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Time Expectancies in Dual Tasking: Evidence for Proactive Resource Sharing?

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The present study explored whether dual-task performance is affected by deviations from the expected time point of a secondary task. In two psychological refractory period experiments, participants responded to two tasks, separated by either a short or long delay. In contrast to traditional dual-tasking studies, however, the identity of Task 1 probabilistically predicted the delay after which Task 2 would occur. Violations of these expectations impaired performance in both Task 2 and Task 1. For Task 2, this effect was more pronounced when Task 2 occurred unexpectedly early, while for Task 1, it was more pronounced when Task 2 occurred unexpectedly late. The results are consistent with the notion that processing resources can be shared, and that even in the absence of Task 2, some resources are withheld from Task 1, based on early available Task 1 features.

Public Significance Statement

When doing two tasks in parallel, performance in at least one task is usually worse than when the two tasks are performed sequentially. Here, we demonstrate that the sole expectation of having to perform things in parallel can likewise lead to multitasking costs. This suggests that limited cognitive resources can be shared between tasks and may already be assigned to a certain task before it actually occurs.

Keywords: cognitive flexibility, capacity sharing, psychological refractory period, time expectancy

Supplemental materials: https://doi.org/10.1037/xhp0001141.supp

Doing two things simultaneously is hard. A popular empirical demonstration of this cognitive limitation is the psychological refractory period (PRP) effect (Telford, 1931). In a typical PRP experiment, the stimuli for two tasks (Task 1 and Task 2) are presented with varying delays (stimulus onset asynchronies [SOAs]). With high temporal task overlap (short SOA), responses are usually slower than with low overlap (long SOA). This performance decrement predominantly affects Task 2 and is commonly attributed to a limited cognitive resource that, with short SOAs, must be shared between the tasks (Navon & Miller, 2002; Tombu & Jolicœur, 2003) or is assigned completely to the first task (Pashler, 1994).

While the notion of an all-or-none allocation of resources can explain many empirical observations (for a review, see Koch et al., 2018), it cannot comprehensively account for situations where the temporal order of the events is unpredictable: Gottsdanker (1979), for example, employed a PRP setup with a fixed SOA of 100 ms. Crucially, the stimulus (and thus the processing demand) for Task 1 was occasionally omitted, which decreased (instead of increased) performance in Task 2. Similarly, knowing the order of stimuli (and thus of processing demands) facilitates the performance of Task 1 (De Jong, 1995; Hirsch et al., 2017; Kübler et al., 2018, 2022a, 2022b; Strobach et al., 2018). In other words, dual-tasking performance benefits from knowledge about *what* is to be performed *when*.

However, dual tasking in everyday life entails more subtle temporal contingencies that go beyond determining what comes first and second. Consider the two activities of braking and shifting gear. Typically, braking (e.g., due to the car ahead slowing down) is quickly followed by the requirement to downshift, whereas chances are that downshifting is not immediately followed by braking. In other words, the activity coming first predicts when the respectively other activity will be required. This poses the question whether such delicate temporal contingencies between the identity of Task 1 and the timing of Task 2 can affect performance.

On the one hand, previous findings cast doubt that such time expectancies would manifest in more constrained PRP designs: Because time perception seems to be generally impaired in dual-tasking situations (Bryce & Bratzke, 2014, 2017; Corallo et al., 2008; Marti et al., 2010; Ruthruff & Pashler, 2010), participants might not be able to notice subtle time-related contingencies. On the other hand, there is evidence that time expectancies established prior to the onset of a trial might influence whether participants share processing resources. For example, Miller et al. (2009) manipulated the SOA distribution between experimental halves and

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observed that Task 2 responses were faster with expected SOAs than with unexpected SOAs. Furthermore, Task 1 responses were generally slowed in blocks with a high probability of short SOAs, suggesting that the likelihood of resource sharing was increased when participants expected short SOAs (see Mattes et al., 2021 for a replication and discussion of alternative explanations revolving around the blockwise manipulation). Interestingly, this affected Task 1 performance even at long SOAs, suggesting that some processing resources are not devoted to Task 1, but rather spared for Task 2, even when Task 2 appears only later (cf. Tombu & Jolicœur, 2002). In other words, some resources are running idle, they are spared from Task 1 and *proactively*[1] shared with Task 2. The notion of proactive resource sharing is supported by the observation that at long SOAs, Task 2 performance is often better than Task 1 performance, even when task difficulty differences are controlled for (Mittelstädt et al., 2022). Thus, it seems possible that the system adjusts the amount of resources held back for the processing of Task 2, depending on which SOA is expected from the Task 1 identity. In a setup in which either a long or a short SOA can occur, the following hypotheses about the influence of SOA expectations can be formulated:

