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The cognitive load effect in working memory: Refreshing the empirical landscape, removing outdated explanations

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ABSTRACT

Maintaining information in working memory often competes with concurrent processing of other information. This is reflected in the cognitive load effect, referring to the observation that processing tasks with a higher cognitive load result in lower memory performance. The cognitive load effect has been shown on many occasions in complex span tasks, which combine maintenance of memory items with a processing demand interleaved in between the presentation of the memory items. Two models of working memory, the Time-Based Resource-Sharing (TBRS) model, and the Serial Order in a Box – Complex Span (SOB-CS) model, offer competing explanations for the cognitive load effect. Both lead to the prediction that a cognitive load effect should also be found in the Brown-Peterson task, in which the processing demand is inserted after the presentation of all of the memory items. Across three experiments, we show that (1) the cognitive load effect is consistently larger in the complex span task than in the Brown-Peterson task, and (2) the cognitive load effect is mostly absent in the Brown-Peterson task, with one exception. The current versions of the TBRS and SOB-CS models cannot account for these findings. We discuss what new assumptions are necessary for these models to explain our findings and consider alternative accounts explaining the current observations purely in terms of free time instead of cognitive load.

Introduction

Working memory refers to the capacity to simultaneously maintain and process information over short periods of time. One of the first models of working memory was introduced by Baddeley and Hitch (1974), and has boosted research on the interplay between concurrent processing and storage activities. This research has mostly investigated tasks in which the short-term maintenance of a memory set is combined with an independent processing demand in the retention interval. The two main variants of this dual-task paradigm are the complex span task (e.g., Conway et al., 2005; Daneman & Carpenter, 1980; Turner & Engle, 1989) and the Brown-Peterson task (Brown, 1958; Geurten, et al., 2016; Peterson & Peterson, 1959). These two kinds of tasks differ in the temporal relation between encoding of the memory set and the processing demand, as illustrated in Fig. 1: Whereas in the complex span task, brief processing episodes are interleaved with the presentation of the memory items, in the Brown-Peterson task a single processing episode follows the presentation of the entire memory list.

Typically, conclusions of studies using these two tasks converge, supporting the idea that both tasks tap into the same working memory processes. For example, both tasks have shown that memory performance decreases when a processing task is added in the retention interval, compared to a task version without any processing demand (e.g., Barrouillet, et al., 2009; Jarrold, et al., 2011), and that working memory capacity increases with children's age (e.g., Barrouillet et al., 2009; Oftinger & Camos, 2018). The two tasks have also shown analogous effects of word length and phonological similarity when the memory items are words (e.g., Tehan, et al., 2001).

However, when it comes to the question of how and why storage and processing affect each other in working memory (e.g., Bayliss, et al., 2003; Doherty & Logie, 2016; Vergauwe, et al., 2010), studies using either the Brown-Peterson tasks or the complex span tasks have reached different conclusions on several occasions (e.g., Ricker & Vergauwe, 2022; Wang, et al., 2015). The divergence of the observations between the two tasks raises the question whether memory maintenance and processing interact with each other in the same way in the two tasks.

One effect that has been studied using both tasks to examine the interplay of storage and processing in working memory is the *cognitive*

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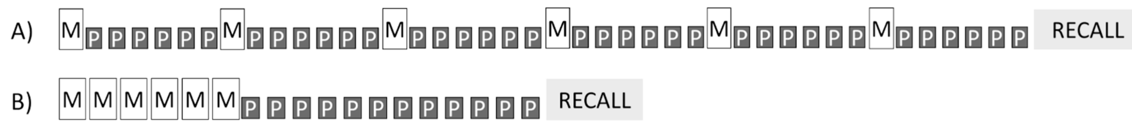

Fig. 1. Schematical representation of a typical example of a complex span task (Panel A) and a Brown-Peterson task. (Panel B). M represents a memory item, P represents a processing operation.

load effect (Barrouillet, et al., 2004; Barrouillet & Camos, 2001). This effect refers to the observation that when the attentional demand of a concurrent processing task per unit time increases, memory performance decreases. Specifically, cognitive load is defined as the ratio of time during which the processing task demands central attention (Navon & Miller, 2002; Pashler, 1994) to the time available for the processing task: cognitive load = aN/T, where a is the duration during which each operation demands central attention (i.e., a domain-general processing resource), N is the number of processing operations during a processing episode, and T is the total duration of the processing episode. Hence, the cognitive load can be varied in three ways: Manipulating the duration of processing operations, the number of operations, or the free time after each processing operation, holding the other two variables constant. The cognitive load effect has been observed on many occasions, crossing processing operations and maintenance items from different domains (e.g., Barrouillet et al., 2004; Barrouillet, et al., 2011; Vergauwe, et al., 2009; Vergauwe et al., 2010).

There are currently two theories of working memory that offer explanations of the cognitive load effect. They share the assumption of a memory restoration process that can only be carried out while attention is not engaged by the distractor processing demand. As such, while attention is used for the processing task, it is not available for memory restoration, resulting in poorer memory performance. The two explanations differ in the nature of the memory-restoration process. On the one hand, Barrouillet et al. (2004) proposed the Time-Based Resource-Sharing (TBRS) model, according to which memory traces decay over time when attention is diverted to the processing task, and during the short moments of free time after each processing operation, an attentional maintenance mechanism called refreshing is applied to restore the memory traces (e.g., Barrouillet, et al., 2007; Barrouillet & Camos, 2015). Refreshing refers to the act of focusing attention on the working-memory representations of the memory items, that is, thinking back of these items to increase their activation (see Camos et al., 2018, for a recent review), with increased memory performance as a result. On the other hand, Oberauer et al. (2012) proposed a different explanation of the cognitive load effect within their Serial Order in a Box – Complex Span (SOB-CS) model. In SOB-CS, the processing task engages representations that are involuntarily encoded into working memory, so that they interfere with the representations of the memory set. During free time, central attention is used to remove the representations related to the processing task, thereby reducing interference and increasing memory performance.

