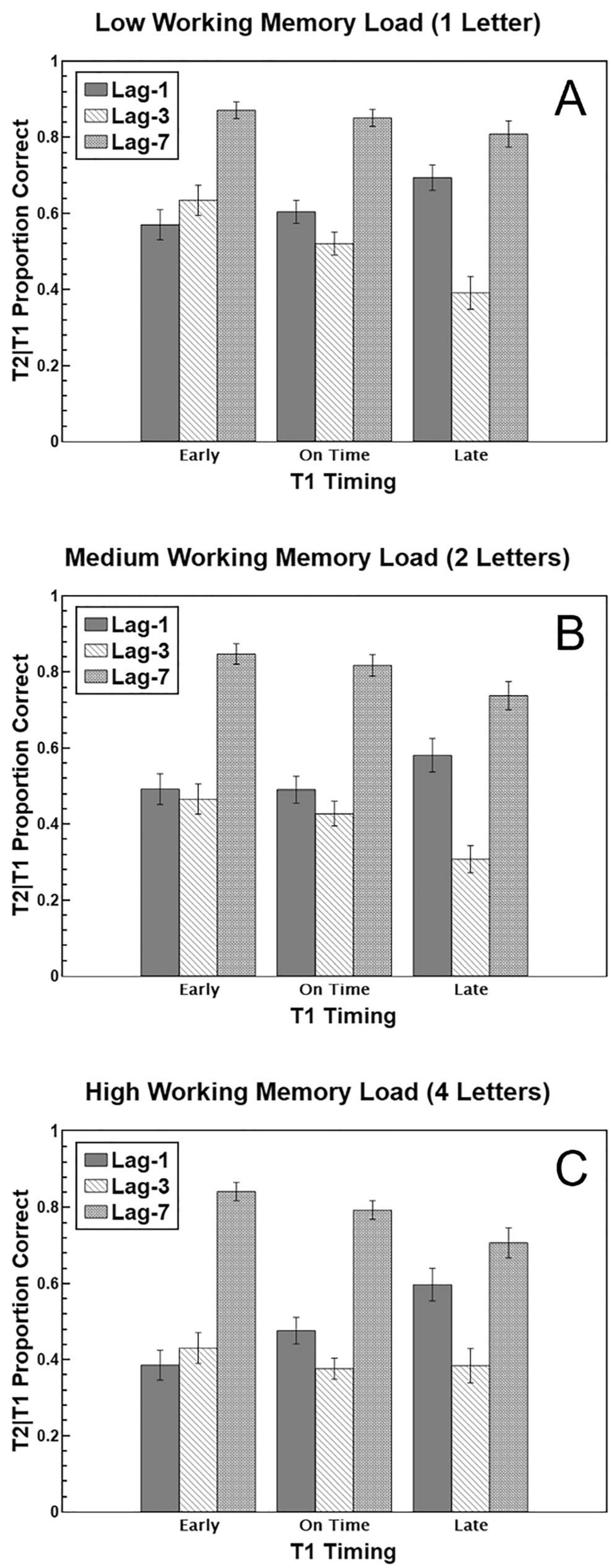

Fig. 2 T2|T1 proportion correct in Experiment 1 for each T1 Timing condition (x-axis) and T1-T2 lag (bars) under (**A**) low, (**B**) medium, and (**C**) high working memory load. Error bars represent ±1 SE