After a long SOA, proactive resource sharing would predict that Task 2 performance is hardly affected by whether this long SOA was expected (Figure 1, mark 4). With long SOAs, Task 1 processing is usually already completed and hence, all resources can be devoted to Task 2 (e.g., Mittelstädt et al., 2022). On the contrary, Task 1 performance should be heavily affected by whether this long SOA was expected (Figure 1, mark 2). If the long SOA was unexpected (i.e., if a short SOA was expected), participants may have already reserved some resources for Task 2, thereby cutting resources from Task 1 processing. Consequently, Task 1 performance with unexpected long SOAs should be worse than with expected long SOAs.

After a short SOA, proactive resource sharing would predict that Task 2 performance is heavily affected by whether this short SOA was expected (Figure 1, mark 3). With unexpected short SOAs (i.e., if a long SOA was expected), participants may not have reserved sufficient resources for Task 2. Consequently, Task 2 performance should be worse with unexpected short SOAs than with expected short SOAs. On the contrary, Task 1 performance might be affected to a lesser degree by whether this short SOA was expected (Figure 1, mark 1). This seems plausible when considering two possible but opposing influences. First, Task 1 performance with unexpected short SOAs should be better than with expected short SOAs because participants withhold some resources for Task 2 in the latter case (cf. Miller et al., 2009, Figure 2). Second, reallocating resources might itself be resource consuming (for a similar speculation see e.g., Navon & Miller, 2002; Tombu & Jolicœur, 2002), with the onset of the Task 2 stimulus triggering such a resource reallocation (Mittelstädt & Miller, 2017), yielding performance decrements with unexpected short SOAs. Consequently, the overall effect of time expectancies on Task 1 is difficult to predict for short SOAs and might be comparatively small. However, it is currently unknown whether such short-term, dynamic scheduling and rescheduling of processing resources is possible in the first place, rendering the previous considerations highly speculative. Thus, the present experiments investigated whether and how participants utilize time-related contingencies in dual-tasking situations.

Experiment 1

In the first experiment, we used a simple PRP setup consisting of two visual-manual tasks with spatially separated imperative stimuli and a random task order. The identity of Task 1 predicted with 80% validity whether Task 2 would occur after a short (200 ms) or long SOA (1,000 ms). All other aspects of the tasks (task order, SOA, stimuli, and responses) were unpredictable prior to Task 1, equalizing possible preparatory processes before Task 1.

Transparency and Openness

We report all data exclusions, manipulations, and measures in the study. All data were collected in 2022. Raw data, analysis scripts, and preregistrations for all experiments are publicly available at osf.io/ug6q2.

Participants

Forty-eight participants (37 females; $M_{age} = 29.0$ years, $SD = 11.2$) were recruited online, provided written informed consent, and received monetary compensation. At an alpha of .05, this sample size provides a power of >.95 to observe effects like in Miller et al. (2009, Exp. 1, RT1 interaction, $\eta_p^2 = .29$; power computed with *BUCSS*, Anderson & Kelley, 2020) and allows for counterbalancing. Four participants were replaced due to high (>25%) error rates.

Method

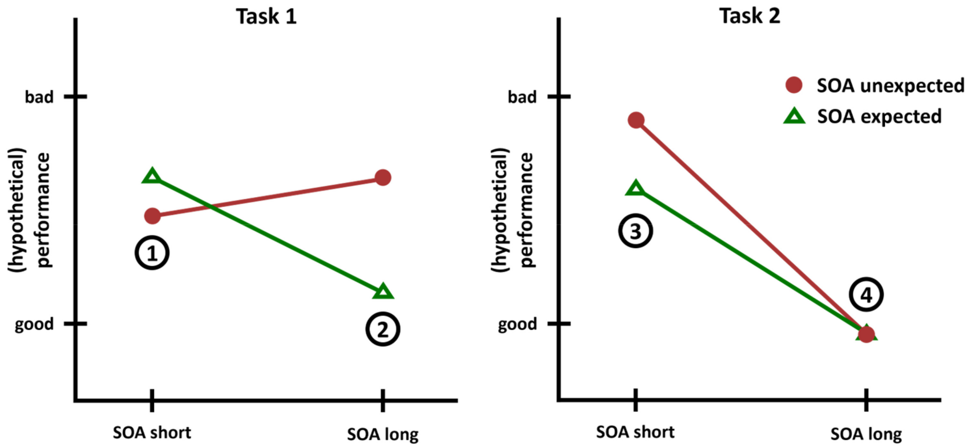
We used two visual-manual tasks, a color task and a letter task (see Figure 2). For the color task, colored squares (red vs. blue) on the left side of the screen required left-hand responses on the "S" or "D" keys. For the letter task, white letters ("H" vs. "S") on the right side of the screen required right-hand responses on the "K" or "L" keys.

