A between-task consequence of temporal expectations

Daniela Gresch[1,2], Sage E. P. Boettcher[1,2], Anna C. Nobre[1,2], Freek van Ede[3]

[1]Department of Experimental Psychology, University of Oxford, Oxford, UK

[2]Oxford Centre for Human Brain Activity, Wellcome Centre for Integrative Neuroimaging, Department of Psychiatry, University of Oxford, Oxford, UK

[3]Institute for Brain and Behavior Amsterdam, Department of Experimental and Applied Psychology, Vrije Universiteit Amsterdam, Netherlands

Corresponding author contact information

Daniela Gresch
Brain & Cognition Lab
Oxford Centre for Human Brain Activity
Department of Experimental Psychology
University of Oxford

Mail: daniela.gresch@psy.ox.ac.uk

Abstract

In everyday life, we often anticipate the timing of one upcoming task or event while actively engaging in another. Here, we investigated temporal expectations within such a multi-task scenario. In a visual working-memory task, we manipulated whether the onset of a working-memory probe could be predicted in time, while also embedding a simple intervening task within the delay period. We first show that working-memory performance benefitted from temporal predictability, even though an intervening task had to be completed in the interim. Moreover, temporal expectations regarding the upcoming working-memory probe additionally affected performance on the intervening task, resulting in faster responses when the memory probe was anticipated early, and slower responses when the memory probe was expected late, as compared to when it was temporally unpredictable. Because the intervening task always occurred at the same time during the memory delay, differences in performance on this intervening task are attributed to a between-task consequence of temporal expectation. Thus, we show that within multi-task settings, knowing when working-memory contents will be required for an upcoming task not only facilitates performance on the associated working-memory task, but can also influence the performance of other, intervening tasks.

Keywords

Working memory, Temporal expectation, Intervening task, Attention

Introduction

In a dynamically unfolding world, regularities help us anticipate future states of the environment and thereby guide adaptive behaviour. One potent source of such anticipation is provided by predictable temporal structures (for review see Nobre & van Ede, 2018). As such, temporal expectations can help prepare for and optimise forthcoming perception and action (Breska & Deouell, 2014; Coull & Nobre, 1998; Denison et al., 2017; Heideman et al., 2018; Jones & Boltz, 1989; Los et al., 2017; Praamstra et al., 2006; Rohenkohl et al., 2012; Shalev et al., 2019; Shin & Ivry, 2002; van Ede et al., 2020; van Elswijk et al., 2007; Vangkilde et al., 2012). Furthermore, temporal expectations can guide prioritisation and access to working-memory contents at moments when they are most relevant (W. Jin et al., 2020; Olmos-Solis et al., 2017; van Ede et al., 2017; Zokaei et al., 2019).

To date, the effects of temporal expectation have tended to be studied within single-task contexts – that is, in the absence of intervening-task demands during the period of anticipation. This fails to capture the important 'multi-task situation' faced during everyday activities, in which we are often required to juggle various tasks across a common time period. In these multi-task scenarios, we may be able to anticipate the timing of an upcoming event for one task (task A), while concurrently having to engage in another task (task B). Here, we investigate whether having a predictable temporal structure for task A (here a working-memory task) may influence performance on task B (here a simple intervening task) in such multi-task situations. We first ask whether the performance of a working-memory task may still benefit from temporal expectations when an intervening task occurs within the period of anticipation. We additionally examine whether a predictable temporal structure for task A may also influence performance of the intervening task B, thereby affecting overall performance when juggling contemporaneous tasks.

To address these questions, we inserted an intervening task within the retention period of a visual working-memory task. Across blocks, the duration of the retention interval was predictable (100% certainty to be short or long) or unpredictable (50% short, 50% long). Critically, the temporal-expectation manipulation applied only to the time when the working-memory items would become probed for report. In contrast, the intervening task always occurred at the same time after memory encoding, irrespective of the expected memory-probe time (Figure 1A). Accordingly, any effects on the performance in the intervening task must be attributed to a between-task consequence of temporal expectations. Our primary aim in the current study was to demonstrate proof-of-concept whether any such between-task effects of temporal expectations exist.

Methods

Participants

The desired sample size was set to *n* = 54, building on a previous online study from our lab that targeted a complementary question using a similar overall task setup (Gresch et al., 2021). To yield the targeted number of participants, we collected data from 75 online participants in total. Data from 20 participants were excluded following our a-priori trial-removal procedure (before splitting data by conditions). One additional participant was also removed due to usage of non-memory-based strategies to complete the task (see 'Analysis' for details). Out of 54 participants (age range: 19 to 40; mean age: 28.37; 15 females; 38 males, 1 non-binary), 45 self-reported to be right-handed (9 left-handed).

