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Frozen in Time: Concurrent Task Performance Interferes With Temporal Shifts of Attention

Troy A. W. Visser
University of Western Australia

It is well known that the requirement to perform a concurrent task interferes with many aspects of perception and cognition. Evidence suggests that this interference extends to spatial shifts of attention, which appear to be reduced in efficiency when they must be performed while processing related to another task is ongoing. Here, the authors investigate whether concurrent tasks also interfere with shifts of temporal attention—that is, with the ability to shift attention to an expected time of stimulus onset. In Experiment 1, using the attentional blink paradigm, the authors show that the requirement to identify a prior target interferes with observer's ability to shift attention to the expected time of second-target onset. In Experiments 2 and 3, they confirm the role of the first-target task by eliminating the shifting deficit when the interval between the targets is increased or the requirement to identify the first target is removed. Together, the results indicate that performing a concurrent task interferes with temporal shifts of attention analogously to how it interferes with spatial shifts of attention, implying an impact of task-related resource limitations on a common set of underlying cognitive and perceptual mechanisms.

Public Significance Statement

Many tasks are more difficult to perform when we are already doing something else. This study shows that this is also true when individuals need to direct attention to a future event while doing another task. Specifically, participants were less able to identify a predictable future target when information about the time that target would appear had to be processed during a concurrent task. This suggests that the utility of predictive information about future events is limited by the mental load of the individuals processing this information.

Keywords: multi-tasking, attention, temporal shift, cuing

Most of us find talking while reading a magazine or writing while watching TV to be a challenging task. In fact, although there are many times in our lives that it would be desirable to be able to do two or more things at once, both our own experience and nearly a half-century of research tell us that this is often very difficult or impossible. Although part of this difficulty stems from limitations in our motor abilities, studies in human perception and cognition have also consistently shown that focusing attention on one activity or perceptual stimulus significantly reduces the likelihood of successfully performing other tasks (e.g., Strayer & Drews, 2007; Bowden, Loft, Tatasciore, & Visser, 2017; Raymond, Shapiro, & Arnell, 1992; Kanwisher, 1987; Mack & Rock, 1998; Di Lollo, Enns, & Rensink, 2000). For example, in the so-called attentional blink (AB), when two targets (T1 and T2, respectively) separated by a variable temporal interval (lag) are presented in rapid succession, identification of the second target (T2) is poorest at shorter lags but improves as lag increases. This pattern of results suggests that the requirement to identify T1 impairs observers' ability to allocate resources (attention) to the immediately trailing T2 (e.g., Chun & Potter, 1995; Dell'Acqua et al., 2015; Di Lollo, Kawahara, Shahab Ghorashi, & Enns, 2005; Olivers & Meeter, 2008; Wyble, Bowman, & Nieuwenstein, 2009; Taatgen et al., 2009).

Among the range of activities that are impaired by performing a concurrent task is the ability to shift the focus of spatial attention. One early study demonstrating this phenomenon was conducted by Visser, Zuvic, Bischof, and Di Lollo (1999) using a variation of the AB paradigm noted above. In their experiment, the two targets were presented at varying lags in the context of a rapid-serial-visual presentation (RSVP) stream of distractors. Targets could appear (a) both at the location of the central RSVP stream; (b) both at the same eccentric location above, below, left, or right of the central RSVP stream; or (c) at different locations with one target in the central RSVP stream and the other at an eccentric location. The chief finding was that when both targets appeared consecu-

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Correspondence concerning this article should be addressed to Troy A. W. Visser, School of Psychological Science, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia. E-mail: troy.visser@uwa.edu.au

tively at the same location, either centrally or peripherally, T2 identification accuracy was relatively high—a phenomenon known as lag-1 sparing (Visser, Bischof, & Di Lollo, 1999; Potter, Chun, Banks, & Muckenhoupt, 1998). However, when the targets appeared at different locations, T2 identification was most impaired when it followed T1 directly and then improved in a linear fashion as lag increased. Visser et al. (1999) argued that this difference reflected the inability of observers to shift attention to the location of T2 while attending to T1 at a different location.

Subsequent research has shown converging evidence for this viewpoint. For example, Jolicoeur, Dell'Acqua and colleagues (Dell'Acqua, Sessa, Jolicoeur, & Robitaille, 2006; Jolicoeur, Sessa, Dell'Acqua, & Robitaille, 2006; Robitaille, Jolicoeur, Dell'Acqua, & Sessa, 2007) indexed spatial shifts of attention during the AB using event-related potentials. They found that the magnitude of the N2pc generated by a peripheral T2 was much smaller when it followed a central T1 at short lags, suggesting that spatial attention was "frozen," whereas T1 was being processed (Dell'Acqua et al., 2006). Analogously, both Du and Abrams (2009) and Visser (2011) found that the benefits of presenting a valid spatial cue prior to the onset of T2 increased with lag, suggesting that the spatial cue was less effective at triggering a shift of spatial attention when T1 processing was ongoing (but see Ghorashi, Enns, Spalek, & Di Lollo, 2009). Finally, there is also substantial evidence that common neural substrates underlie dual-target deficits and spatial shifts of attention (Marois, Chun, & Gore, 2000; Gross et al., 2004; Corbetta & Shulman, 2002; Corbetta, Patel, & Shulman, 2008; Husain, Shapiro, Martin, & Kennard, 1997), implying the likely existence of interference between these processes.