While the cognitive load effect has been replicated numerous times, it has mainly been demonstrated in studies using the complex span task (e.g., Barrouillet et al., 2004; Langerock, et al., 2014; Vergauwe et al., 2010). It has less often been investigated with the Brown-Peterson task, and has resulted in a more variable outcome in these cases. While there are studies that report a cognitive load effect in a Brown-Peterson task (e.g., Liefooghe et al., 2008; Vergauwe, Langerock et al., 2014), several other studies using the Brown Peterson task did not observe a cognitive load effect, or in a less convincing way than in complex span tasks. For example, Ricker and Vergauwe (2020) presented four experiments using a Brown-Peterson task, of which none demonstrated a cognitive load effect. Souza et al. (2018) also presented several experiments (in their supplementary materials) using the Brown-Peterson task that did not show any evidence for a cognitive load effect. Other studies did observe a cognitive load effect when using a Brown-Peterson task, yet a closer inspection of the results often shows the effect to be variable across conditions without clear theoretical assumptions as to why that should be the case (e.g., Oftinger & Camos, 2018). And yet other studies show the cognitive load effect to be less pronounced in the Brown-Peterson task than in the complex span task when applying similar task parameters across different experiments or studies. For example, Langerock et al. (2014) did observe a cognitive load effect with a Brown-Peterson task, but this effect was much smaller when compared to the cognitive load effect they had observed in a similar experiment using a complex span task with similar maintenance and processing materials, similar presentation times, and similar cognitive load manipulations (Langerock et al., 2014). Ricker and Vergauwe (2022) similarly showed that across different experiments, similar experimental conditions resulted in a cognitive load effect in the complex span task but not in the Brown-Peterson task. We could find only one study that compared the cognitive load effect in the complex span and the Brown-Peterson task within subjects. Wang et al. (2015) observed a cognitive load effect in both tasks but the cognitive load effect was substantially smaller in the Brown-Peterson task than in the complex span task (partial η^2 = .11 vs.50 respectively). The authors concluded that the processing demand has almost no effect on memory performance in the Brown-Peterson task, whereas it has a more substantial effect in the complex span task (although one should note that the interaction had not been tested statistically).

In summary, while the cognitive load effect has been observed occasionally in Brown-Peterson tasks too, the effect does not appear to be as robust in this type of task. Compared to the cognitive load effect in complex span tasks, the cognitive load effect appears to be substantially reduced, and perhaps eliminated, in the Brown-Peterson task. The lack of clear and consistent evidence for cognitive load effect in the Brown-Peterson paradigm is problematic for both theories that offer explanations of the cognitive load effect.

Both the TBRS model and the SOB-CS model predict a cognitive load effect for the Brown-Peterson paradigm. In the TBRS model, lower cognitive load provides more opportunity to refresh the memory list that has been encoded before the processing episode, which is at risk of decaying during processing. Simulations with TBRS*, a computational implementation of the TBRS theory, confirm that the theory predicts a substantial cognitive load effect for the Brown-Peterson paradigm (Oberauer & Lewandowsky, 2011, Figure 20). The SOB-CS model has not yet been applied to the Brown-Peterson paradigm, but Oberauer and Lewandowsky (2016) have applied it to a very similar experiment, in which a series of processing operations preceded rather than followed encoding of the memory list. They assumed that all representations involved in a trial – the memory items and the distractor representations used in the processing task – are bound to context representations that have a component in common (i.e., the trial context). This partial context overlap explains how distractor representations interfere with memory representations – an assumption that is necessary for SOB-CS to explain why distractor processing impairs memory in the Brown-Peterson paradigm. Lower cognitive load provides more opportunity to remove distractor representation from their context, including the context that they share with the memory items. This should reduce the interference between distractor processing and memory. Simulations by Oberauer and Lewandowsky (2016) demonstrate that SOB-CS predicts a cognitive load effect for distractor processing that precedes encoding of a memory list. Because interference in SOB-CS is symmetric, the same prediction applies for the Brown-Peterson paradigm in which distractor processing follows memory encoding.

To conclude, the existing literature on the cognitive load effect in the Brown-Peterson task calls into question the two currently available explanations for the cognitive load effect, and with them, the underlying assumptions about the relation between storage and processing in working memory. The present study was designed to better understand this relation between storage and processing, by varying a number of parameters that seemed to have an influence on it.

The present study

The goal of the present study was to directly compare the cognitive load effect in complex span and Brown-Peterson tasks, under varying task parameters. We started with a within-subject comparison of the cognitive load effect in the two tasks in Experiment 1. To anticipate the results, the cognitive load effect was indeed found to be different between the tasks, and we found evidence for a cognitive load effect in the complex span task yet evidence against a cognitive load effect in the Brown-Peterson task. Next, Experiments 2 and 3 were run in parallel to investigate where this difference in the cognitive load effect between the two tasks might come from. In particular, we investigated the role of the total processing duration in Experiment 2. In Experiment 3 we compared the effect of free time in between the presentation of the memory items (as in complex span tasks) and after the presentation of all memory items (as in Brown-Peterson tasks), with and without a processing demand. To foreshadow the results, Experiment 2 showed that the complex span task consistently resulted in a cognitive load effect, independently of the total processing duration, whereas the Brown-Peterson task only resulted in a cognitive load effect in combination with a longer total processing duration. Moreover, when the Brown-Peterson task did show a cognitive load effect, it was still less pronounced than in the complex span task. Using a manipulation of cognitive load through free time, Experiment 3 showed again evidence for a cognitive load effect in the complex span task and evidence against that effect in the Brown-Peterson task. Additionally, the results suggest that free time operates in a similar way when no processing task is present.

None of the experiments was preregistered. The raw data for all included experiments, as well as the code used to analyze these data, can be found on the Open Science Framework (https://osf.io/swdqu/).

Experiment 1

The goal of this experiment was to test whether the cognitive load effect is indeed more pronounced in a complex span task than in a Brown-Peterson task. Therefore, we ran a complex span and a Brown-Peterson task, using the same, fairly standard, processing tasks, processing durations, memory items and memory presentation durations in both tasks, aiming to minimize methodological differences that go beyond the inherent, structural differences between these two tasks. Participants had to maintain letters, combined with a tone discrimination task. This processing task has often been used as a domain-neutral processing task (e.g., Elsley & Parmentier, 2009; Imbo, et al., 2007; Langerock et al., 2014) as its stimuli have little overlap with either verbal or spatial memory items. In the complex span task, the presentation of each letter was followed by a processing episode including several tones to be discriminated, and the letters were to be recalled in correct order after the final processing episode. In the Brown-Peterson task, all letters were presented one after the other, followed by a single processing episode including several tones to be discriminated. After this processing episode, the letters had to be recalled in their correct order (see Fig. 1 for a schematic representation of these two paradigms). In both tasks, the cognitive load of the processing task was manipulated by increasing the number of processing operations to be executed within a fixed amount of time. With regards to the formula of the cognitive load given in the introduction, this comes down to increasing N while keeping a and T constant.

Method

Participants and design

Fifty-three undergraduate students (49 females, 4 males, M age = 21.92 years old, SD=5.79) of the University of Geneva participated in this experiment,[1] in exchange for course credits. This number is higher than in other similar studies (e.g., Barrouillet et al., 2004; Liefooghe et al., 2008; Souza et al., 2018) and has been obtained after running 2 batches of data collection. We started with 41 participants in batch 1 and increased until 53 in batch 2, to obtain more conclusive evidence about the interaction of interest between task and cognitive load. Task (complex span vs. Brown-Peterson) and Cognitive Load (low vs. high) were manipulated within subjects. The experiment was approved by the ethical committee of the Faculty of Psychology and Educational Sciences of the University of Geneva. All participants signed an informed consent before starting the experiment.