Each trial started with the onset of a central fixation cross. After 500 ms, the stimulus to Task 1 appeared. Both tasks were equally likely to be Task 1 (i.e., to be presented first) and the SOA was overall equally likely short or long (200 ms vs. 1,000 ms). However, for one half of the participants, a color Task 1 was frequently (80% probability) paired with a short SOA to the letter task, and a letter Task 1 was frequently paired with a long SOA to the color task. For the other half of the participants, this probabilistic Task 1 identity – SOA length mapping was reversed. Hence, both SOAs had the same baseline probability, but participants could derive expectations about the onset of Task 2 from the identity of Task 1.

Participants were instructed to work on the tasks in the order of their presentation. Consequently, responses to Task 2 ended the trial. If responses were not given within 2,000 ms after Task 2 onset, the trial counted as omission. In case of commission errors, omission

[1] Miller et al. (2009) assume that the cognitive system determines prior to the onset of Task 1 whether resources are shared. Our design equalizes processes prior to Task 1, ruling out that possible time expectancy effects result from pretrial processes (see Method section). Thus, what we refer to as "proactive" sharing is sharing that occurs prior to the onset of Task 2, even if this sharing is influenced by Task 1 features and could in this sense be regarded as "reactive" to such Task 1 features.

Figure 1
Possible Predictions



Note. Hypothetical results for performance measures in Task 1 (left) and Task 2 (right) if participants share capacity between the tasks, depending on which SOA they expect. Green triangles represent trials with an expected SOA, whereas red points represent trials with an unexpected SOA. SOA = stimulus onset asynchrony. See the online article for the color version of this figure.

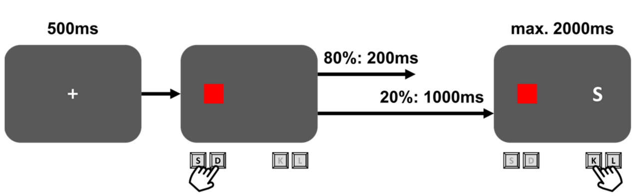
errors, or order reversal errors, appropriate feedback was displayed for 1,000 ms. Otherwise, the next trial started after 1,000 ms.

Participants completed 30 blocks consisting of 40 trials, with each combination of Task 1 identity (color vs. letter task), color stimulus (red vs. blue), and letter stimulus ("H" vs. "S") presented four times with the frequently paired SOA and once with the infrequently paired SOA. The Task 1 identity – SOA mapping and the stimulus –response mappings for both tasks were counterbalanced between participants.

Results

We reclassified Task 1 as omission error if the reaction time (RT) was larger than 2,000 ms.[2] For RT analyses, we excluded trials with errors (11.1%). The remaining trials were screened for outliers, and we removed trials in which RTs for any task deviated more than 2.5 *SD*s from the corresponding cell mean, computed separately for each participant and condition (3.9%). The final sample for RT analyses consisted of 85.0% of the original trials. Data were analyzed via 2 × 2 ANOVAs with SOA length (short vs. long) and SOA expectedness (expected vs. unexpected) as within-subjects factors (see Figure 3).

Figure 2
Trial Procedure



Note. In one task, participants responded to the color of a square by pressing the S or D key. In the other task, participants had to classify a letter by pressing the K or L key. Both tasks were equally likely Task 1, but one task was frequently paired with a short SOA, while the other was frequently paired with a long SOA. Exemplary trial with a color Task 1 and a mapping where this Task 1 identity was frequently paired with the short SOA. SOA = stimulus onset asynchrony. See the online article for the color version of this figure.