The present work investigated whether performing a concurrent task also interferes with observers' ability to shift attention in the temporal domain. Analogous to findings from studies of spatial attention, there is substantial evidence that attention can be shifted to at a particular point in time in response to a variety of sources of temporal information. For example, Coull and Nobre (1998) showed that presenting a central information cue that validly indicates the onset time of a peripheral target improves target response times (RTs) even when the location of the target is unknown (see also Correa, Lupiáñez, Madrid, & Tudela, 2006; Correa, Lupiáñez, & Tudela, 2005). In addition, knowing when a target will appear benefits its identification in the face of resource limitations, such as those imposed during the AB (Badcock, Badcock, Fletcher, & Hogben, 2013; Martens & Johnson, 2005; Shen & Alain, 2012; Rolke & Hofmann, 2007; Vangkilde, Coull, & Bundesen, 2012; Tang, Badcock, & Visser, 2014; Visser, Tang, Badcock, & Enns, 2014; Visser, Ohan, & Enns, 2015). This is the case whether temporal information is provided by explicit cues (Martens & Johnson, 2005; Visser et al., 2014), regularities in the number of stimuli presented prior to targets or between targets (Badcock et al., 2013; Martens & Johnson, 2005; Tang et al., 2014), or due to statistical properties of trials themselves (Visser et al., 2015).

Although it is clear that information about the expected time that a stimulus will appear can facilitate temporal shifts of attention, it is not known whether such shifts can be accomplished while performing a concurrent task. On the face of it, the fact the temporal information ameliorates the AB might seem to provide evidence that this is the case. However, existing studies have typically provided temporal information about T2 prior to the onset of a trial, either via an explicit cue or as the result of repeated exposures to stimulus displays with temporal regularities. This means that observers could prepare for the onset of T2 prior to processing T1. Instead, what is required is for observers to perform a task prior to presenting information about the expected onset time of a target stimulus. This methodology is analogous to that used in previous studies investigating spatial cueing (e.g., Ghorashi et al., 2009; Du & Abrams, 2009; Visser, 2011).

To this end, the present work used a modified version of the AB paradigm used by Martens and Johnson (2005) and Visser et al. (2014). On each trial, participants viewed two targets in the context of an RSVP paradigm, separated by a short or long lag. In addition, prior to the onset of the RSVP stream, a central cue stimulus was presented that either (a) contained no temporal information or (b) indicated the intertarget lag with 80% validity. Of particular interest were trials on which T2 was invalidly cued at the short lag, leading participants to believe that that T2 would appear at lag 3 when it was actually presented at lag 8. Previous studies (Correa, Lupiáñez, Milliken, & Tudela, 2004; Visser et al., 2015) have shown that participants are sensitive to cumulative probability and thus will actively attempt to shift attention toward longer cue-target or intertarget intervals if the target does not appear at an expected shorter interval. This indicates that when a target is expected at lag 3 but fails to appear, participants should then attempt to shift temporal attention to the longer lag. To the extent that this shift requires central resources, however, the need to process T1 should lead to interference. Such interference would manifest in reduced accuracy for invalidly cued targets presented at lag 8 (i.e., targets that had been expected to appear at lag 3) compared to targets presented at lag 8 when the cue contained no temporal information.

Experiment 1

Method

Participants. Thirty-two undergraduate students (mean age = 21.58 years, males = 12) were recruited in exchange for partial credit toward course completion. All participants gave written informed consent prior to testing. The procedure was conducted in accordance with the Declaration of Helsinki and approved by the University of Western Australia's Human Research Ethics Office.

Materials. Stimuli were presented on a BenQ XL2420T monitor running at a refresh rate of 100 Hz, attached to a Pentium computer running Presentation software (Version 17; Neurobehavioral Systems, Berkley, CA) located in a dimly lit room. The software also recorded responses from the computer keyboard. Participants were seated approximately 50 cm from the computer monitor.

All stimuli were presented in medium gray (RGB: 167, 167, 167) against a black background and subtended approximately 1° of visual angle. Targets consisted of all upper-case letters from the English alphabet, except I, O, Q, and Z due to their high degree of similarity to digits. Target masks consisted of Arabic digits from 1 to 9. Targets and masks were presented in 28-pt Arial font. Distractors consisted of 10 "pseudoletter" geometric shapes formed from rearranging letter segments (see Visser, 2007 for further details).

Procedure. Participants completed two experimental conditions in counterbalanced order. In the neutral condition, the fixation consisted of a plus sign that gave no information about the intertarget lag on the upcoming trial; in the cued condition, the fixation consisted of one dash or three dashes, which indicated with 80% validity whether the upcoming trial had a short (300 ms) or long (800 ms) intertarget interval. Every trial began with the presentation of a fixation at the center of the display. Participants were instructed to focus their eyes on this fixation, to take note of the information it provided about the likely onset time of T2, and then to press the space bar when ready to begin the trial. When participants initiated the trial, the fixation then disappeared and a RSVP began with a series of six distractors presented at the center of the display, followed by T1 and a digit mask. The mask was then followed by (a) a distractor and T2 (lag 3) or (b) six distractors and T2 (lag 8). The second target was followed by a digit mask and six (lag 3), or two (lag 8) additional distractors so that the total RSVP stream length was always 17 items. Each item appeared on the display for 20 ms and was separated from the next item by a blank display for 80 ms. After the final distractor disappeared, participants were prompted to enter T1 and T2, respectively, using the keyboard. Once they had done this, the fixation reappeared, and participants began the next trial by pressing the space bar.