Participants were recruited via Prolific Academic (https://www.prolific.co/) and pre-screened based on demographic criteria (i.e., age range 18 to 40, fluent in English), general health (i.e., normal or corrected-to-normal vision, no history of mental illnesses) and previous participation history on Prolific Academic (i.e., participated in at least 10 studies, with a study approval rate above 90%). All participants provided informed consent prior to participation and were paid £7.50 per hour. An additional monetary reward of up to £5 could be earned depending on participants' task performance in the memory task. Specifically, performance above 80% received a bonus payment scaling from £0.01

at 80% to £5 at 100%, with an average bonus payment of £0.67 (*SD* = 0.85) across all participants. The study was approved by the Central University Research Ethics Committee of the University of Oxford.

Task and procedure

Participants performed a web-based visual working-memory task in which they were required first to memorise the angles of two oriented bars and then, when probed after a retention interval, to reproduce the exact angle of one of those memory items (as in Gresch et al., 2021). In addition, they had to perform an intervening task between encoding of the memory array and retrieval of the probed item (Figure 1A). There were two main experimental manipulations. (1) Within experimental blocks, the memory probe occurred after either a short (1250 ms) or long (2500 ms) retention interval (delay condition: early vs. late). (2) Between blocks, the duration of the retention interval was either predictable or unpredictable (temporal expectation condition: predictable block vs. unpredictable block). Critically, the intervening event always occurred at the same time after disappearance of the initial array (1000 ms), independent from the memory-probe time.

Participants completed the experiment in a web browser on their personal computers. The recommended internet browsers were Mozilla Firefox and Google Chrome; participating via mobile phone or tablet was not allowed. Prior to the experiment, participants' individual screen resolution was estimated by asking them to adjust an image of a credit card such that it matched the size of a physical credit card placed on the screen. In this manner, we could calculate the ratio between the card image width in pixels and the actual card width in centimetres to obtain a measure of pixel density (i.e., pixel per cm). Together with the instructed viewing distance of approximately 60 cm (i.e., one arm's length away from the monitor), this allowed us to present stimuli in degrees of visual angle, regardless of monitor size (Li et al., 2020). The experimental script was generated in PsychoPy (Peirce et al., 2019) and hosted online using Pavlovia (https://pavlovia.org/). Experimental code will be shared on OSF (https://osf.io/) upon acceptance.

At the start of each trial, two tilted bars were simultaneously presented against a grey background (RGB value: [128,128,128]) for 250 ms. One bar was always positioned to the left and the other to the right of the central fixation cross. Independent of location, one of the bars was tilted to the left (anticlockwise) and the other to the right (clockwise). To avoid angles too close to vertical and horizontal meridians, the items' angles were randomly drawn in increments of 5° between ±5° and ±85°. Across trials, a leftward or rightward oriented bar was equally likely to appear in the left or right position on screen. The stimuli were approximately 0.8° in width and 5.7° in length and were centred at a viewing distance of approximately 5.7° visual angle from fixation. At encoding, both lateralised items were equally likely to be probed, rendering them equally relevant.

Array disappearance was followed by a delay period of 1000 ms, in which the fixation cross remained on the screen. After this delay, the 'intervening item' (a tilted bar) was presented in the centre of the screen for 250 ms. Participants were required to respond to the intervening item by pressing the 'F' key with their left index finger if the bar was tilted to the left, or the 'J' key with their right index finger if the bar was tilted to the right.

Within blocks, left- and rightward angles of the intervening items were counterbalanced. The intervening item was always presented in a different colour than the two memory items that preceded it. The colour of the memory items and the intervening item were always drawn from a set of three highly distinguishable colours (RGB values: blue [0,225,228], orange [254,163,0], pink [253,142,253]). The colours used for the memory items and the intervening item varied randomly across trials. The intervening item had the same size as the memory items and its angle was also randomly drawn between ±5° and ±85° in increments of 5°.

The offset of the intervening item was followed by a second delay period (1250 ms or 2500 ms) before the fixation cross changed to match the colour of one of the two memory items, to indicate which memorised tilt would need to be reported. Importantly, the colour of the probe would never match that of the intervening item, but both memory items were equally likely to be probed. In predictable blocks, the second delay interval had a fixed duration of 1250 ms (early blocks) or 2500 ms (late blocks) across all trials. In unpredictable blocks, half of the trials had a retention interval of 1250 ms, whereas the other half had a memory delay of 2500 ms. The order of trials within unpredictable blocks was randomised.

For the working-memory task, participants had to try to reproduce the exact angle of the probed memory item. As such, in contrast to the intervening task requiring a simple discrimination (leftwards or rightwards), the memory task demanded a precision response. Following the appearance of the probe, participants had unlimited time to decide on their response. After response initiation, a visual response dial was displayed on the screen, always starting in vertical position. The response dial included markers along a circle that corresponded to the ends of a bar and always appeared surrounding the fixation.