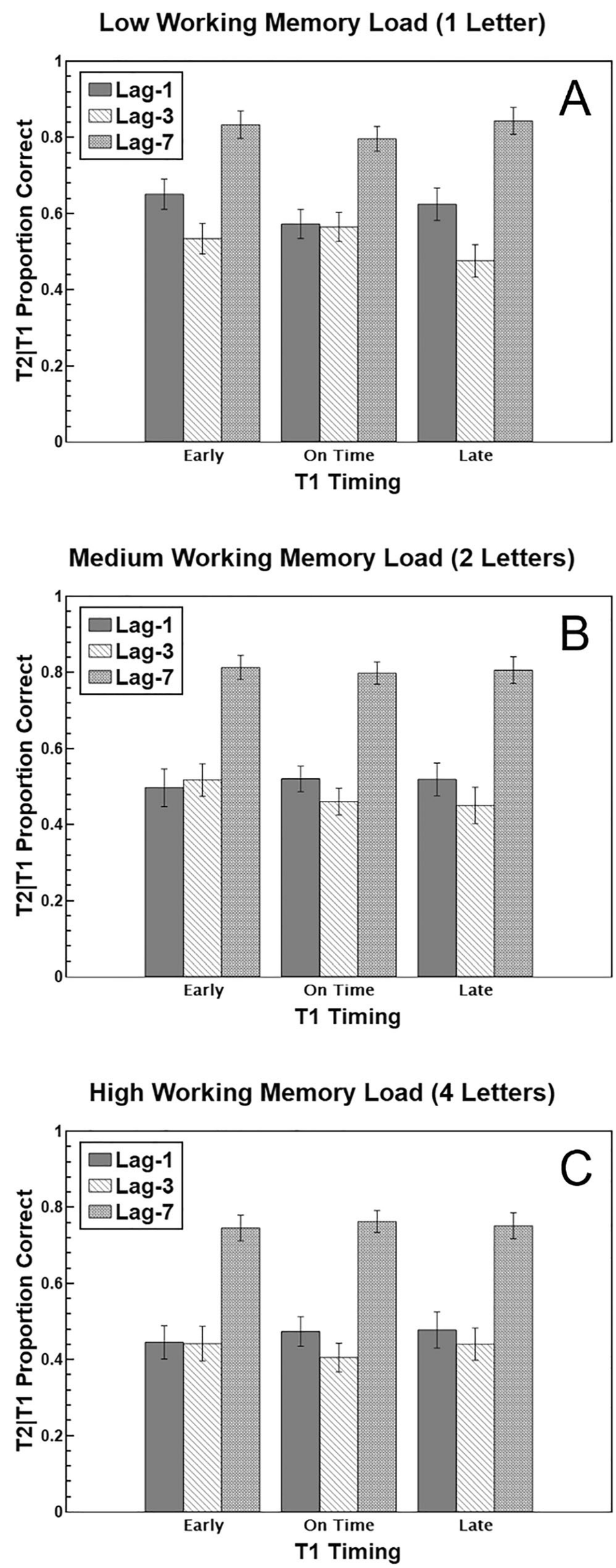

Fig. 3 T2|T1 proportion correct in Experiment 2 for each T1 Timing condition (x-axis) and T1-T2 lag (bars) under (**A**) low, (**B**) medium, and (**C**) high working memory load. Error bars represent ±1 SE

Increasing working memory load decreased T2|T1 accuracy at lag-1, but this effect was not moderated by T1 Timing. Additionally, T2|T1 accuracy at lag-1 was highest when T1 appeared later than expected for all WML conditions. We explore whether the T1 Timing effect was due to the interstimulus interval (ISI) prior to or following T1 in Experiment 2. If a timing difference of 32 ms between T1 and T2 at lag-1 produces the observed T1 Timing effect, then theories of temporal attention highlighting the importance of T1 processing time would be supported (e.g., Boost and Bounce: Olivers & Meeter, 2008; eSTST: Wyble et al., 2009; Threaded Cognition: Taatgen et al., 2009).

Experiment 2

In Experiment 2 we tested whether the magnitude of the AB was determined by the temporal interval between T1 and the stimulus preceding or following it. Fifty-six undergraduates participated for course credit. Experiment 2 was identical to Experiment 1 except that the ISI between T1 and the stimulus following it was held constant at 80 ms across all T1 Timing conditions; thus, all stimuli following T1 were shifted by 80 ms. If the temporal interval between T1 and the T1+1 stimulus resulted in changes in attention to T1, then we should observe the same pattern of results as in Experiment 1. If, however, the temporal interval between T1 and the T1-1 stimulus is the primary determinant of the results of Experiment 1, then we should see no effects of the T1 timing manipulation.