Both the neutral and cued conditions consisted of 320 self-paced trials presented in a single, self-paced block. Participants were encouraged to task rest breaks when appropriate. T1 and T2 were chosen randomly from the set of possible targets with the constraint that the targets had to be different. Lags occurred equally often across trials.

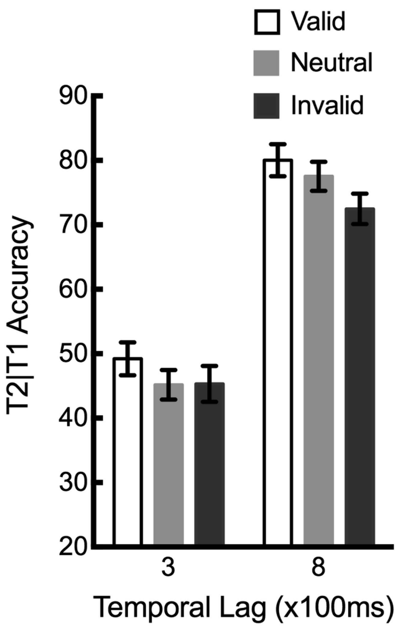

Figure 1. Mean percentage of T2 accuracy (given T1 correct) separated as a function of the lag that T2 actually appeared and cue validity. Error bars represent one within-subjects standard error of the mean, calculated using the Cousineau–Morey method (O'Brien & Cousineau, 2014).

Results

The main finding of this study, shown in Figure 1, is that the requirement to attend to T1 interfered with the shift of temporal attention to the longer lag on trials with invalidly cued targets presented at lag 8. This suggests that temporal shifts of attention require central cognitive resources. These conclusions are supported by the following statistical analyses.

Data from one participant was excluded from analysis because their overall T1 accuracy across conditions was more than 2.5 standard deviations below the group mean.

T1 accuracy. Mean T1 accuracy was calculated (regardless of response order) separately as a function of cue validity (neutral, valid, invalid) and lag (3, 8). These means (see Table 1) were then submitted to a 3 (Cue Validity) × 2 (Lag) within-subjects analysis of variance (ANOVA). The results revealed no significant main effects or interactions (Fs < 2.28, ps $> .11$, η^2s $< .08$).

T2|T1 accuracy. Mean T2 accuracy was calculated (regardless of response order) only on trials in which T1 was correctly reported, separately as a function of cue validity and lag. Inspection of these means (see Figure 1), suggests broad benefits for T2 occurred on validly cued trials replicating previous studies. Critically, however, it also appears that performance for invalidly cued targets presented at lag 8, where a shift of temporal attention was required, was impaired. Validating these impressions, a 3 (Cue Validity) × 2 (Lag) within-subjects ANOVA revealed a significant main effect of cue validity, $F(2, 60) = 8.64$, $p < .01$, $\eta^2 > .22$), indicating that T2 accuracy varied across neutral, validly cued and invalidly cued trials, and a significant main effect of Lag, $F(1, 30) = 153.71$, $p < .001$, $\eta^2 > .83$), indicating a conventional AB deficit with T2 accuracy lower at lag 3 than lag 8. The Cue Validity × Lag interaction approached significance, $F(2, 60) = 2.82$, $p < .07$, $\eta^2 > .08$).

To verify that participants shifted attention in response to the temporal cue, as in previous studies (e.g., Martens & Johnson, 2005; Visser et al., 2014), we conducted t tests comparing T2 accuracy on validly cued and neutral trials. As expected, accuracy was significantly higher on validly cued trials when T2 was presented at lag 3, $t(30) = 2.05$, $p = .048$. This difference also approached significance at lag 8, $t(30) = 1.93$, $p = .062$.

To examine the key question of whether T1 processing impairs shifts of temporal attention, we compared accuracy when T2 was presented at lag 8 on invalidly cued trials (where observers expected T2 to be presented at lag 3 and then needed to shift temporal attention) to accuracy when T2 was presented at lag 8 on neutral trials (where no temporal attention shift was required). This analysis showed that T2 accuracy was significantly lower on invalidly cued trials, $t(30) = 3.03$, $p = .005$. Moreover, the accuracy decrement on invalid trials was limited to when T2 was presented at lag 8. No similar deficit occurred when T2 was presented at lag 3 on invalidly cued trials ($p = .95$).

Although the present results are consistent with the notion that performing a concurrent task interferes with shifts of temporal attention, it is important to provide converging evidence that the need to perform the T1 task was the key factor mediating reduced performance when T2 was presented at lag 8 on invalid trials. One prediction of this account is that increasing the interval between T1 and T2 on long lag trials should reduce the costs to T2 arising from invalid cues. This is because a longer interval would allow more

Table 1
Mean Percentage Accuracy on Target 1 in Experiments 1 and 2, Separated by the Lag at Which Targets Actually Appeared and Cue Validity

Experiment and cue condition	Lag 3	Lag 8	Lag 16
Experiment 1			
Valid	92.31 (1.21)	90.35 (1.23)	N/A
Invalid	90.52 (1.63)	91.73 (1.44)	N/A
Neutral	90.18 (1.10)	90.75 (1.12)	N/A
Experiment 2			
Valid	84.21 (2.55)	N/A	81.54 (2.80)
Invalid	85.18 (2.73)	N/A	82.36 (2.89)
Neutral	84.04 (2.72)	N/A	81.97 (2.85)

Note. N/A indicates that the lag was not used in that experiment. Numbers in parentheses represent one standard error of the mean.

time for observers to process T1 and still be able to shift temporal attention to the expected later onset time of T2. To test this prediction, we repeated Experiment 1 but increased the long lag from 800 ms to 1,600 ms.