Material

Participants had to memorize a series of six letters (memory task) and perform a tone discrimination task (processing task). The letters were drawn with equal probability from a pool of 18 possible consonants (W, Y and Z excluded), without repetition within a series. Capital letters were presented in Courier new font 32, in the middle of the computer screen. In the processing task, participants were presented with a series of tones and had to decide for each tone, presented through a headphone during 200 ms, whether it corresponded to a low (262 Hz) or a high (524 Hz) frequency tone by pressing keys (A and L, for low vs. high tones, respectively). Both tones had equal probabilities of being presented at each time.

Procedure

The experiment was run in person on a computer using Open Sesame (Mathôt, et al., 2012). There were two experimental blocks, each preceded by a training block. One experimental block used the complex span task and the other used the Brown-Peterson task; their order was counterbalanced across participants. The two experimental blocks contained 12 trials each, six of a low cognitive load and six of a high cognitive load, randomly intermixed. In total, there were hence 24 experimental trials.

Each experimental trial started by indicating the cognitive load condition: "lent" (French for "slow") for the low cognitive load trials, and "rapide" (French for "fast") for the high cognitive load condition trials. Next, participants initiated the trial by pressing ENTER. Upon this, a fixation asterisk was shown on screen for 500 ms, followed by the first memory item for 750 ms, which was followed by a blank screen for 250 ms. What happened next depended on the task (see Fig. 2).

In the complex span task, the first memory item and its accompanying 250 ms blank interval were followed by a processing episode of 6000 ms during which either three or six tones were to be discriminated, in the low and the high cognitive load conditions, respectively (i.e., one tone every 2000 ms vs. one tone every 1000 ms, respectively). After this first processing episode, a second memory item was displayed for 750 ms, followed by a blank of 250 ms, which was followed by a second processing episode of 6000 ms with three or six tones, and so on, until all six memory items and processing episodes had been presented. After the sixth processing episode, the word "RAPPEL" (French for "recall") appeared and participants had to type the correct letters in the correct order using the keyboard. Participants were encouraged to guess if they did not remember certain letters, so that the remaining letters would be

[1] This is the number of participants before applying performance-based exclusion criteria.

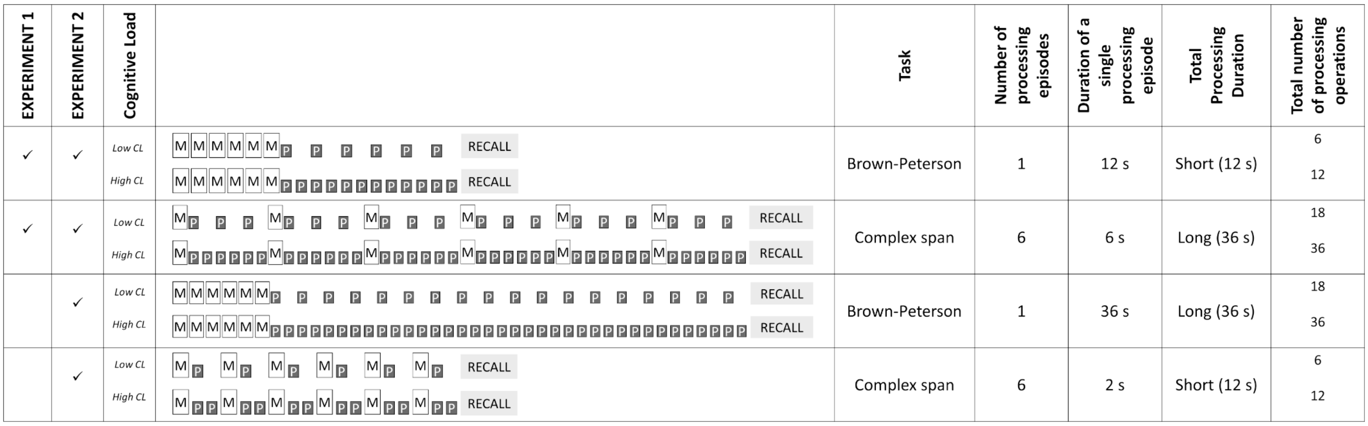

Fig. 2. Example of the different trials of the Brown-Peterson task and the complex span task as used in Experiments 1 and 2. M refers to memory item; P refers to processing operation; CL refers to cognitive load.

in their corresponding serial position. The letters were presented on screen, and pressing ENTER validated participants' responses. Corrections were allowed when ENTER had not been pressed yet.

In the Brown-Peterson task, after the fixation asterisk, all six memory items were shown sequentially for 750 ms, each followed by a blank screen of 250 ms. Then, a single processing episode of 12 s started, during which either six or twelve tones were to be discriminated, in the low and the high cognitive load conditions, respectively (i.e., 1 tone every 2000 ms vs. 1 tone every 1000 ms, respectively, keeping the cognitive load manipulation identical between the two tasks). This single processing episode was followed by the recall phase, which was identical to the one of the complex-span task.

The experimental trials were preceded by a training block. First, participants were trained on the tone discrimination task until they reached an accuracy score of 80 % using a fast presentation rate (i.e., one tone every 1000 ms). After each cycle of 10 tones, their accuracy was evaluated. If they had reached the 80 % criterion, the training moved on. If not, participants had to redo a cycle of 10 tones, with a maximum of 5 repeated cycles after which the training moved on anyhow. Next, participants received the instructions regarding the task they were to perform in the first experimental block, followed by two training trials (one in the low and one in the high cognitive load condition). Next, they performed the first experimental block. After this first experimental block, participants received the instructions regarding the task to be performed in the second block as well as two training trials (one of each cognitive load condition), before performing the second experimental block.

Results

The data and code of this analysis are available on OSF (https://osf.io/swdqu/).

Performance-based exclusions

We applied two different performance-based exclusion criteria to our dataset, which led to convergent data patterns. The first exclusion criterion was the strictest and aimed to make sure to analyze data only of those participants who performed the processing task very accurately (80 %), a criterion that is often used in this kind of paradigms (e.g., Vergauwe et al., 2010). This exclusion criterion was determined beforehand for Experiments 1 and 2, and then applied in the same way to Experiment 3. Participants were excluded if their overall processing accuracy (unweighted over task or cognitive load conditions) fell below 80 %, as well as those for whom the processing accuracy fell below 70 % in either the complex span or the Brown-Peterson task. This strict criterion led to excluding the data of 10 participants and concerns hence 19 % of the participants. The second and more lenient exclusion criterion aimed to include as much data as possible. Therefore, we aimed to include all participants who actively engaged with the task demands, operationalized as performing at least just-above chance. Participants were excluded if their processing accuracy fell below 55 % in either the complex span or the Brown-Peterson task. This lenient criterion allowed to keep all participants in Experiment 1. For both exclusion criteria, we also planned to exclude participants having a mean recall performance below at least one memory item recalled in its correct serial order in both tasks, but this did not apply to any of the participants in this experiment. Mean accuracy for the processing task was high after applying either the strict or lenient criterion: 88 and 84 %, respectively, for the complex span task, and 90 and 87 %, respectively, for the Brown-Peterson task.