To report a leftward (rightward) angle, participants were (as for the intervening task described above) asked to press the F or J key on the keyboard using their left or right index finger. The dial rotated leftwards when pressing F and rightwards when pressing J (either holding key down or pressing key repeatedly; always in increments of 5°). The dial could only be rotated in the direction that was initially indicated by the participant. For example, if a participant started pressing the F key after the probe, the dial would only move leftwards, and it would therefore not be possible to move the dial towards the right with the J key. Since the response dial always started in a vertical position and because it could not be rotated beyond ±90°, a leftward (or rightward) oriented bar could only be correctly reported with the left (or right) key. Consequently, the hand required for responding was directly linked to the angle of the bar that was probed. This builds on previous tasks from our lab (Boettcher et al., 2021; Gresch et al., 2021; van Ede et al., 2019), though we note that the specifics of this response implementation were not essential to the current study. Once participants started rotating the dial, they were given only limited time (4000 ms) to complete the angle reproduction. This was intended to encourage participants to recall the exact orientation before starting to move the dial. When the dial aligned with the remembered tilt of the item, participants pressed the space bar to verify their response and continue with the task.

At the end of each trial, participants received feedback about their working-memory performance, and when relevant, also about their intervening-task performance. The working-memory feedback provided information on how well participants reproduced the probed item. Feedback was presented for 500 ms in the form of a number ranging from 0 to 100, with 100 indicating a perfect report and 0 indicating that the adjusted orientation was perpendicular to the angle of the probed item. However, if time to adjust the angle ran out, the message 'Too slow' was presented instead for 750 ms. Additional feedback could also appear to indicate if participants responded with the wrong key or did not respond at all to the intervening item. To incentivise fast responses in the intervening task, participants also received a feedback message when their reaction time (RT) was slower than 1000 ms. This feedback message was combined with an image reminding participants to press F (or J) when the intervening item was tilted to the left (or right). Feedback was presented for a minimum of 750 ms and until the space key was pressed to encourage participants to read the feedback message before being able to continue to the next trial. Trials were separated by an inter-trial interval randomly drawn between 500 and 800 ms.

The experiment consisted of 384 trials divided across 12 blocks (each including 32 trials). In six blocks, the delay between intervening item offset and probe onset was predictable – with the probe only occurring early in three of the blocks, and only occurring late in the other three. In the remaining six blocks, probe onset was unpredictable (pseudo-randomly varying between early and late within each block). As such, the total number of trials in which the probe would appear at any one delay interval after offset of the intervening item (early vs. late) was equal between predictable blocks and across unpredictable blocks. The order of blocks was pseudo-randomised in groups of four containing two unpredictable blocks, one predictable-early, and one predictable-late block.

To become familiarised with the procedure of the experiment, participants performed 32 practice trials each with an unpredictable delay period. Participants were informed that they would never have to reproduce the tilt of the intervening item – however, they were not informed about the temporal predictability (i.e., predictable vs. unpredictable) or the two possible probe-onset times (i.e., early vs. late). The instructions also stressed that for both the intervening and working-memory task, participants should respond as quickly and accurately as possible. At the end of the experiment, participants were redirected to the survey website Qualtrics (http://www.qualtrics.com/), where they were asked about comprehension of the instructions, potential strategies used to complete the task, and whether they thought their data should be analysed. The experiment lasted approximately 50 minutes in its entirety.

Analysis

Data were analysed in R Studio (RStudio Team, 2019) and will be shared alongside the analysis script on OSF (https://osf.io/) upon acceptance. During pre-processing, trials were removed when (reaction times) RTs in the working-memory task (calculated from probe onset to response onset) were below 200 ms or exceeded 5000 ms. Next, we removed trials for which the remaining RTs were 2.5 *SD* above the individual mean across all conditions, or if participants took longer than 4000 ms to reproduce the probed angle after response initiation. Regarding the intervening task, we excluded trials if participants either did not respond at all, or if they did not respond within a time window ranging from 200 ms to 1500 ms after the intervening-task onset. Datasets with more than 25% of trials rejected during these pre-processing steps or with average reproduction errors higher than 40° in the working-memory task (across all conditions) were removed from further analysis (n = 20). Additionally, one dataset was also removed in which the participant self-reported as having employed explicit non-memory-based strategies to maintain the encoding display (e.g., physically aligning their fingers with the memory items at encoding). After this exclusion step, datasets from the remaining 54 participants (in which an average of 95.18% [*SD* = 2.78] of trials were retained) were entered into the main analysis. Detailed information regarding the removal of trials per participant can be found in the analysis script.

For the working-memory task, we examined the average RTs for the conditions predictable-early, unpredictable-early, predictable-late, and unpredictable-late. Moreover, we also evaluated reproduction errors by averaging the absolute difference between the original angle of the target (i.e., probed) item and the reported angle.