Results

T1 proportion correct decreased as WML increased, $F(2,110) = 22.38$, $p < .001$, $\eta_p^2 = .28$, and as the T1-T2 lag decreased, $F(1.78,98.26) = 26.90$, $p < .001$, $\eta_p^2 = .32$; however, no effects concerning T1 Timing were observed.

Lags-3 and -7

First, a 3 (WML) × 2 (Lag: Lags-3 and -7) × 3 (T1 Timing) repeated-measures ANOVA was performed on T2|T1 accuracy. A main effect of WML, $F(2,106) = 12.83$, $p < .001$, $\eta_p^2 = .19$, was observed. Post hoc comparisons with Bonferroni corrections suggested that accuracy was lower in the high WML condition ($M = .60$, $SD = .20$) than in both the low ($M = .69$, $SD = .19$; $p < .001$) and the medium ($M = .65$, $SD = .19$; $p = .004$) WML conditions; however, proportion correct was not different between the low and medium WML conditions, ($p = .144$). A main effect of Lag, $F(1,53) = 173.54$, $p < .001$, $\eta_p^2 = .76$, such that proportion correct at Lag-3 ($M = .48$, $SD = .23$) was lower than at lag-7 ($M = .80$, $SD = .17$), reflected the typical AB. No other interactions or effects reached significance, $ps > .10$. Thus, T1 Timing did not influence T2|T1 accuracy.

As in Experiment 1, we investigated more directly how WML influences the magnitude of the AB by performing a 3 (WML) × 2 (Lag: Lags-3 and -7) repeated-measures ANOVA on T2|T1 accuracy for only cases in which T2 appeared on time. In this case, T2|T1 accuracy decreased with increasing WML more when T2 appeared at Lag-3 than when T2 appeared at Lag-7, $F(2,110) = 7.26$, $p = .001$, $\eta_p^2 = .11$.

Lag-1

Next, a 3 (WML) × 3 (T1 Timing) repeated-measures ANOVA was performed on T2|T1 accuracy at Lag-1. Only a main effect of WML, $F(2,108) = 20.18$, $p < .001$, $\eta_p^2 = .27$, was observed, such that accuracy was higher for the low WML condition ($M = .62$, $SD = .25$) than for both the medium ($M = .51$, $SD = .25$; $p < .001$) and the high ($M = .46$, $SD = .26$; $p < .001$) WML conditions; however, no difference was observed between the medium and high WML conditions, $p = .146$. No effects of T1 Timing were observed, $ps > .40$.

Discussion

Experiment 2 examined whether the temporal interval between T1 and its preceding or subsequent stimulus accounted for the effects of T1 Timing found in Experiment 1. When the ISI between T1 and the T1+1 stimulus was held constant, no effects of T1 Timing were observed. This result suggests that the temporal interval between T1 and the T1+1 stimulus accounted for the timing-related changes in AB magnitude observed in Experiment 1 – as the temporal interval between T1 and the T1+1 distractor decreased, the magnitude of the AB increased. Similarly, when T2 appeared at lag-1, T1 Timing did not influence T2|T1 accuracy as observed in Experiment 1, suggesting that the timing-related changes in T2 performance at Lag-1 were influenced by the temporal interval between T1 and T2 at Lag-1 in that experiment.

General discussion

The present research explored the relationship between temporal attention and WM. While the link between WM and spatial attention has been well established (e.g., Awh & Jonides, 2001), research concerning the interaction between WM and temporal attention is rare. The present experiments sought to fill this gap and demonstrated that WML influences overall performance on a two-target RSVP task, suggesting a common link between WM and temporal attention.

The present study replicated the findings of Akyürek et al. (2007) that increasing WML increased the magnitude of the attentional blink. One interpretation of this finding is that, like spatial attention, temporal attention and WM share a common cognitive resource (Baddeley, 2002; Barrouillet et al., 2004).

When the demand for this resource was increased by the WML manipulation, performance in a secondary task declined. The mechanisms of this interaction were not explored in the present research; however, the fact that the ISI after T1 determined the magnitude of AB suggests that processing time is an important factor. Similarly, proportion correct for T1 decreased with increasing WML and as the temporal interval between T1 and the T1+1 stimulus decreased, potentially reflecting increased masking effects on T1 processing.