Analyses

Analyses were done in R (R Core Team 2017), using Bayes factors for hypothesis testing. Bayes factors (BF) provide evidence in favor of or against a hypothesis, quantifying the evidence in favor of a statistical model representing the hypothesis over a model representing its negation. BF_{10} gives the evidence in favor of a hypothesis while BF_{01} represents the evidence against this hypothesis. The higher the BF, the more evidence there is *in favor* or *against* the hypothesis. As a guideline, Bayes Factors are considered weak between 1 and 3, moderate between 3 and 10, and strong above 10 (Schönbrodt & Wagenmakers, 2018), although a continuous interpretation of the Bayes Factors is recommended.

Bayesian logistic mixed-effects models were applied to the data using the *brm* function from the brms package in R (Bürkner, 2017). Data were analyzed on the level of individual trials. The model predicted the number of letters recalled in their correct serial position in each trial (ranging from 0 to 6) through a binomial distribution, linked to the regression model through a logistic link function. We estimated the full model including fixed effects and random effects for all predictor variables and their interactions, together with a random intercept. All predictor variables were z-standardized so that effect sizes are on a standard effect-size scale. Priors for effect sizes (i.e., regression coefficients) were logistic distributions with location = 0 and scale = 0.75. We chose these priors because they were only mildly informative and at the same time reflect the general prior knowledge that smaller effect sizes are more frequent than larger ones.[2] We estimated the BF for each fixed effect in

[2] When effect sizes are sampled from a logistic distribution with scale = 1, and these effects are added to an intercept of 0 on the logit scale, the distribution of predicted probabilities is uniform. With the reduced scale, probabilities at the extremes are given relatively lower priors.

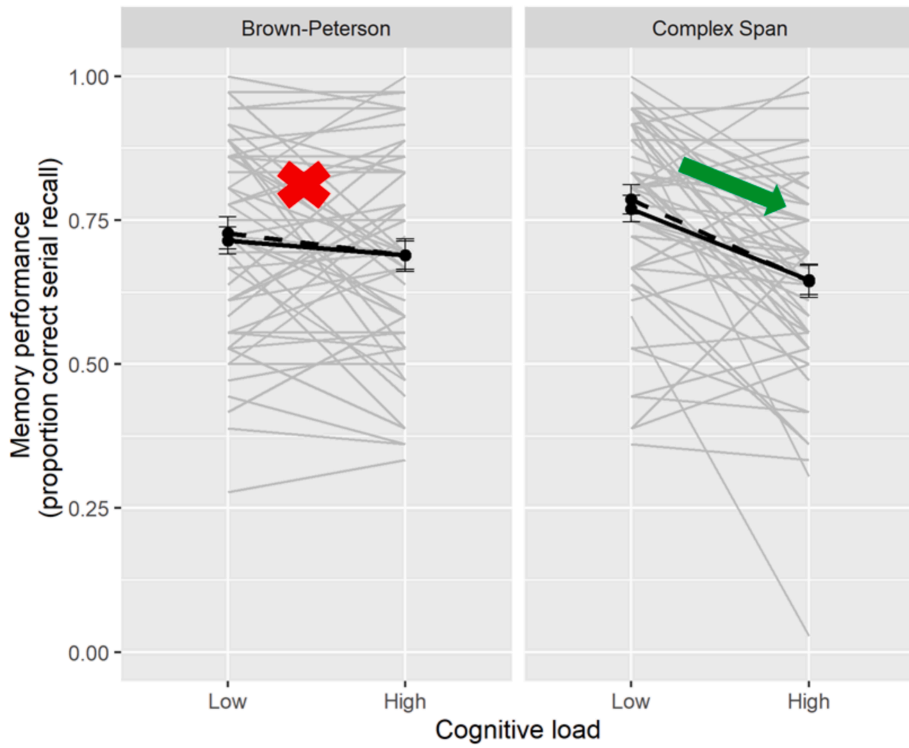

Fig. 3. Mean memory performance observed in Experiment 1, as a function of Task and Cognitive Load condition. Dotted lines correspond to the strict exclusion criterion while full lines correspond to the lenient exclusion criterion. Error bars represent the standard error of the mean. The thin grey lines represent the individual scores of all participants who passed the lenient exclusion criterion. An arrow indicates evidence in favor of a cognitive load effect, while a cross indicates evidence against a cognitive load effect. Filled symbols (green arrow or red cross in the color version) indicate a BF≥3, with a green arrow indicating evidence in favor and a red cross indicating evidence against the effect. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the data through the Savage-Dickey method (Wagenmakers et al., 2010). We report BF_{10} as the strength of evidence in favor of an effect. In cases where the evidence goes against the effect in question, we report its inverse, BF_{01}, in the text. The tables always report BF_{10}, and values < 1 indicate evidence against an effect.

First, we tested for the presence of a cognitive load effect in each task separately through a logistic model with Cognitive Load (low vs. high) as the only fixed effect. This was followed by a comprehensive model including Task (complex span vs. Brown-Peterson) and Cognitive Load (low vs. high) as predictors. Of specific interest in this latter logistic regression is the interaction between task and cognitive load, as a test of our hypothesis that the cognitive load effect is more pronounced in complex span tasks than in Brown-Peterson tasks.

Fig. 3 shows a clear disruptive effect of increased cognitive load in the complex span task, but not in the Brown-Peterson task. The logistic regressions performed on both tasks separately confirmed this pattern. In the complex span task, there was very strong evidence for a cognitive load effect, both when applying the strict or the lenient exclusion criterion ($BF_{10} = 1.8 * 10^3$ and $3.2 * 10^3$, respectively), whereas in the Brown-Peterson task there was moderate to strong evidence *against* a cognitive load effect ($BF_{01} = 5.6$ and 11, respectively).

An overview of the general logistic regression with the factors Task and Cognitive Load can be found in Table 1. There was evidence for the predicted interaction between task and Cognitive Load according to the strict and lenient criteria, though modest in strength ($BF_{10} = 3.0$ and 6.6, respectively).

Table 1
Bayes Factors for each fixed effect from the general logistic regression in Experiment 1.

Effect	BF in favor of fixed effect (according to the strict / lenient criterion)
Cognitive Load*Task	3.0/ 6.6
Cognitive Load	180 / 81
Task	.071 /.058

Discussion

The first experiment shows that the cognitive load effect is larger in the complex span than in the Brown-Peterson task. Moreover, whereas we observed very strong evidence for a cognitive load effect in the complex span task, we observed evidence *against* an effect of cognitive load in the Brown-Peterson task. The results are highly similar between the strict and more lenient criterion we applied for the performance-based exclusions, suggesting that effects observed for participants who performed very well on the processing task can be generalized to all participants who actively engaged with the task demands.