Experiment 2

Method

Participants. Thirty-two undergraduate students (mean age = 22.13 years, males = 11) were recruited in exchange for partial credit toward course completion. All participants gave written informed consent prior to testing and none had participated in Experiment 1. The procedure was conducted in accordance with the Declaration of Helsinki and approved by the University of Western Australia's Human Research Ethics Office.

Materials. The equipment and stimuli were identical to Experiment 1.

Procedure. The procedure was identical to Experiment 1 except that the longest lag was increased from 800 to 1,600 ms (lag 16), consisting of 14 distractors interposed between the T1 mask and T2. As a result of this change, the total length of the RSVP stream was also increased to 25 items.

Results

The main finding of this study, shown in Figure 2, is that the requirement to identify T1 no longer interfered with identification accuracy when T2 was presented at the long lag on invalidly cued trials. This suggests that increasing the duration of the interval between the targets was sufficient to allow the T1 task to be completed and temporal attention to be shifted prior to the appearance of T2. These conclusions were supported by the following statistical analyses.

Data from two participants were excluded from analysis because their overall T1 accuracy across conditions was more than 2.5 standard deviations below the group mean.

T1 accuracy. Mean T1 accuracy was calculated in the same manner as Experiment 1. These means (see Table 1) were submitted to a 3 (Cue Validity) × 2 (Lag) within-subjects ANOVA that revealed a significant main effect of Lag, $F(1, 29) = 10.99$, $p < .01$, $\eta^2 > .27$, indicating that T1 accuracy was lower at lag 16. This reduction may reflect the relatively long interval that observers were required to remember T1 before reporting it at the end of the trial. No other main effects or interactions were significant (Fs < 1, ps > .74, η^2s < .02).

T2|T1 accuracy. Mean T2 accuracy was calculated in the same manner as Experiment 1. Inspection of these means (see Figure 2) suggests accuracy increased when T2 was presented at lag 3 on validly cued trials, replicating both Experiment 1 and previous studies. However, unlike Experiment 1, accuracy was unaffected when T2 was presented at lag 16 on invalidly cued trials. Indeed, a 3 (Cue Validity) × 2 (Lag) within-subjects ANOVA revealed a significant main effect of Lag, $F(1, 29) = 219.97$, $p < .001$, $\eta^2 > .88$, indicating that T2 accuracy was reduced at lag 3 relative to lag 16, replicating the conventional AB effect. However, neither the main effect of cue validity, $F(2, 58) = 0.25$, $p > .77$, $\eta^2 < .01$) nor the Cue Validity × Lag interaction, $F(2, 58) = 1.29$, $p > .28$, $\eta^2 < .05$) were significant.

As in Experiment 1, we conducted t tests to verify that participants shifted attention in response to the temporal cue. Consistent with this prediction, accuracy was significantly higher when T2 as presented at lag 3 on validly cued trials than on neutral trials, $t(29) = 1.82$, $p = .039$, although this difference was not significant when T2 was presented at lag 16 ($p > .60$). The absence of a benefit on validly cued trials when T2 was presented at lag 16 is not unsurprising given that observers had ample opportunity to shift temporal attention on neutral trials when T2 failed to appear at lag 3 (Coull & Nobre, 1998).

Most importantly, to examine whether the T1 task impaired shifts of temporal attention, we compared accuracy when T2 was

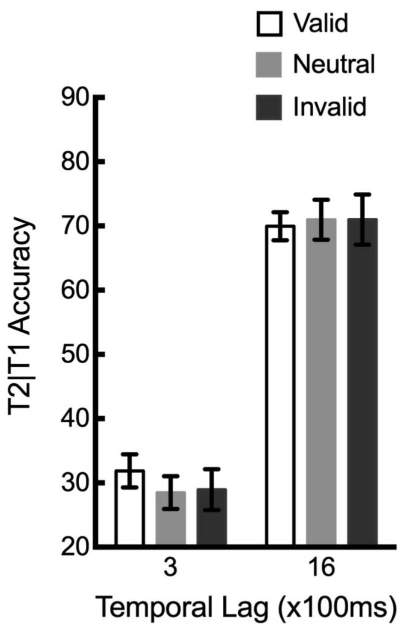

Figure 2. Mean percentage of T2 accuracy (given T1 correct) separated as a function of the lag that T2 actually appeared and cue validity. Error bars represent one within-subjects standard error of the mean, calculated using the Cousineau–Morey method (O'Brien & Cousineau, 2014).

presented at lag 16 on invalidly cued trials to accuracy when T2 was presented at lag 16 on neutral trials. This analysis showed no significant difference, $t(29) = 0.15$, $p = .998$, indicating that shifting temporal attention to the long lag on invalidly cued trials was unimpaired by the requirement to identify T1.