For the intervening task, we analysed the average RTs for the predictable-early, predictable-late, and the unpredictable condition (we did not split the unpredictable condition by early and late trials, as at time of intervening-task onset, it could not have yet been known whether the working-memory probe would occur early or late). For the same conditions, we also calculated the average error rates. Participants committed an error when using the wrong key to respond to the intervening item. Since we expected error rates for this simple discrimination task to be quite low, RTs were deemed the more sensitive dependent variable for the intervening-task performance.

When comparing more than two means, we applied a repeated-measures analysis of variance (ANOVA) and reported η^2_G as a measure of effect size. For post hoc *t* tests, we report Bonferroni-corrected *p* values that we denote as "$p_{\text{Bonferroni}}$". We used the ggplot2 package (version 3.3.3; Wickham, 2009) for plotting results. Where relevant, the within-subject standard error of the mean was calculated from normalized data using the approach from (Morey, 2008).

Results

Temporal expectations improve working-memory performance

We first confirmed that our manipulation of temporal expectations for the working-memory task was effective despite an intervening task occurring in the period of anticipation. For this, we evaluated RTs, which we defined as the time between the onset of the memory probe and response initiation. RTs served as a proxy for the time it took participants to access the relevant memory information before starting to reproduce the probed angle. We found a significant interaction between the delay condition and temporal expectation (Figure 1C; $F_{(1,53)} = 48.396$, $p < 0.001$, $\eta^2_G = 0.009$). This interaction was due to the fact that temporal expectation had a significant effect (i.e., lead to faster response initiation) for early probes ($t_{(53)}$ = -7.437, $p_{\text{Bonferroni}}$ < 0.001, d = 1.012), but not for late probes ($t_{(53)}$ = 1.568, $p_{\text{Bonferroni}}$ = 0.246, d = 0.213). This finding is typical in studies of temporal expectation (as reviewed in Nobre & van Ede, 2018) and is attributed to the fact that, once the early interval passes, participants always know the memory will be probed at the later interval, regardless of which block they are in. This pattern of interaction was paired with two main effects: RTs to the probe were faster in late as compared to early trials ($F_{(1,53)}$ = 62.517, p < 0.001, η^2_G = 0.024) and when probe onset was predictable compared to unpredictable ($F_{(1,53)}$ = 22.491, p < 0.001, η^2_G = 0.005).

Next to RTs, we additionally considered the influence of temporal expectations on the quality of working-memory reports. To this end, we analysed the average reproduction error (i.e., the absolute deviation between the reported angle and the true angle of the probed item), for which lower values indicate better performance. We observed a significant effect of temporal expectation on reproduction errors (Figure 2B; $F_{(1,53)}$ = 4.854, p = 0.032, η^2_G = 0.002), with smaller errors when the memory probe was predictable vs. unpredictable. In contrast to RTs, however, for errors we did not find a systematic difference between early and late probes ($F_{(1,53)}$ = 0.313, p = 0.578, η^2_G < 0.001), nor did we find an interaction between temporal expectation and delay condition ($F_{(1,53)}$ = 0.865, p = 0.357, η^2_G < 0.001).

These data reveal that temporal expectations were employed to anticipate upcoming memory-guided behaviour, building on our prior demonstrations of similar effects in the absence of intervening tasks (W. Jin et al., 2020; van Ede et al., 2017; Zokaei et al., 2019). The current results show that benefits of temporal expectation on working-memory guided behaviour occur even when an intervening task must be completed during the retention interval.

Temporal expectations have consequences for the intervening-task performance

Next, we asked whether temporal expectation regarding the working-memory probe influenced performance on the intervening task. Critically, the intervening task always occurred at the same time after encoding, so that any potential differences in performance to this task must be attributed to a between-task consequence of temporal expectation for the working-memory task. Note that we did not divide unpredictable blocks by the eventual time of the memory probe (i.e., early vs. late) since participants could not have known whether the memory items would be probed early or late at the time of the intervening task.

As shown in Figure 1B, performance of the intervening task was fastest when the memory probe was expected early, slowest when the memory probe was expected late, and intermediate when the memory probe occurred unpredictably. This was confirmed by a significant effect of block type on RTs to the intervening task ($F_{(1,53)}$ = 18.282, p < 0.001, η^2_G = 0.007). Pairwise comparisons showed significantly faster RTs in predictable-early as compared to both the unpredictable ($t_{(53)}$ = -3.067, $p_{\text{Bonferroni}}$ = 0.010, d = 0.417) and the predictable-late blocks ($t_{(53)}$ = -5.427, $p_{\text{Bonferroni}}$ < 0.001, d = 0.739), as well as significantly faster RTs to unpredictable as compared to predictable-late blocks ($t_{(53)}$ = -3.443, $p_{\text{Bonferroni}}$ = 0.003, d = 0.468). These results show that temporal expectations do not merely influence performance of the task to which they apply (in our case, the working-memory task), but also affect performance in another task that occurs during the period of temporal anticipation – even when this task itself always comes at exactly the same time after memory encoding.