Task 1 RTs

Task 1 RTs were higher with short SOAs (755 ms) than with long SOAs (684 ms), $F(1, 47) = 11.33$, $p = .002$, $\eta_p^2 = .19$. Furthermore, Task 1 responses were faster with expected SOAs (709 ms) than with unexpected SOAs (730 ms), $F(1, 47) = 13.64$, $p = .001$, $\eta_p^2 = .22$. SOA length and expectedness interacted, $F(1, 47) = 4.57$, $p = .038$, $\eta_p^2 = .09$, with no significant influence of SOA expectedness for short SOAs, $t < 1$, and slower responses with unexpected long rather than expected long SOAs, $t(47) = 3.75$, $p < .001$, $d = 0.54$, $\Delta = 45$ ms.

Task 1 Error Rates

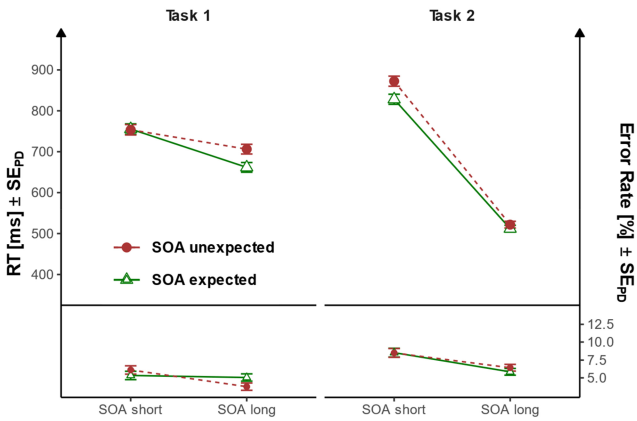
Task 1 error rates were higher with short SOAs (5.7%) than with long SOAs (4.4%), $F(1, 47) = 13.59$, $p = .001$, $\eta_p^2 = .22$. There was no significant influence of SOA expectedness, $F < 1$. SOA length and expectedness interacted, $F(1, 47) = 4.66$, $p = .036$, $\eta_p^2 = .09$, with no significant influence of SOA expectedness for short SOAs, $t(47) = 1.31$, $p = .196$, and less errors with unexpected long rather than expected long SOAs, $t(47) = 2.51$, $p = .015$, $d = 0.36$, $\Delta = 1.3\%$.

Task 2 RTs

Task 2 RTs were higher with short SOAs (850 ms) than with long SOAs (517 ms), $F(1, 47) = 448.76$, $p < .001$, $\eta_p^2 = .91$.

[2] This affected 0.5% and 2.3% of the trials in Exp. 1 and Exp. 2, respectively. While this was not preregistered, it does not change the pattern of results and allows for a direct comparison of Task 1 and Task 2 RTs as reported in footnotes 3 and 4.

Figure 3
Results of Experiment 1



Note. Response times (RTs; top) and error rates (bottom) for Task 1 (left) and Task 2 (right). Green triangles represent trials with an expected SOA, whereas red points represent trials with an unexpected SOA. Error bars denote the standard error of paired differences, computed separately for each comparison of SOA expectedness (Pfister & Janczyk, 2013). SOA = stimulus onset asynchrony. See the online article for the color version of this figure.

Furthermore, Task 2 responses were faster with expected SOAs (670 ms) than with unexpected SOAs (697 ms), $F(1, 47) = 15.86$, $p < .001$, $\eta_p^2 = .25$. SOA length and expectedness interacted, $F(1, 47) = 4.67$, $p = .036$, $\eta_p^2 = .09$, with slower responses with unexpected short rather than expected short SOAs, $t(47) = 3.59$, $p = .001$, $d = 0.52$, $\Delta = 44$ ms, and no significant influence of SOA expectedness for long SOAs, $t(47) = 1.19$, $p = .240$.

Task 2 Error Rates

Task 2 error rates were higher with short SOAs (8.5%) than with long SOAs (6.1%), $F(1, 47) = 27.25$, $p < .001$, $\eta_p^2 = .37$. All other Fs < 1.

Discussion

In Experiment 1, we observed that Task 2 performance deteriorated with decreasing SOA, showing the standard PRP effect. Moreover, Task 1 performance deteriorated with decreasing SOA as well, possibly indicating that processing resources are shared between tasks. In line, Task 2 responses were faster than Task 1 responses at long SOAs,[3] although Task 1 and Task 2 identities were counterbalanced, again suggesting that resources are reserved for Task 2 processing (Mittelstädt et al., 2022). This interpretation would align with our observation that Task 1 responses with long SOAs were slower if participants expected Task 2 to occur after the short SOA, an observation that directly follows from the assumption that resources assigned to an expected early onset of Task 2 are withheld from Task 1 processing until Task 2 eventually occurs. However, as Task 1 responses with long SOAs were also more accurate if participants expected Task 2 to occur after the short SOA, a speed–accuracy tradeoff cannot be ruled out. Thus, this interactive influence must be replicated in a second experiment before it can be interpreted. Finally, Task 2 performance was particularly affected when the SOA was shorter than predicted, whereas it was to a lesser degree or not at all affected by expectancy violations when the SOA was longer than predicted. The latter observation is in line with the idea that resources are completely devoted to Task 2 once Task 1 is completed, irrespective of initial assignments.