In the next two experiments, we aimed to replicate this pattern of results, while at the same time exploring what might cause this divergence between the two tasks. Experiment 2 examined the role of the total processing duration in the two tasks. In Experiment 1, we used a duration of six seconds per processing episode in the complex span task. Processing episodes in the complex span task often range between four and eight seconds (e.g., Barrouillet et al., 2004; Chein, et al., 2011;

Hudjetz & Oberauer, 2007; Langerock et al., 2014; Vergauwe, et al., 2010). For the Brown-Peterson task, we used a single processing episode of 12 s, which is also fairly typical (e.g., Jarrold, et al., 2011; Klauer & Zhao, 2004; Ricker & Cowan, 2014; Vergauwe, Camos, et al., 2014). As a result, the total processing duration on any given trial in Experiment 1 was 6 x 6 s = 36 s in the complex span task, but only 12 s in the Brown-Peterson task. It could be that the cognitive load effect becomes more pronounced at longer total processing durations. This hypothesis was tested in Experiment 2, which was a direct follow-up of Experiment 1 and was also run at the University of Geneva.

In parallel, and without prior knowledge of the existence of Experiments 1 and 2, Experiment 3 was run at the University of Zurich. Experiment 3 examined again the cognitive load effect in a complex span task and a Brown-Peterson task, this time by manipulating the amount of free time after each processing item (as opposed to manipulating the number of processing items per processing phase). Moreover, Experiment 3 included additional analogous conditions in which free time was manipulated but in the absence of a processing demand. This was done to explore the role of distractor processing for the cognitive load effect. The two current theoretical accounts of the cognitive load effect both explain the effect in terms of damage occurring during the processing task that needs to be undone by restoration during the subsequent free time. Comparing variations in free time when combined with or without a processing task should inform us about how crucial the role of this processing demand is in explaining the cognitive load effect.

Experiment 2

The goal of this second experiment was to test whether the cognitive load effect increases with a longer total processing duration. To this end, we varied the Total Processing Duration (short: 12 vs. long: 36 s) independently of the Task (complex span vs. Brown-Peterson) and the Cognitive Load (low vs. high).

Method

Participants and design

Fifty-two undergraduate students (45 females, 7 males, M age = 21.96 years old, SD=4.70) of the University of Geneva participated in this experiment, in exchange for course credits. This number is similar to Experiment 1 and was also obtained from two batches of data collection (batch 1: 20 participants; batch 2: 32 participants). Task, Cognitive Load, and Total Processing Duration were all manipulated within subjects. The experiment was approved by the ethical committee of the Faculty of Psychology and Educational Sciences of the University of Geneva. All participants signed an informed consent before starting the experiment.

Material and procedure

The same tasks and the same memory and processing materials were used as in Experiment 1, as well as the same presentation rates for the memory items and processing operations. One minor change was made for the recall: instead of guessing a letter if participants did not remember, they could put an asterisk. The experiment was run on a computer using E-prime (Schneider, et al., 2002). Experiment 2 started with a training block, followed by two experimental blocks defined by the task used: the complex span task or the Brown-Peterson task. The order of these two experimental blocks was counterbalanced across participants. Each experimental block consisted of 20 trials, presented in two subblocks of 10 trials between which the total processing duration (short vs. long) was varied. Each of these subblocks comprised 5 trials with a low and 5 trials with a high cognitive load, randomly intermixed. In total, each participant thus performed 40 experimental trials. In both experimental blocks, the order of the subblocks (short vs. long) was counterbalanced across participants.

The experimental trials used the same structure and parameters as in Experiment 1. Memory items were again presented 750 ms on screen followed by a blank screen for 250 ms. The presentation rate of the tone discrimination task also remained the same, i.e. 2000 ms per tone in the low and 1000 ms per tone in the high cognitive load condition. Fig. 2 shows an overview of the different experimental trials according to the eight different experimental conditions (2 Tasks x 2 Cognitive Loads x 2 Total Processing Durations).

The long version of the complex span task was the same as in Experiment 1. The short version of the complex span task used processing episodes lasting only two seconds instead of six. To keep cognitive load constant across manipulations of Task and Total Processing Duration, only one processing operation was presented per processing episode in the low cognitive load condition (i.e., 1 tone every 2000 ms), and two processing operations per processing episode in the high cognitive load condition (i.e., 1 tone every 1000 ms) in the short version of the complex span task.

The short version of the Brown-Peterson task was the same as in Experiment 1. The long version of the Brown-Peterson task used a single processing episode of 36 s instead of 12 s. To keep cognitive load constant across manipulations of Task and Total Processing Duration, 18 tones were presented in the low cognitive load condition (i.e., 1 tone every 2000 ms), and 36 tones in the high cognitive load condition (i.e., 1 tone every 1000 ms) in the long version of the Brown-Peterson.

The initial training block was the same as in Experiment 1. The first experimental block was still preceded by two training trials (one low and one high cognitive load; as in Experiment 1) while the next three experimental blocks were now preceded by only one training trial (high cognitive load). The instruction between two blocks of the same Task in Experiment 2 only stated that everything would be the same except for the total duration of the trial.

Results

The data and code of this analysis are available on OSF (https://osf.io/swdqu/).

Performance based exclusions

The same strict and lenient exclusion criteria were used as in Experiment 1. Twenty-six participants passed the strict exclusion criterion and forty-four participants passed the more lenient criterion. The number of participants reaching the criteria is lower than in Experiment 1.[3] None of the participants had to be excluded based on their mean memory performance being below one item. The mean accuracy scores for the tone discrimination task corresponded to 86 and 79 % with the strict and lenient exclusion criterion, respectively, for the complex span task, and 91 and 85 %, respectively, for the Brown-Peterson task.

Analyses

Recall performance was scored as in Experiment 1 by the number of letters recalled in their correct positions in each trial. We analyzed the data as in Experiment 1 through logistic mixed-effects models. We first tested the effect of cognitive load separately for each combination of task and processing duration. Next, we ran a 2 (Task: Complex span vs.

[3] In the first batch of 20 participants, responses on the processing task were not recorded during the last 250 ms of the time window, with missing responses counting as incorrect. This was corrected in batch 2. Additionally, Experiment 2 took almost twice as long as Experiment 1, which may have caused drops in alertness. Finally, the tone judgment is easier to perform if a different tone precedes the to-be-judged tone. In the newly added complex span condition with the short total processing duration, each processing phase includes only one or two tones, which makes it rather rare that another tone differing from the one to be judged precedes, reducing performance in this condition. Each of these factors probably contributed to overall lower processing accuracy in Experiment 2.

Table 2
Bayes Factors for each fixed effect from the general logistic regression in Experiment 2.