Showing a similar trend as the RTs, error rates for the intervening task (Figure 2A) appeared to be the smallest in predictable-early and largest in predictable-late blocks. However, for error rates we did not find a significant difference between conditions ($F_{(2,106)}$ = 1.060, p = 0.350, η^2_G = 0.004). This may reflect error rates being very close to ceiling (i.e., below 3%). Hence, we refrained from further analysing and interpreting accuracy on the intervening task.

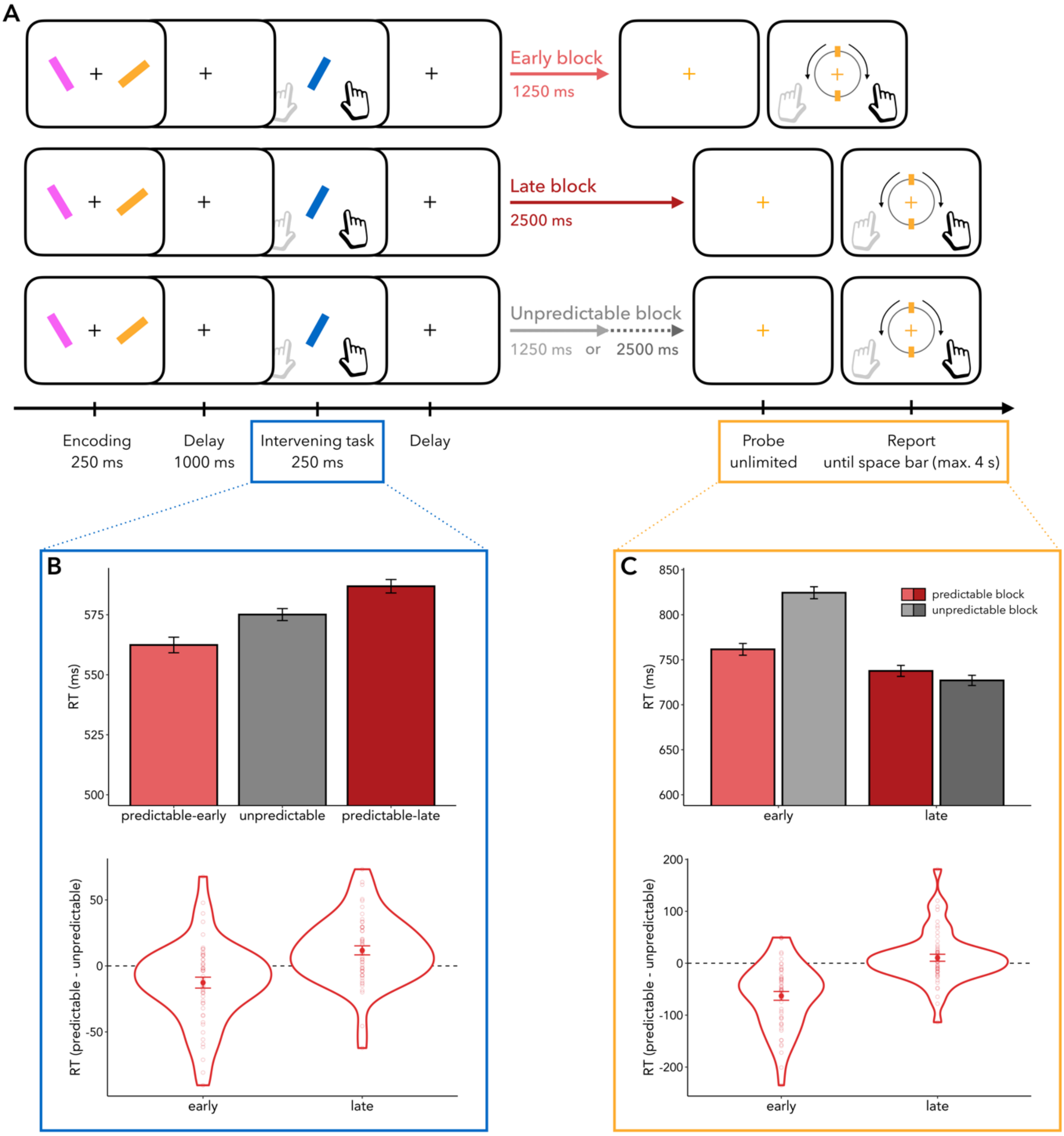

Figure 1. Task schematic and temporal-expectation effects on reaction times. (A) Two lateralised oriented bars were presented for 250 ms for encoding. For the working-memory task, participants were asked to remember the angle of both bars, of which one had to be reported at the end of the trial. Following a delay of 1000 ms, an intervening task occurred wherein another tilted bar was presented centrally for 250 ms. For this intervening task, participants had to indicate as quickly as possible whether this bar was tilted to the left or to the right. In “Early blocks”, the intervening item offset was followed by a delay of 1250 ms, whereas in “Late blocks”, it was followed by a delay of 2500 ms. In “Unpredictable blocks”, the delay between the intervening item offset and the memory probe onset was either 1250 ms or 2500 ms equally often. After this delay, a colour change of the central fixation cross indicated which of the two bars from the encoding display would have to be reproduced from memory. (B) Intervening task performance. Top panel: Reaction times (RTs) in the intervening task significantly increased from predictable-early to unpredictable and from unpredictable to predictable-late blocks. Bottom panel: Between-task effects of temporal expectation in predictable-early and predictable-late blocks, relative to unpredictable blocks. The between-task effect of temporal expectation of each delay was calculated by taking the difference in RTs between predictable-early/predictable-late blocks and unpredictable blocks (predictable - unpredictable). Dots represent individual participants. (C) Working-memory task performance. Top panel: RTs to early probes were faster when the probe could be temporally predicted as compared to when it was temporally unpredictable. Bottom panel: Temporal expectations reduced RTs in the early condition. The temporal expectation benefit of each delay was calculated by taking the difference in RTs between predictable blocks and unpredictable blocks (predictable - unpredictable). Dots represent individual participants.

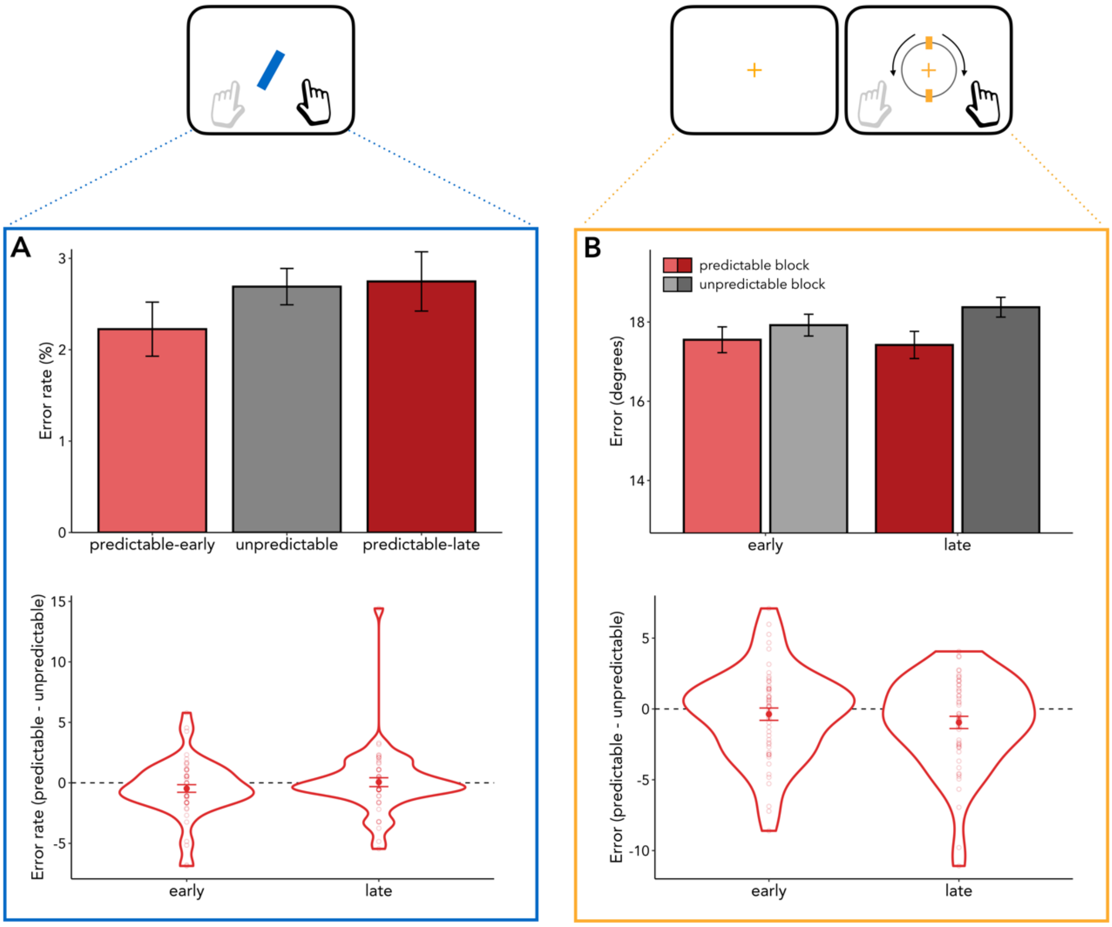

Figure 2. Temporal-expectation effects on errors. (A) Intervening task. Top panel: Error rates did not significantly differ between conditions. Bottom panel: Violin plots for each delay were calculated by taking the difference in error rates between predictable-early/predictable-late blocks and unpredictable blocks (predictable - unpredictable). Dots represent individual participants. **(B)** Working-memory task. Top panel: Reproduction errors were significantly higher in unpredictable as compared to predictable blocks. Bottom panel: Temporal expectations decreased reproduction errors for both delays. The temporal expectation benefit of each delay was calculated by taking the difference in reproduction errors between predictable blocks and unpredictable blocks (predictable - unpredictable). Individual participants' differences are plotted as dots.