We also extended the work of Akyürek et al. (2007) by including a condition in which T2 appeared at lag-1. The effect of T1 timing on T2|T1 accuracy at lag-1 did not differ depending on WML. Instead, T2|T1 accuracy at lag-1 was highest for the shortest T1-T2 ISI for all WML conditions. This pattern contrasts with Livesey and Harris' (2011) results demonstrating a larger lag-1 sparing effect when SOAs were 106 ms than when SOAs were 59 ms (similar to our T1 timing manipulation). The notable difference between our two studies is that ours included a working memory task embedded into the T1 task, suggesting that engaging in a working memory task, but not the difficulty of the task, might be the critical factor determining how target timing affects lag-1 sparing.

A unique contribution of the present research was the finding that WML moderated the influence of T1 timing relative to the subsequent stimulus on the AB. Specifically, decreasing the temporal interval between T1 and the T1+1 distractor (Experiment 1) increased the AB effect, but only within the low WML condition. Our initial hypothesis concerning this relationship assumed that increasing WML would disrupt the attentional entrainment to the RSVP stimuli because people would attend less to the RSVP stream. However, the results from Experiment 2 in which the ISI following T1 was held constant did not reveal an effect of entrainment on the RSVP task. Therefore, we did not find evidence that WML influences attentional entrainment.

Instead, a more interesting effect was observed that can help explain why Akyürek et al. (2007) found that WM influences temporal attention, but Zanto et al. (2020) did not. If we consider Olivers and Meeter's (2008) assumption that the "boost" in attending following detection of the target-identifying feature in T1 is stimulus-driven and attention to the T1+1 distractor is important for the AB, then the timing of T1 relative to the T1+1 distractor would influence the AB. If WML influences this transient, stimulus-driven attentional boost, then differences in the AB would arise. In contrast, Zanto et al. (2020) manipulated temporal attention by precueing a target stimulus – a presumably top-down orienting of attention (Visser et al., 2014). Their failure to observe an effect of WM on temporal attention can be explained by Olivers and Meeter's (2008) other assumption that attention is inhibited prior to T1 by a top-down attentional process that is unaffected by WM. Similarly, the present study showed evidence of an effect of WM on T1 Timing only when the temporal interval between T1 and the following stimulus was manipulated and not when that ISI was held constant. That is, the ISI prior to T1 would not be influenced by WM because attending is already suppressed during that time.

Researchers have repeatedly demonstrated that T1 masking is an important determinant of the AB (e.g., Chun & Potter, 1995; Martens & Wyble, 2010; Raymond et al., 1992; Seiffert & Di Lollo, 1997; Visser, 2007). While this previous research found that removing the masking stimulus can eliminate the AB, our experiments demonstrated the effect of a timing manipulation on the T1+1 stimulus also influenced the AB. The findings that increasing WML decreased the influence of the temporal interval between T1 and the T1+1 stimulus on the AB implies that WM performance is similarly influenced by processing time and perhaps is comprised of attentional processes.

Despite the novel contributions of our results, a limitation needs to be addressed in future research. Specifically, in Experiment 1, the temporal interval between T1 and T2 varied by up to 64 ms depending on T1 Timing – when T1 appeared late, the T1-T2 temporal interval was 64 ms shorter than when T1 appeared early – whereas this was not the case in Experiment 2. Because the temporal interval between T1 and T2 was held constant in Experiment 2, but not Experiment 1, we cannot be sure that the three-way interaction in Experiment 1 was due to the interval between T1 and the following distractor or the interval between T1 and T2.

Conclusion

Our results supported research showing that WM influences the AB (Akyürek et al., 2007) and T2|T1 performance at lag-1. Because WM interacted with these temporal dynamics of attending, these processes potentially share a common cognitive resource or may be mechanistically intertwined. Future theories of temporal attention could benefit from further research examining how people attend in time under different WM conditions.

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Open practices statement Data are not currently available in a repository; however, they are available upon request. None of the experiments were preregistered.

Declarations

Conflicts of interest We have no conflicts of interest to disclose.

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