Experiment 2

The first experiment is promising as it provided first evidence that participants make use of the expected time point of Task 2, based on the identity of Task 1. However, the employed setup comes with a certain peculiarity. As it utilized two spatially separated, univalent imperative stimuli, the observed expectancy effects could stem from expectancy-dependent allocation of visual attention (e.g., Marcus et al., 2006; Pfeuffer et al., 2016, 2020). In other words, the effects on Task 2 may not indicate changes in central processing but rather the covert or overt allocation of visuo-spatial attention to certain screen areas. To rule out this possibility, we used a bivalent imperative stimulus in the second experiment.

Participants

Forty-eight new participants (33 females; $M_{age} = 23.7$ years, $SD = 3.5$) were recruited online, provided written informed consent, and received monetary compensation. At an alpha of .05, this sample size provides a power of $>.95$ to replicate the expectancy effect we observed in Exp. 1 for Task 1 RTs at long SOAs ($d = 0.54$). Nineteen participants were replaced due to high ($>$25%) error rates.

Method

We replaced the fixation cross by seven gray rectangles resembling the "8" of a seven-segment display. For the color task, the segments changed their color to blue or red, and for the letter task, two segments disappeared, yielding an "H" or "S." Apart from the changes to the stimuli, the procedure was exactly as in Exp. 1.

Results

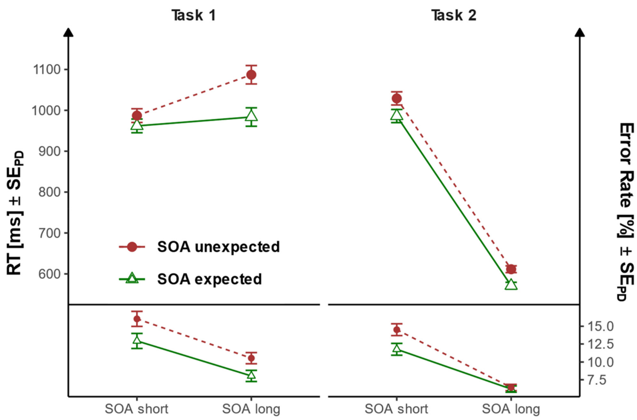
Data were treated and analyzed as in Exp. 1 (see Figure 4). After excluding trials with errors (16.1%) or outliers (3.0%), the sample for RT analyses consisted of 80.9% of the original trials.

Task 1 RTs

There was no significant influence of SOA length, $F(1, 47) = 2.47$, $p = .123$. Furthermore, Task 1 responses were faster with expected SOAs (973 ms) than with unexpected SOAs (1,037 ms), $F(1, 47) = 35.41$, $p < .001$, $\eta_p^2 = .43$. SOA length and expectedness interacted, $F(1, 47) = 5.52$, $p = .023$, $\eta_p^2 = .11$, with no significant influence of SOA expectedness for short SOAs, $t(47) = 1.51$, $p = .139$, and slower responses with unexpected long rather than expected long SOAs, $t(47) = 4.59$, $p < .001$, $d = 0.66$, $\Delta = 103$ ms.

[3] Task 1 RTs at long SOAs versus Task 2 RTs at long SOAs, collapsed across SOA expectedness: $t(47) = 6.28$, $p < .001$, $d = 0.91$, $\Delta = 157$ ms. Not preregistered.

Figure 4
Results of Experiment 2



Note. Response times (RTs; top) and error rates (bottom) for Task 1 (left) and Task 2 (right). Green triangles represent trials with an expected SOA, whereas red points represent trials with an unexpected SOA. Error bars denote the standard error of paired differences, computed separately for each comparison of SOA expectedness (Pfister & Janczyk, 2013). SOA = stimulus onset asynchrony. See the online article for the color version of this figure.