Discussion

By manipulating temporal expectations within a multi-task context, we made two relevant observations. First, temporal expectations about when to utilise working-memory contents confer significant benefits to memory performance even when other intervening tasks must be performed in the interim. Second, temporal expectations about the later working-memory task also had significant consequences for performance of the intervening task, even though the temporal expectation manipulation did not apply to this task. Responses to an intervening task were expedited when the requirement for memory-guided behaviour was expected to occur early and slowed when the working-memory task was expected late, as compared to when the timing of the working-memory task was unpredictable. Thus, we unmask a between-task consequence of temporal expectations.

A between-task consequence of temporal expectations

Our work clearly demonstrates the presence of a between-task consequence of temporal expectations in a multi-task setting. It invites consideration of what mechanisms account for the effects, and this remains an important direction for future research. At this juncture, we can only speculate regarding potential underlying mechanisms.

First, it is possible that the between-task effect may result from more efficient 'scheduling' of both tasks when the timing of either of them is predictable. In line with this, Kushleyeva and colleagues (2005) propose that, in multi-task scenarios, temporal aspects of each task are used to flexibly schedule when to prioritise one task or the other. Given there was less time between the intervening item and memory probe in the predictable-early blocks, participants may have felt urged to complete the intervening task as soon as possible to refocus on the working-memory task in time for the probe. In contrast, when the working-memory probe was expected late – yielding less time pressure – participants may have allowed themselves more time for the intervening task, rendering their responses slower.

Another potential interpretation is that temporal expectations for an early working-memory probe may have resulted in an elevated state of 'alertness' (Weinbach & Henik, 2012), and in decreased levels of alertness when the probe was expected late. This could have resulted in a differential overarching state of preparation that effectively 'spilled over' to the intervening task. An alternative spill-over interpretation relates to a suggestion in the time-perception literature that cross-contamination between temporal intervals occurs when more than a single interval is estimated simultaneously (Moon & Anderson, 2013; Taatgen & van Rijn, 2011). Specifically, representations of shorter or longer intervals can shift the representation of an intermediate interval in those respective directions. Such a contamination effect may also contribute to our observed between-task effect of temporal expectations. For example, in predictable-late trials, the representation of time used for guiding performance in the intervening task may have expanded and thereby slowed responses. Likewise, faster RTs in predictable-early trials may have been mediated through a compression of represented time. Future studies are required to take a more granular, and complementary physiological approach to understand exactly how these factors contribute to the between-task consequence of temporal expectations that we exposed here.

In addition to scenarios above, it is also conceivable that it was easier to anticipate the intervening task in blocks where the working-memory task itself was also temporally predictable. However, this is unlikely to account for our results, as this would have led to faster reactions to the intervening task regardless of whether the working-memory probe occurred early or late. In contrast, we found that it was not the temporal predictability per se that affected performance of the intervening task, but rather the time at which the probe was expected in the predictable blocks (early vs. late). Yet, it remains an interesting question whether we would observe similar results if the intervening task itself had occurred at random moments in the anticipatory period.

At first glance, the beneficial consequence that temporal expectation in one task has on performance in another task may seem to contradict findings related to the selective nature of temporal expectations. For example, previous research has demonstrated that directing attention to a target occurring at one point in time leads to performance benefits at that specific time but simultaneously to impairments earlier and later (Denison et al., 2017, 2021). Instead, we show that temporal expectations can facilitate performance of the task to which they are applied, as well as the preceding intervening task. In reconciling these findings, it is important to note at least two key differences which may contribute to this apparent discrepancy. In Denison et al.'s (2017, 2021) study, participants performed only one task. Stimuli within that task had overlapping sensory properties and action associations, competing for priority in guiding performance. As one of the stimuli was more likely to be irrelevant, a trade-off between prioritising the likely-relevant stimulus and ignoring the likely-irrelevant stimulus was therefore an effective strategy. By contrast, a strategic trade-off would have been counterproductive in our study, as participants completed two separate tasks that were equally relevant. This provides for a scenario wherein both tasks potentially benefitting from temporal expectation – through either temporal structuring or spill-over effects – would be much more advantageous. The divergence between these two findings highlights the context-dependency and flexibility of temporal expectation.