Effect	BF in favor of fixed effect (according to the strict / lenient criterion)
Cognitive Load*Task	.48 / 735
Cognitive Load*Duration	.58 /.51
Task*Duration	.12 /.035
Cognitive Load*Task*Duration	.066 /.031
Cognitive Load	$4.9*10^8$/ $3.3*10^{19}$
Task	.12 /.11
Duration	.11 /.090

Brown-Peterson) x 2 (Cognitive Load: low vs. high) x 2 (Total Processing Duration: short vs. long) Bayesian logistic regression analysis. Our main interest in this latter analysis concerned the interaction between Task and Cognitive Load, as well as the interactions between Cognitive Load and Total Processing Duration and the triple interaction between Task, Cognitive Load, and Total Processing Duration.

Fig. 4 shows cognitive load effects in the complex span task at each processing duration, whereas in the Brown-Peterson task only the long total processing duration seems to result in a cognitive load effect. The analyses per task and duration condition show very strong evidence for a cognitive load effect in the complex span task, both for the short total processing duration ($BF_{10} = 450$ and $1.4 * 10^6$ for the strict and lenient exclusion criterion, respectively) and for the long duration ($BF_{10} = 2.8 * 10^4$ and $4.3 * 10^{13}$, respectively). In the Brown-Peterson task, there was moderate evidence *against* a cognitive load effect in the short total processing duration condition ($BF_{01} = 7.7$ and 7.1, respectively), whereas there was strong evidence in favor of a cognitive load effect in the long duration condition ($BF_{10} = 33$ and 28, respectively).

An overview of the Bayes factors from the full model can be found in Table 2. With the strict exclusion criterion, there was inconclusive evidence about the interaction of interest between Task and Cognitive Load ($BF_{01} = 2.1$). Including more data when applying the lenient exclusion criterion, however, resulted in very strong evidence in favor of this interaction ($BF_{10} = 735$), reflecting a larger cognitive load effect in the complex span task than in the Brown-Peterson task. There is strong evidence *against* the triple interaction between Task, Cognitive Load and Total Processing Duration ($BF_{01} = 15$ and 32 for the strict and lenient criterion, respectively), indicating that the difference in cognitive load effect between the two tasks was not credibly dependent on the total processing duration.

Experiment 2 was set up to explicitly test whether lengthening the Total Processing Duration would increase the Cognitive Load effect. Evidence for the interaction between Cognitive Load and Total Processing Duration was inconclusive ($BF_{01} = 1.7$ and 2.0 according to the strict and the lenient exclusion criteria, respectively) so we cannot conclude that lengthening the Total Processing Duration increases the Cognitive Load effect.

Discussion

The results of Experiment 2 replicate and extend the results of Experiment 1. Looking at the same conditions as in Experiment 1, Experiment 2 also shows a clear cognitive load effect for the complex span condition (with long total processing duration) and the absence of a cognitive load effect for the Brown-Peterson task (with short total processing duration). The newly added conditions in Experiment 2 show that a complex span task with shorter total processing duration also results in a cognitive load effect. The Brown Peterson task with longer processing duration now also results in a cognitive load effect, although

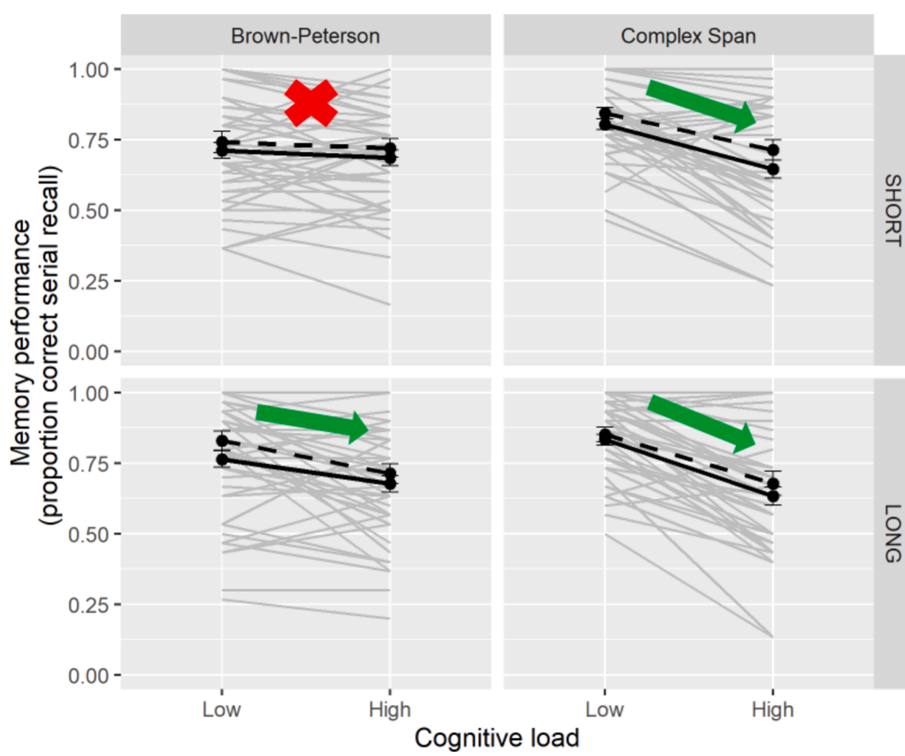

Fig. 4. Mean memory performance observed in Experiment 2, as a function of Task, Cognitive Load and Total Processing Duration. Dotted lines correspond to the strict exclusion criterion while full lines correspond to the lenient exclusion criterion. Error bars represent standard errors of the mean. The grey lines represent the individual scores of all participants who passed the lenient exclusion criterion. An arrow indicates evidence in favor of a cognitive load effect, while a cross indicates evidence against a cognitive load effect. Filled symbols (green arrow or red cross in the color version) indicate a BF≥3, with a green arrow indicating evidence in favor and a red cross indicating evidence against the effect. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

it is smaller than in the comparable complex span task condition (i.e., with the longer total processing duration). Across short and long processing durations, the results of Experiment 2 thus show again a more pronounced effect of cognitive load in the complex span than in the Brown-Peterson task.

On the descriptive level (see Fig. 4) one can see how the strict and the lenient exclusion criterion converge, as was the case in Experiment 1 as well. The lenient exclusion criterion resulted overall in more convincing statistical evidence, probably related to the substantially larger sample size than with the strict criterion in this experiment.

Experiment 3

In Experiment 3, we further explored the difference in the cognitive load effect between the complex span and the Brown-Peterson task by using a different manipulation of cognitive load. Whereas the cognitive load was varied in Experiments 1 and 2 by demanding fewer or more processing operations in the same amount of time, the cognitive load was varied in Experiment 3 by providing more or less free time after each processing operation, while holding the number of processing operations constant. With regards to the formula of the cognitive load given in the introduction, we manipulate T while keeping a and N constant. We expected to observe again a larger cognitive load effect in the complex span task than in the Brown-Peterson task. In addition, to examine the role of the processing demand for the cognitive load effect we also included corresponding task conditions in which the processing demand was entirely removed. Thus, stretches of free time of varying durations were given either in between the memory items, or after the entire list had been presented. Doing so reduces the cognitive load manipulation to a manipulation of free time, either inserted in between presentation of the memory items (as in the complex span task) or added after the presentation of all memory items (as in the Brown-Peterson task).