Task 1 Error Rates

Task 1 error rates were higher with short SOAs (14.5%) than with long SOAs (9.3%), $F(1, 47) = 45.85$, $p < .001$, $\eta_p^2 = .49$. Furthermore, Task 1 responses were more accurate with expected SOAs (10.5%) than with unexpected SOAs (13.3%), $F(1, 47) = 26.64$, $p < .001$, $\eta_p^2 = .36$. SOA length and expectedness did not interact, $F < 1$.

Task 2 RTs

Task 2 RTs were higher with short SOAs (1,008 ms) than with long SOAs (591 ms), $F(1, 47) = 674.71$, $p < .001$, $\eta_p^2 = .93$. Furthermore, Task 2 responses were faster with expected SOAs (779 ms) than with unexpected SOAs (820 ms), $F(1, 47) = 22.45$, $p < .001$, $\eta_p^2 = .32$. SOA length and expectedness did not interact, $F < 1$.

Task 2 Error Rates

Task 2 error rates were higher with short SOAs (13.1%) than with long SOAs (6.3%), $F(1, 47) = 179.02$, $p < .001$, $\eta_p^2 = .79$. Furthermore, Task 2 responses were more accurate with expected SOAs (9.0%) than with unexpected SOAs (10.5%), $F(1, 47) = 16.78$, $p < .001$, $\eta_p^2 = .26$. SOA length and expectedness interacted, $F(1, 47) = 5.19$, $p = .027$, $\eta_p^2 = .10$, with more errors with unexpected short rather than expected short SOAs, $t(47) = 3.32$, $p = .002$, $d = 0.48$, $\Delta = 2.7\%$, but no significant influence for long SOAs, $t < 1$.

Supplementary Analyses

One factor that can explain influences of Task 2 features (here: SOA length and SOA expectancy) on Task 1 performance is response grouping (Pashler & Johnston, 1989; Ulrich & Miller, 2008). To investigate whether our results originate from trials where participants withhold their Task 1 response until they finished preparing their Task 2 response, we reran the RT analyses for both experiments but excluded trials with interresponse intervals of less than 50 ms, 100 ms, or 150 ms (not preregistered; for similar approaches see e.g., Fischer et al., 2018; Miller & Durst, 2015; Miller et al., 2009; Mittelstädt & Miller, 2017; Tombu & Jolicœur, 2005). However, the general pattern of results was not affected (for details, see the online supplemental material), suggesting that response grouping is not the driving force behind the current results.

Discussion

Experiment 2 replicated the key findings of Experiment 1: First, short SOAs decreased the performance of both Task 2 and Task 1, though in the latter, this was only evident in error rates. Second, with long SOAs, responses to Task 2 were faster than to Task 1,[4] although the Task 1 and Task 2 identities were counterbalanced. Third, Task 1 performance suffered from violated time expectancies, and this effect was again particularly pronounced at long SOAs. Crucially, this effect at long SOAs cannot be attributed to a speed–accuracy tradeoff as it was now evident in both response times and error rates. Thus, violated time expectancies seem to be particularly detrimental for Task 1 when most of Task 1 processing occurs before Task 2 (i.e., with unexpected long SOAs), whereas an unexpectedly early onset of Task 2 (i.e., an unexpected short SOA) might possibly reallocate resources scheduled for a late Task 2 occurrence (Mittelstädt & Miller, 2017). Finally, Task 2 performance likewise suffered when Task 2 was presented at an unexpected point in time. While this detrimental influence of expectancy violations was similar across both SOAs for RTs, it was more pronounced at the short SOA for error rates. Taken together, the convergent data pattern of Exp. 1 and 2 suggests that the influence of temporal expectancies is not confined to the allocation of visuo-spatial attention, but rather seems to reflect the allocation of a more general processing resource.

General Discussion

Can the human cognitive system prepare itself to process certain tasks at certain points in time while simultaneously processing still other tasks? The present data suggest that our participants indeed prepared for the onset of Task 2 based on the identity of Task 1. This observation accords with the view that participants in PRP scenarios can share resources among two sequentially presented tasks. Yet, it seems as if resources are already reserved for specific tasks prior to the onset of the corresponding stimuli. While shifts of the sharing probability have been reported for SOA expectancies derived from a long-term timeframe (i.e., manipulated across a block of trials; Miller et al., 2009), SOA expectancies in our design could only be derived from the identity of Task 1, providing evidence that the resource allocation strategy can be adjusted on a short-term timeframe (i.e., after the trial already started).