The results of Experiment 2 provide converging evidence that performing a concurrent task interferes with shifts of temporal attention. Specifically, the fact that increasing the interval between the targets eliminated the deficit when T2 was presented at the long lag on invalidly cued trials is consistent with the notion that the T1 task could be completed and a temporal attention shift made prior to T2 onset. That said, however, it is possible that increasing the length of the long lag might have had other beneficial effects that were not related to T1 processing. Perhaps, for example, the greater interval between the expected and actual onset times for T2 increased alerting effects, rather than ameliorating the effects of performing the T1 task. With this in mind, in Experiment 3, we directly tested whether the T1 identification task interferes with shifts of temporal attention by repeating Experiment 1 but omitting the requirement to identify T1. If performing the T1 task interferes with shifts of temporal attention, then the identification deficit seen when T2 is presented at lag 8 on invalidly cued trials in Experiment 1 should disappear in Experiment 3.

Experiment 3

Method

Participants. Thirty-two undergraduate students (mean age = 20.44 years, males = 11) were recruited in exchange for partial credit toward course completion. All participants gave written informed consent prior to testing and none had participated in Experiments 1 or 2. The procedure was conducted in accordance with the Declaration of Helsinki and approved by the University of Western Australia's Human Research Ethics Office.

Materials. The equipment and stimuli were identical to Experiment 1.

Procedure. The procedure was identical to Experiment 1, except that T1 always consisted of three zeroes. Participants were instructed to use the temporal cue when possible to anticipate the onset time of T2 following T1, but were not required to identify or respond to T1.

Results

The main finding of this study, shown in Figure 3, is that omitting the requirement to identify T1 eliminated accuracy decrements when T2 was presented at lag 8 on invalidly cued trials. This is consistent with the suggestion that the requirement to perform the T1 task interferes with shifts of temporal attention (as seen in Experiment 1). These conclusions were supported by the following statistical analyses.

T2 accuracy. Mean accuracy was calculated separately as a function of cue validity and lag. Inspection of these means (see Figure 3) indicates that accuracy increased when T2 was presented at lag 3 on validly cued trials, and critically, that accuracy was not impaired when T2 was presented at lag 8 on invalidly cued trials. A 3 (Cue Validity) × 2 (Lag) within-subjects ANOVA revealed a significant main effect of Lag, $F(1, 31) = 41.54$, $p < .001$, $\eta^2 > .57$, indicating that T2 accuracy was reduced at lag 3 relative to lag 8. This difference is not entirely unexpected as it was likely that participants allocated some resources to the T1 stimulus both because it was distinct from the other RSVP items, and to make use of the temporal cueing information given at the beginning of the trial (Chun, 1997). Neither the main effect of Cue Validity, $F(2, 62) = 1.88$, $p > .16$, $\eta^2 < .06$) nor the Cue Validity × Lag interaction, $F(2, 62) = 0.09$, $p > .91$, $\eta^2 < .01$) were significant.

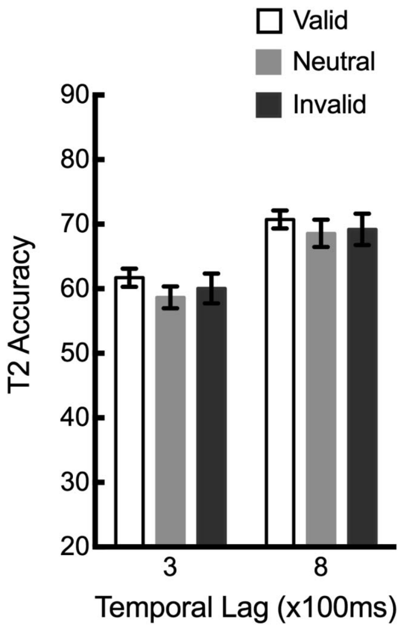

Figure 3. Mean percentage of T2 accuracy separated as a function of the lag that T2 actually appeared and cue validity. Error bars represent one within-subjects standard error of the mean, calculated using the Cousineau–Morey method (O'Brien & Cousineau, 2014).

As in Experiments 1 and 2, we conducted *t* tests to verify that participants shifted attention in response to the temporal cue. As expected, accuracy was significantly higher when T2 was presented at lag 3 on validly cued trials compared to neutral trials, $t(31) = 2.10$, $p = .044$; however, as in Experiment 2, this difference was not significant at Lag 8 ($p > .51$).

Critically, as in Experiment 1, we compared accuracy when T2 was presented at lag 8 on invalidly cued trials to accuracy when T2 was presented at lag 8 on neutral trials. This analysis showed no difference in T2 accuracy on these trials, $t(31) = 0.28$, $p = .781$, indicating that shifting temporal attention was unimpaired when participants were not required to identify T1.

The outcome of Experiment 3 suggests that devoting resources to perform the T1 identification task in Experiment 1 interfered with the observers' ability to shift temporal attention. By omitting this requirement in the present experiments, resources were freed up to enable a shift of temporal attention to the long lag when T2 did not appear at the expected short lag. Taken together, the evidence indicates that performing a concurrent task interferes with shifts of temporal attention as it does spatial attention.