The comparison of tasks with and without a processing demand enables us to test the importance of the processing demand in the explanation of the cognitive load effect. Both current explanations of the cognitive load effect are based on the interplay between damage to memory traces, occurring during the execution of the processing task, and restoration, taking place during the free time presented right after the processing operations. When there is no processing task, no damage is occurring and thus restoration is unnecessary. Based on the current explanations of the cognitive load effect, working memory tasks without a processing task should hence not, or at least to a lesser extent, show a beneficial effect of additional free time. Observing a similar effect of free time in tasks with and without a processing demand[4] would severely challenge the current explanations of the cognitive load effect.

In the literature, evidence can be found that free time given in between memory presentation (complex span-style) while not presenting a processing task has a beneficial effect. For example, Bhatarah et al. (2009) as well as Souza and Oberauer (2017; see also Oberauer, 2022) showed that adding free time in between item presentation, thereby yielding a slower presentation rate of the memory items, results in better immediate recall. In contrast, tasks that added free time after the presentation of the entire memory set (Brown-Peterson-style) while not presenting a processing task, which delays recall, showed slightly lower memory performance (e.g., Tam, et al., 2010), or no difference between the conditions (e.g., Oberauer & Lewandowsky, 2016). These findings suggest that free time has different effects on memory when inserted in between the presentation of memory items than when it is added after the presentation of the entire memory set. This appears to be the case not only when free time is added to a processing demand – as in the complex span and the Brown-Peterson task, thereby reducing its cognitive load – but also in the absence of a processing demand.

Experiment 3 served to test two predictions. First, when varying the cognitive load through the duration of free time in the presence of a processing task, we expected to again observe a larger cognitive load effect in the complex span than in the Brown-Peterson task. That is, adding free time after a processing item that occurs in between memory items would be beneficial, while adding free time after a processing item that occurs after the presentation of the memory list would not have this effect. Second, when varying free time without a processing demand, we predicted to observe similar results, based on the literature: A beneficial effect of free time when it is given in between the presentation of the memory items but not when it is added after the presentation of all memory items. To test these predictions, we crossed three within-subjects variables: The position of the free time (either complex-span style, in between the presentation of the memory items, or Brown-Peterson style, after the presentation of all memory items), the duration of free time, and the presence or absence of a processing task.

Experiment 3 was run independently from, and without prior knowledge of, Experiments 1 and 2. Therefore, Experiment 3 differed from the preceding experiments not only with respect to the manipulations for testing our two predictions, but also with respect to a number of ancillary features, such as the choice of the processing task, the stimuli, and the temporal parameters. This variance between experiments on dimensions that we expect to be immaterial is not a weakness but a strength of the present study, as it broadens the generalizability of our findings (Baribault et al., 2018; DeKay, et al., 2022).

Method

Participants and design

Sixty psychology students (all aged between 18 and 35 years) of the University of Zurich participated in exchange for course credits (32 in batch 1 and 28 in batch 2). Each participant performed the memory task in all eight conditions generated by crossing Position of the Free Time (in between or after the presentation of the memory items), the Duration of Free Time (long or short), and the Presence of the Processing Task (absent or present). This experiment was carried out in accordance with the regulations of the ethics committee of the Faculty of Arts and Social Sciences at the University of Zurich. All participants signed an informed consent before starting the experiment.

Material

As in Experiments 1 and 2, participants had to remember series of consonants, this time drawn from a pool of 20 consonants (Y excluded). The letters were presented on screen in red in Arial with the font size corresponding to 4/10 of the screen height. The processing task was a spatial fit task (Vergauwe et al., 2010). In this spatial fit task participants had to judge whether a horizontal bar can fit into a gap between two dots. The bar can either be presented above or below the invisible horizontal line connecting the two dots. In half of the cases, the bar could fit between the two dots (press left arrow) and for the other half the bar could not fit (press right arrow). The spatial fit stimuli were presented in the center of the screen (see Oberauer & Lewandowsky, 2013, for details).

Procedure

The experiment was run in person on a computer using the Psychophysics toolbox for Matlab (Brainard, 1997). Each participant performed two experimental blocks, preceded by a short training. The two experimental blocks coincided with the two Positions of the Free Time (in between vs. after), and their order was counterbalanced across participants. Each block consisted of 24 experimental trials; six for each combination of the Duration of Free Time (long vs. short) and the

[4] i.e., a beneficial effect of free time when given in between memory presentation but not when given after memory presentation

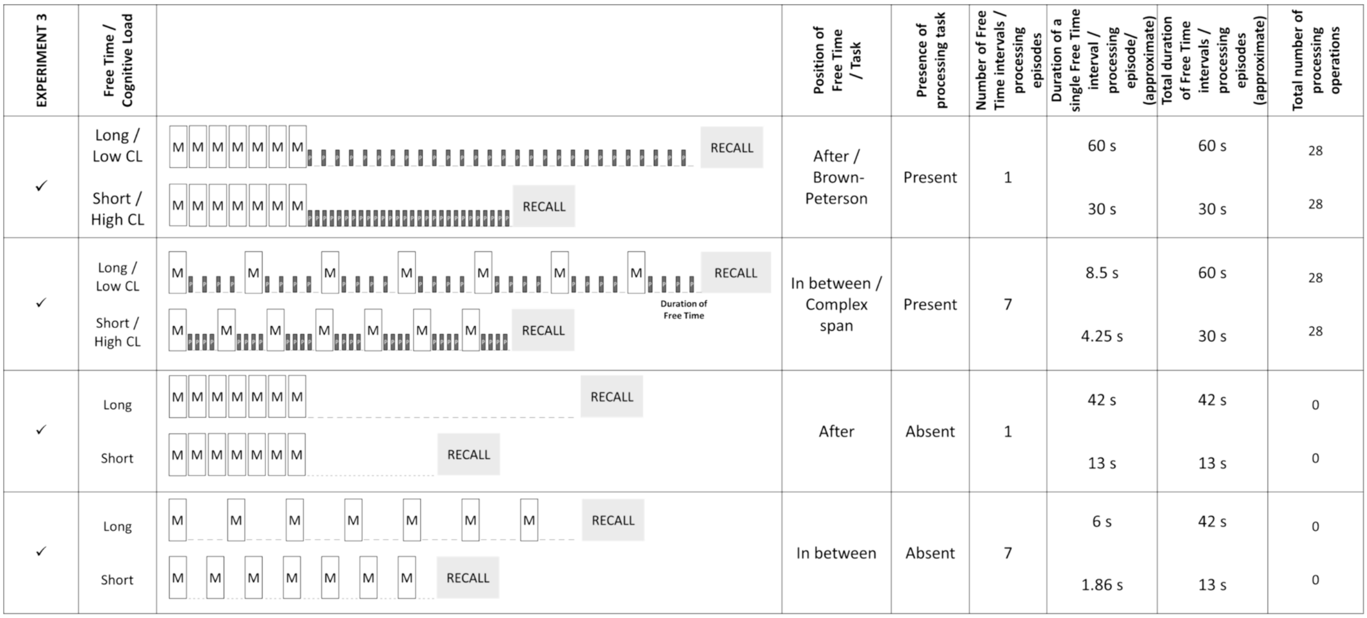

Fig. 5. Overview of the different experimental conditions in Experiment 3. M refers to memory item; P refers to processing operation; "_" refers to Free Time.