For Task 2, this dynamic allocation seems to be particularly helpful at short SOAs, thus when task overlap is high and an allocation of

[4] Task 1 RTs at long SOAs versus Task 2 RTs at long SOAs, collapsed across SOA expectedness: $t(47) = 10.82$, $p < .001$, $d = 1.56$, $\Delta = 424$ ms. Not preregistered.

sufficient resources to Task 2 is crucial. By contrast, if the SOA is long, and Task 2 is processed after Task 1 is already completed, flexible allocation of resources becomes less relevant. For Task 1, the consequences are different though. Here, withholding resources for a Task 2 that is expected to occur early seems to be particularly detrimental at unexpected long SOAs, thus when Task 1 runs without resources that were spared for (but not used by) Task 2. By contrast, if the SOA is short, the onset of Task 2 seems to trigger a reallocation of resources (see Figure 5 for an illustration of the allocation of resources that is in line with the observed data pattern). Why, then, are resources proactively shared when they could likewise be assigned with the respective stimulus onset? If resources could be reallocated instantaneously and without costs, holding back resources would yield no beneficial effects for Task 2 and only adverse effects for Task 1. Thus, the idea of proactive resource sharing inherently assumes that reallocating resources is itself resource consuming, indicated by the expectancy effect we observed in Task 2 at short SOAs.

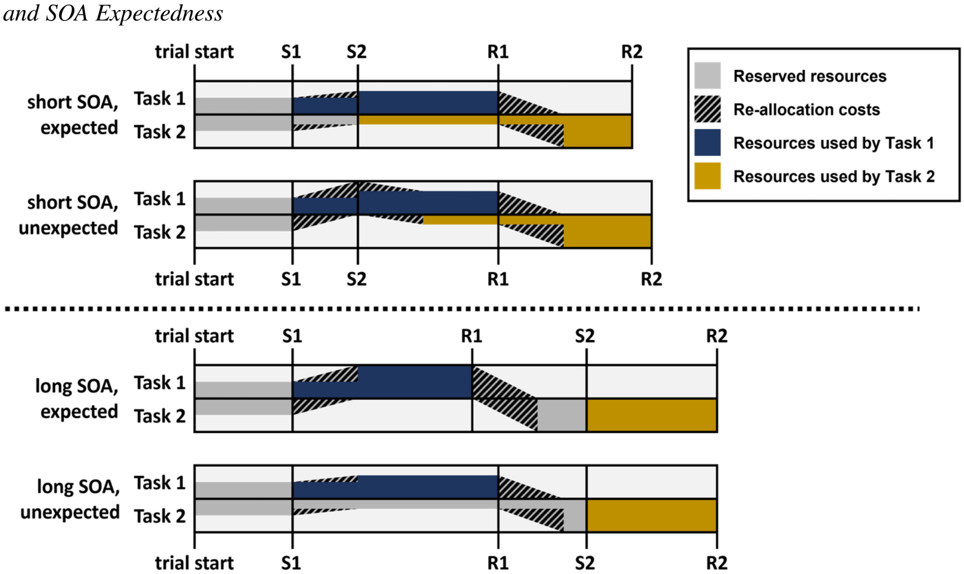
While the empirical data fit with the notion of flexible resource sharing, extensions to the structural bottleneck model can at least partly account for the observed data pattern. First, the main effect of SOA length in Task 1 might result from greater difficulty to detect the correct task order if the SOA is short rather than long (Strobach et al., 2021). In a similar vein, task order reconfiguration costs could explain why responses to Task 1 were slower than to Task 2 at long SOAs, although the task identities were counterbalanced: For Task 1, reconfiguration costs would add to the processing time at either SOA, while for Task 2, the upcoming identity can be derived from the identity of Task 1 and thus, reconfiguration can take place prior to Task 2 at sufficiently long SOAs (Pashler, 1990).

Second, the asymmetry of the expectancy effect in Task 2, that is the large influence at short SOAs and the smaller influence at long SOAs, can be explained via an updating of SOA expectancies. After all, if the stimulus of Task 2 did not appear at the short SOA, it evidently must appear at the long SOA because this is the only remaining time point (Correa et al., 2004; Coull & Nobre, 1998; Elithorn & Lawrence, 1955; Näätänen, 1970; but see Los et al., 2017). But what constitutes the functional underpinning of time expectancies in this context? Following the locus of slack logic (for further information on stage logic, see Fischer & Janczyk, 2022; Pashler, 1994), any perceptual effect in Task 2 would be swallowed into the idle time created by Task 1 processing when the SOA is short. Thus, a perceptual locus can be ruled out. Furthermore, a global increase in central processing capacity seems unlikely because Task 2 RTs were heavily affected at short SOAs, but we did not observe any influence on Task 1 RTs at short SOAs. Thus, a motor locus of the time expectancy effect, for example, via a preactivation of specific effectors (Thomaschke & Dreisbach, 2013; Volberg & Thomaschke, 2017; but see Bausenhart et al., 2006), seems most likely when upholding the assumption of a structural central bottleneck.