General Discussion

A substantial experimental history suggests that when cognitive resources are depleted by the requirement to perform a concurrent task, performance in a variety of domains is impaired. The aim of the present work was to determine whether cognitive resources are also required to shift temporal attention. In Experiment 1, participants were given an 80% valid cue about the expected onset time of T2 in a conventional AB paradigm. Critically, this resulted in accuracy deficits when T2 was presented at a long lag on invalidly cued trials—that is, on trials when temporal attention needed to be shifted from a short lag where T2 had been anticipated to appear to a long lag, whereas T1 processing was ongoing. Follow-up studies confirmed the role of performing the T1 task in the T2 deficit. Performance deficits did not occur when T2 was presented at the long lag on invalidly cued trials when the lag between targets was increased (Experiment 2) or when the T1 identification task did not need to be performed (Experiment 3). Taken together, the results strongly suggest that performing a concurrent task interferes with the ability to shift temporal attention. This outcome is analogous to earlier studies showing that performing a concurrent task interferes with shifting spatial attention to different locations.

One interpretation of the parallel effects of performing a concurrent task on both temporal and spatial attention shifts is that they both reflect the impact of reducing the availability of resources on a common set of underlying mechanisms. As noted earlier, a number of studies suggest that spatial and temporal attention shifts are generated in similar brain regions (Marois, Chun, & Gore, 2000; Gross et al., 2004; Corbetta & Shulman, 2002; Corbetta et al., 2008; Husain et al. (1997). For example, in a study with patients suffering from visual neglect, Husain et al. (1997) showed that the magnitude of the AB deficit was positively correlated with the extent of spatial neglect symptoms. This intimates a strong role for regions in the right hemisphere, including the inferior temporal lobe (Shapiro, Hillstrom, & Husain, 2002; Marois et al., 2000) and the right posterior parietal cortex (Giesbrecht & Kingstone, 2004), in both spatial and temporal attention impairments.

In addition to considering the main research questions addressed here, it is also important to discuss the effects of valid and invalid cues in conditions not critical for testing our main research question. In particular, across all experiments inspection of Figures 1–3 suggest that (a) accuracy did not increase when T2 was presented at the long lag on validly cued trials, and (b) accuracy did not decrease when T2 was presented at lag 3 on invalidly cued trials. With respect to the lack of benefits on validly cued trials, inspection of the data suggests that this was unlikely to be due to ceiling effects, as T2 accuracy was relatively low across experiments. Rather, we suggest that less reliable temporal cues meant that accuracy benefits on valid trials were correspondingly smaller, and thus more difficult to detect, than in previous studies. For example, the benefit of 100% valid temporal cues in an identical paradigm used by Visser et al. (2014) were nearly 2.5× larger than for the 80% valid cues used here (11% vs. 4%). Thus, a more sensitive dependent measure, such as T2 RTs, might reveal benefits that were not evident in T2 accuracy (see Visser et al., 2015, for an example).

With respect to the finding that performance was not impaired when T2 appeared at lag 3 on invalidly cued trials, several explanations seem plausible. One possibility, as outlined above, is that our T2 accuracy measure simply lacked appropriate sensitivity. Alternatively, on trials where T2 appeared at lag 3 in both the neutral condition and the invalidly cued conditions, participants were not anticipating T2's appearance. Thus, given the substantially similar expectations in both conditions, it would be unsurprising that little or no significant difference in performance was found. A third option can be derived from Olivers and Meeter (2008) who propose that the AB arises when T1 processing triggers inhibitory processes that suppress allocation of attention to T2. This account implies that with attention to T2 already suppressed, no further detriments could arise as the result of the unexpected appearance of T2 on invalidly cued trials.

Before concluding, the implications of the present results for theoretical accounts of the AB should also be considered. Although such theories share many similarities, it is helpful here to consider them in two groups. In one group, the second-target deficit is said to arise from broad impairments to a variety of central mechanisms necessary for target processing. For example, Chun and Potter (1995) and Dell'Acqua et al. (2015) suggest resources required for response planning, memory encoding, and response execution are unavailable for T2 during the AB. Similarly, Olivers and Meeter (2008) propose inhibitory processes are engaged to protect the integrity of T1 processing, while Taatgen et al. (2009) argue that the process of consolidating T1 into memory impedes a variety of other processes, negatively impacting T2. In the second group of theories, the AB is said to arise from processes more directly related to stimulus perception. For example, Shapiro, Raymond, and Arnell (1994) argued that interitem competition between visual representations in short-term memory was critical to obtaining an AB. Di Lollo et al. (2005) suggested that processing T1 interferes with visual input filters, and Nieuwenhuis, Gilzenrat, Holmes, and Cohen (2005) propose that natural modulations in locus coeruleus activation in response to T1 lead to a refractory period that directly impairs T2 perception.

The present work clearly accords more easily with the former group of theories than the later. The fact that T1 processing interferes with the ability to shift temporal attention suggests that the impact of target processing extends significantly beyond the perceptual level. Note here that there were no perceptual triggers for the shift of temporal attention as in prior studies that initiated a shift of spatial attention in response to a peripheral stimulus. Rather, the temporal shift of attention was internally triggered by the failure of T2 to appear at the expected temporal interval. For this reason, it is not easy to see how the interference arising from T1 processing could have stemmed from mechanisms such as those proposed by Shapiro et al. (1994); Di Lollo et al. (2005) or Nieuwenhuis et al. (2005). Of course, it is possible that processing of T1 could also interfere with multiple mechanisms, including both those required for temporal shifts of attention and T2 perception more directly. However, it would still be the case that existing perceptual-level accounts do not provide a complete picture of the impact of T1 processing on subsequent cognitive activity.

In conclusion, the present work has shown that the need to perform a concurrent task takes up central resources required for making shifts of temporal attention. This finding mirrors earlier results with spatial shifts of attention, and strongly implies common underlying mechanisms are impaired by resource limitations imposed by concurrent task performance. In future work, it would be desirable to expand this behavioral work to more fully understand the underlying neural processes at play.