Temporal expectations benefit working-memory guided behaviour, despite intervening-task demands

Beyond providing evidence for a between-task consequence of temporal expectations, our study also yields new insights into the dynamic and prospective nature of working memory. Extending a growing literature showing benefits of temporal expectation for working-memory performance (Boettcher et al., 2021; Gresch et al., 2021; W. Jin et al., 2020; Olmos-Solis et al., 2017; van Ede et al., 2017; Wilsch et al., 2015, 2018; Zokaei et al., 2019), our results uniquely demonstrate that performance benefits of temporal expectations during working memory remain robust, even when having to perform an intervening task in the period of anticipation.

From the time perception literature, there is abundant evidence that the ability to track time explicitly can be biased when performed in complex multi-task situations (Block et al., 2010; Brown, 1997, 2006; Brown et al., 2013; Fortin et al., 2007; Hemmes et al., 2004; Polti et al., 2018). Accordingly, having to engage in the intervening task could have eradicated the formation and utilisation of temporal expectations regarding the working-memory task. Indeed, prior studies have shown that temporal-expectation effects can be substantially reduced by performing a concurrent demanding task (Capizzi et al., 2012, 2013; van der Mijn & van Rijn, 2021). At the same time, recent work from our lab has revealed that learned (spatio)temporal regularities regarding external events can guide visual-search performance even when interacting with temporally unpredictable intervening events (Boettcher et al., in press). Similarly, temporal expectations affect performance even during dynamic streams that require inhibition of temporally competing distractors (Chauvin et al., 2016; Davranche et al., 2011; Zokaei et al., 2021). These results suggest that it is possible to maintain and utilise representations of temporal regularities across other intervening events. The current results extend these findings, by demonstrating that temporal regularities can also be highly effective for facilitating working-memory-guided behaviour during multi-task situations.

Nevertheless, our ability to keep track of time might be dependent on the specific demands of the intervening tasks, whereby more cognitively taxing intervening tasks may be more detrimental the formation of temporal expectations. Moreover, the utilisation of temporal expectations for memory-guided behaviour may be further affected by the sensorimotor overlap between intervening and memory items. Prior research has found evidence for working-memory performance to be most impaired when perceptual distractors are similar to the memory content (Clapp et al., 2010; Hermann et al., 2021; Jha et al., 2004; Sreenivasan & Jha, 2007; Yoon et al., 2006). If 'time' is part of (visual and motor) working-memory representations (Heuer & Rolfs, 2021; D. Z. Jin et al., 2009), a high similarity in the associated objects and actions between tasks may further modulate the benefit of temporal expectations. Thus, in future work it will be of interest to investigate more directly whether and how different types of intervening tasks exert distinct influences on our ability to use temporal expectations.

Temporal expectations have reported to benefit performance particularly at short as opposed to long delays (Coull, 2009; Coull et al., 2000; Griffin et al., 2002; W. Jin et al., 2020; Miniussi et al., 1999; Nobre, 2001). This effect is usually attributed to the hazard rate: once the potential time of the early probe passes, expectations can be updated, and attention can be reoriented towards the longer interval. Thus, even in unpredictable trials, the late memory probe becomes predictable as soon as the early interval has passed. Our RT results in the working-memory task reflected this typical hazard rate of temporal expectations. At the same time, however, memory representations were more accurate in predictable as compared to unpredictable trials, even when the memory probe appeared late (see also Chauvin et al., 2016; Cravo et al., 2017). This is distinct from our earlier study with a comparable temporal-expectation manipulation in working memory (W. Jin et al., 2020). Critically, however, in this prior study, no intervening task occurred during the working-memory delay. The intervening task in the present study may thus be critical for the here-observed effect of temporal expectations on working-memory performance in the late trials. We recently showed that working memory can be shielded against intervening tasks demands when the intervening task itself can be temporally predicted (Gresch et al., 2021). In a similar vein, having temporal expectations about the memory probe may have helped to shield the working-memory representations from the intervening task, yielding higher ensuing memory accuracy in predictable trials, regardless of whether items would subsequently become probed early or late.

Conclusion

In the current work, we focussed on the intersection of several lines of research often studied in isolation, including working memory, temporal expectations, and multitasking. We provide evidence (1) that learned temporal expectations regarding task A can be utilised even when having to engage in an intervening task B during the period of anticipation, and (2) that temporal expectations regarding task A can affect the performance of intervening task B. Thus, the predictable temporal structure of one task facilitates not only the performance of this task but can affect and improve performance of multiple tasks in temporally structured multi-task situations.

Acknowledgements

The authors would like to thank Gordon Dodwell for his thoughtful comments on this manuscript. This research was funded by an ERC Starting Grant from the European Research Council (MEMTICIPATION, 850636) to F.v.E. and a Wellcome Trust Senior Investigator Award (104571/Z/14/Z) and a James S. McDonnell Foundation Understanding Human Cognition Collaborative Award (220020448) to A.C.N., and by the NIHR Oxford Health Biomedical Research Centre. The Wellcome Centre for Integrative Neuroimaging is supported by core funding from the Wellcome Trust (203139/Z/16/Z).

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