However, there is one phenomenon that is particularly challenging to explain without the concept of proactive resource sharing. We observed an asymmetry of the expectancy effect in Task 1, that is, a large influence at long SOAs and a smaller influence at short SOAs. Any hypothetical main effect of temporal predictions

Figure 5

Assumed (Re-)Allocation of Resources to Task 1 (Blue) and Task 2 (Yellow), Depending on SOA Length and SOA Expectedness



Note. Prior to S1, the same amount of resources is reserved for both Task 1 and Task 2 because the identity of Task 1 is unpredictable. After S1, resources are either fully allocated to Task 1 if a long SOA is expected (i.e., short, unexpected SOA and long, expected SOA) or some resources remain reserved for Task 2 if a short SOA is expected (i.e., short, expected SOA and long, unexpected SOA). Hatched areas denote a resource-consuming reallocation process of fixed length. Once Task 1 is complete, resources can be fully (re-)allocated to Task 2. Reallocation conceivably also takes place if a long SOA is expected but S2 appears after a short SOA (i.e., short, unexpected SOA). S1 and S2 denote the first and second stimuli, R1 and R2 the respective responses. Pre- and postcentral stages are omitted for simplicity. SOA = stimulus onset asynchrony. See the online article for the color version of this figure.

in Task 1 could be interpreted as costs arising from a generic *stop* signal that is issued after detecting an expectancy violation (Wessel, 2018; Wessel et al., 2012) which would lead to an interruption of Task 1 processing. Yet, the finding that the unexpected absence of a stimulus leads to more pronounced effects than the unexpected presence of a stimulus seems difficult to reconcile with an all-or-none allocation of resources.

While the question of whether (and how) a general central resource might be shared between tasks was the primary motivation of the present experiments, our results might also be informative for alternative accounts of multitasking like those revolving around motor bottlenecks (Bratzke et al., 2009; De Jong, 1993; Klapp et al., 2019; Ulrich et al., 2006) or between-task interference (Hazeltine et al., 2006; Logan & Gordon, 2001; Navon & Miller, 1987; Schacherer & Hazeltine, 2021). In the latter context, the increased response latencies of Task 1 might not reflect higher resource sharing (i.e., increased parallel processing), but rather costs associated with task shielding (i.e., decreased parallel processing). Albeit speculative, this would accord with previous research suggesting that between-task crosstalk is reduced when the stimuli of Task 1 predict a short SOA (Fischer & Dreisbach, 2015).

Thus, from a theoretical view, resource sharing is a parsimonious model capable of explaining the observed data pattern, but other models can likewise explain selective aspects of our results. What we can safely conclude, though, is that our results rest on the contingency between the Task 1 identity and the Task 2 time point of occurrence, as all other aspects of the dual-task setting (SOA, stimuli, responses, task order) were unpredictable prior to Task 1. This raises at least two further questions: First, which component of Task 1 serves as indicator for time expectancies? Since we found influences of expectancy violations even at short SOAs of 200 ms, it is likely that it is an early accessible component of Task 1 (e.g., its stimulus or its specific processing requirements), whereas later components of Task 1 (e.g., its response) appear less likely. Second, can this contingency be used in the reversed direction? In other words, while a certain task identity predicted a certain SOA in our design, PRP setups where a certain SOA predicts the occurrence of a certain task identity seem promising for future research (see, e.g., Aufschnaiter et al., 2018, 2020; Jurczyk et al., 2021 for such work in the context of task switching).

To conclude, we found that humans benefit from knowing when a second task occurs, based on the identity of the task they ought to do first. One possible explanation revolves around the flexible allocation of processing resources. While this is not the only possible explanation of this interesting phenomenon, the observed time expectancy effect challenges the notion of a structural, serial bottleneck of information processing. Thus, we believe that our results can serve as a fruitful foundation for further inquiries that dissect the theoretical origins of why doing two things simultaneously is hard.

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