References

Badcock, N. A., Badcock, D. R., Fletcher, J., & Hogben, J. (2013). The role of preparation time in the attentional blink. *Vision Research, 76,* 68–76. http://dx.doi.org/10.1016/j.visres.2012.10.010

Bowden, V. K., Loft, S., Tatasciore, M., & Visser, T. A. W. (2017). Lowering thresholds for speed limit enforcement impairs peripheral object detection and increases driver subjective workload. *Accident Analysis and Prevention, 98,* 118–122. http://dx.doi.org/10.1016/j.aap.2016.09.029

Chun, M. M. (1997). Temporal binding errors are redistributed by the attentional blink. *Perception & Psychophysics, 59,* 1191–1199. http://dx.doi.org/10.3758/BF03214207

Chun, M. M., & Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 109–127. http://dx.doi.org/10.1037/0096-1523.21.1.109

Corbetta, M., Patel, G., & Shulman, G. L. (2008). The reorienting system of the human brain: From environment to theory of mind. *Neuron, 58,* 306–324. http://dx.doi.org/10.1016/j.neuron.2008.04.017

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience, 3,* 201–215. http://dx.doi.org/10.1038/nrn755

Correa, Á., Lupiáñez, J., Madrid, E., & Tudela, P. (2006). Temporal attention enhances early visual processing: A review and new evidence from event-related potentials. *Brain Research, 1076,* 116–128. http://dx.doi.org/10.1016/j.brainres.2005.11.074

Correa, Á., Lupiáñez, J., Milliken, B., & Tudela, P. (2004). Endogenous temporal orienting of attention in detection and discrimination tasks. *Attention, Perception, & Psychophysics, 66,* 264–278. http://dx.doi.org/10.3758/BF03194878

Correa, Á., Lupiáñez, J., & Tudela, P. (2005). Attentional preparation based on temporal expectancy modulates processing at the perceptual level. *Psychonomic Bulletin & Review, 12,* 328–334. http://dx.doi.org/10.3758/BF03196380

Coull, J. T., & Nobre, A. C. (1998). Where and when to pay attention: The neural systems for directing attention to spatial locations and to time intervals as revealed by both PET and fMRI. *The Journal of Neuroscience, 18,* 7426–7435.

Dell'Acqua, R., Dux, P. E., Wyble, B., Doro, M., Sessa, P., Meconi, F., & Jolicœur, P. (2015). The attentional blink impairs detection and delays encoding of visual information: Evidence from human electrophysiology. *Journal of Cognitive Neuroscience, 27,* 720–735. http://dx.doi.org/10.1162/jocn_a_00752

Dell'Acqua, R., Sessa, P., Jolicoeur, P., & Robitaille, N. (2006). Spatial attention freezes during the attention blink. *Psychophysiology, 43,* 394–400. http://dx.doi.org/10.1111/j.1469-8986.2006.00411.x

Di Lollo, V., Enns, J. T., & Rensink, R. A. (2000). Competition for consciousness among visual events: The psychophysics of reentrant visual processes. *Journal of Experimental Psychology: General, 129,* 481–507. http://dx.doi.org/10.1037/0096-3445.129.4.481

Di Lollo, V., Kawahara, J., Shahab Ghorashi, S. M., & Enns, J. T. (2005). The attentional blink: Resource depletion or temporary loss of control? *Psychological Research, 69,* 191–200. http://dx.doi.org/10.1007/s00426-004-0173-x

Du, F., & Abrams, R. A. (2009). Onset capture requires attention. *Psychonomic Bulletin & Review, 16,* 537–541. http://dx.doi.org/10.3758/PBR.16.3.537

Ghorashi, S., Enns, J. T., Spalek, T. M., & Di Lollo, V. (2009). Spatial cuing does not affect the magnitude of the attentional blink. *Attention, Perception, & Psychophysics, 71,* 989–993. http://dx.doi.org/10.3758/APP.71.5.989

Giesbrecht, B., & Kingstone, A. (2004). Right hemisphere involvement in the attentional blink: Evidence from a split-brain patient. *Brain and Cognition, 55,* 303–306. http://dx.doi.org/10.1016/j.bandc.2004.02.026

Gross, J., Schmitz, F., Schnitzler, I., Kessler, K., Shapiro, K., Hommel, B., & Schnitzler, A. (2004). Modulation of long-range neural synchrony reflects temporal limitations of visual attention in humans. *Proceedings of the National Academy of Sciences of the United States of America, 101,* 13050–13055. http://dx.doi.org/10.1073/pnas.0404944101

Husain, M., Shapiro, K., Martin, J., & Kennard, C. (1997). Abnormal temporal dynamics of visual attention in spatial neglect patients. *Nature, 385,* 154–156. http://dx.doi.org/10.1038/385154a0

Jolicoeur, P., Sessa, P., Dell'Acqua, R., & Robitaille, N. (2006). On the control of visual spatial attention: Evidence from human electrophysiology. *Psychological Research, 70,* 414–424. http://dx.doi.org/10.1007/s00426-005-0008-4

Kanwisher, N. G. (1987). Repetition blindness: Type recognition without token individuation. *Cognition, 27,* 117–143. http://dx.doi.org/10.1016/0010-0277(87)90016-3

Mack, A., & Rock, I. (1998). *Inattentional blindness* (Vol. 33). Cambridge, MA: MIT Press.

Marois, R., Chun, M. M., & Gore, J. C. (2000). Neural correlates of the attentional blink. *Neuron, 28,* 299–308. http://dx.doi.org/10.1016/S0896-6273(00)00104-5

Martens, S., & Johnson, A. (2005). Timing attention: Cuing target onset interval attenuates the attentional blink. *Memory & Cognition, 33,* 234–240. http://dx.doi.org/10.3758/BF03195312

Nieuwenhuis, S., Gilzenrat, M. S., Holmes, B. D., & Cohen, J. D. (2005). The role of the locus coeruleus in mediating the attentional blink: A neurocomputational theory. *Journal of Experimental Psychology: General, 134,* 291–307. http://dx.doi.org/10.1037/0096-3445.134.3.291

O'Brien, F., & Cousineau, D. (2014). Representing error bars in within-subject designs in typical software packages. *The Quantitative Methods for Psychology, 10,* 56–67. http://dx.doi.org/10.20982/tqmp.10.1.p056

Olivers, C. N., & Meeter, M. (2008). A boost and bounce theory of temporal attention. *Psychological Review, 115,* 836–863. http://dx.doi.org/10.1037/a0013395

Potter, M. C., Chun, M. M., Banks, B. S., & Muckenhoupt, M. (1998). Two attentional deficits in serial target search: The visual attentional blink and an amodal task-switch deficit. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24,* 979–992. http://dx.doi.org/10.1037/0278-7393.24.4.979

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance, 18,* 849–860. http://dx.doi.org/10.1037/0096-1523.18.3.849

Robitaille, N., Jolicoeur, 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. http://dx.doi.org/10.1016/j.brainres.2007.09.004

Rolke, B., & Hofmann, P. (2007). Temporal uncertainty degrades perceptual processing. *Psychonomic Bulletin & Review, 14,* 522–526. http://dx.doi.org/10.3758/BF03194101

Shapiro, K., Hillstrom, A. P., & Husain, M. (2002). Control of visuotemporal attention by inferior parietal and superior temporal cortex. *Current Biology, 12,* 1320–1325. http://dx.doi.org/10.1016/S0960-9822(02)01040-0

Shapiro, K. L., Raymond, J. E., & Arnell, K. M. (1994). Attention to visual pattern information produces the attentional blink in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception* *and Performance, 20,* 357–371. http://dx.doi.org/10.1037/0096-1523.20.2.357

Shen, D., & Alain, C. (2012). Implicit temporal expectation attenuates auditory attentional blink. *PLoS ONE, 7*(4), e36031. http://dx.doi.org/10.1371/journal.pone.0036031

Strayer, D. L., & Drews, F. A. (2007). Cell-phone–induced driver distraction. *Current Directions in Psychological Science, 16,* 128–131. http://dx.doi.org/10.1111/j.1467-8721.2007.00489.x

Taatgen, N. A., Juvina, I., Schipper, M., Borst, J. P., & Martens, S. (2009). Too much control can hurt: A threaded cognition model of the attentional blink. *Cognitive Psychology, 59,* 1–29. http://dx.doi.org/10.1016/j.cogpsych.2008.12.002

Tang, M. F., Badcock, D. R., & Visser, T. A. W. (2014). Training and the attentional blink: Limits overcome or expectations raised? *Psychonomic Bulletin & Review, 21,* 406–411. http://dx.doi.org/10.3758/s13423-013-0491-3

Vangkilde, S., Coull, J. T., & Bundesen, C. (2012). Great expectations: Temporal expectation modulates perceptual processing speed. *Journal of Experimental Psychology: Human Perception and Performance, 38,* 1183–1191. http://dx.doi.org/10.1037/a0026343

Visser, T. A. W. (2007). Masking T1 difficulty: Processing time and the attenional blink. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 285–297. http://dx.doi.org/10.1037/0096-1523.33.2.285

Visser, T. A. W. (2011). A re-examination of the impact of object processing on shifts of spatial attention. *Attention, Perception, & Psychophysics, 73,* 688–694. http://dx.doi.org/10.3758/s13414-010-0058-6

Visser, T. A. W., Bischof, W. F., & Di Lollo, V. (1999). Attentional switching in spatial and nonspatial domains: Evidence from the attentional blink. *Psychological Bulletin, 125,* 458–469. http://dx.doi.org/10.1037/0033-2909.125.4.458

Visser, T. A. W., Ohan, J. L., & Enns, J. T. (2015). Temporal cues derived from statistical patterns can overcome resource limitations in the attentional blink. *Attention, Perception, & Psychophysics, 77,* 1585–1595. http://dx.doi.org/10.3758/s13414-015-0880-y

Visser, T. A. W., Tang, M. F., Badcock, D. R., & Enns, J. T. (2014). Temporal cues and the attentional blink: A further examination of the role of expectancy in sequential object perception. *Attention, Perception, & Psychophysics, 76,* 2212–2220. http://dx.doi.org/10.3758/s13414-014-0710-7

Visser, T. A. W., Zuvic, S. M., Bischof, W. F., & Di Lollo, V. (1999). The attentional blink with targets in different spatial locations. *Psychonomic Bulletin & Review, 6,* 432–436. http://dx.doi.org/10.3758/BF03210831

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,* 787–807. http://dx.doi.org/10.1037/a0013902

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