Presence of the Processing Task (absent vs. present). The 24 trials were randomly intermixed. Fig. 5 shows an overview of the different conditions in Experiment 3.

When there was a processing task, the number of processing operations (i.e., spatial-fit judgments) remained constant across the short and long Duration of Free Time. In the complex span task, each of the now 7 processing episodes contained four processing operations, resulting in 28 processing operations per trial. In the Brown-Peterson task, the single processing episode contained 28 processing operations as well. The variation of the free time after each processing operation in the long and short Duration of Free Time resulted in a variation of the total duration of the processing episode(s).

The durations of the processing episode(s) in the different conditions were calculated as follows: The time demand for each processing operation in the absence of a concurrent memory task was estimated based on the first experiment reported by Oberauer and Lewandowsky (2014), which measured RTs in the same spatial-fit task as used here; details can be found in the Supplementary Materials. This time demand ranged between 548 and 676 ms for different positions in the four-trial sequence. The presentation durations of spatial-fit stimuli were set to 1.5 times the time demand for high CL, and 3 times the time demand for low CL. The resulting presentation times were followed by a blank-screen period of 20 % of the presentation time. This resulted in an approximate presentation rate of one spatial-fit stimulus per 2000 ms in the Long Free Time condition, and one per 1000 ms in the Short Free Time condition (similar to what was used in Experiments 1 and 2).

We calculated the expected free time in the two conditions by subtracting the estimated time demand for the spatial-fit judgments from the time between successive spatial-fit stimuli. This resulted in approximately 1450 ms and 450 ms free time in the long and short Duration of Free Time conditions, respectively. In the conditions without a processing task, the estimated time demand for the spatial-fit judgments was cut out, and only the estimated free time was added as blank-screen intervals. Hence, the free time intervals inserted between item presentations in the complex-span style condition were approximatively 4 x 450 ms (≈ 1.86 s, adding up to about 13 s over the seven processing episodes) or approximately 4 x 1450 ms (≈ 6 s, adding up to about 42 s over the seven processing episodes) for the short and long Free Time conditions, respectively. The single free time interval added after the presentation of all memory items in the Brown-Peterson style condition was about 13 s (≈28 x 450 ms) and 42 s (≈ 28 x 1450) in the short and long Free Time conditions, respectively. For the exact durations see the Supplementary Materials.

Each trial started with a fixation cross for 1000 ms, followed by the presentation of a first letter that remained on screen for 1000 ms. In the complex span task, the first letter was followed directly by a processing episode of four processing operations, followed by a second letter and a second processing episode of four items, and so on until all seven letters and processing episodes had been presented. In the complex-span style condition without a processing task, this first letter was followed by a pure free time interval, followed by the second letter, followed by a second free time interval, and so on until all seven letters had been presented. In the Brown-Peterson task, the first letter was followed by the second letter, the third letter and so on until all seven letters had been presented. The seventh letter was then followed by a single processing episode, including all 28 processing operations. In the Brown-Peterson style condition without processing demand, presentation of the seven letters was followed by a single pure free time interval. In all four conditions, the Duration of the Free time could be either long or short, resulting in eight experimental conditions. At the end of the trial, recall was prompted by an underscore appearing on screen, and participants had to enter the seven letters on the keyboard; each typed letter briefly replaced the underscore. Guessing when one did not remember the correct letter was encouraged in the same way as in Experiment 1; only letters could be entered (no asterisk). No corrections were allowed. After the last letter had been entered, a delay of 2 s followed before the next trial began.

Before the start of the two experimental blocks, participants were given instructions for the spatial fit task. Then followed a first experimental block, starting with four training trials. The second experimental block also started with four training trials.

Results

The data and code of this analysis are available on OSF (https://osf.io/swdqu/).

Performance-based exclusions

The same strict and lenient exclusion criteria were used as in Experiments 1 and 2. The data of four participants were excluded based on their performance on the processing task according to the strict criterion. No participants had to be excluded according to the lenient criterion. Additionally, the data of one participant with a memory recall score of 0 on all trials in the block with free time given in between the memory items was excluded, as well as the data of one participant who did not perform the block with the free time given after the presentation of all memory items. The data of 54 and 58 participants were retained for further analysis according to the strict and lenient exclusion criterion, respectively. The mean processing accuracy in the trials with the processing task present was 90 and 88 % in the complex span task after applying the strict vs. the lenient criterion, respectively, and 91 and 90 % in the Brown-Peterson task, after applying the strict vs. the lenient criterion, respectively.

Analyses

Scoring of the recall performance and analysis were done as in Experiments 1 and 2.

Fig. 6 shows that in tasks with a processing task, we observe a clear free time effect (i.e., a cognitive load effect) when this free time is presented in between the presentation of the memory items (i.e., complex span task) but not when it is presented after the presentation of all memory items (i.e., Brown-Peterson task). In tasks without a processing task, there still seems to be a small free time effect when this free time is presented in between the presentation of the memory items but no such benefit when this free time is presented after the presentation of all memory items. The logistic models applied separately to each of these four conditions confirm this pattern. For conditions with a processing task, there is clear evidence for better memory performance when more free time is given in between the presentation of the memory items ($BF_{10} = 229$ and 90 for the strict and lenient criterion, respectively), and clear evidence *against* a difference in memory performance when more free time is given after the presentation of all memory items ($BF_{01} = 10$ and 14 for the strict and lenient criterion, respectively). This replicates the pattern of results observed in Experiments 1 and 2. In Experiment 3 in tasks without a processing task, there is anecdotical evidence for an effect of free time when it is given in between the presentation of the memory items ($BF_{10} = 1.7$ and 2.3 for the strict and lenient criterion, respectively), and strong evidence *against* an effect of free time when it is given after the presentation of all the memory items ($BF_{01} = 18$ and 17, respectively).

An overview of the BFs from the model applied to all conditions jointly can be found in Table 3. There is moderate evidence for the interaction of interest between the Position of Free Time and the Duration of Free Time ($BF_{10} = 4.1$ and 7.0 for the strict and the lenient criterion, respectively), with free time being more beneficial when inserted in between the memory items than when inserted after the presentation of all memory items. Additionally, there is strong evidence against the triple interaction ($BF_{01} = 34$ and 37 for the strict and the lenient criterion, respectively), suggesting that this more beneficial effect of free time when presented in between the memory items as compared to after the presentation of the memory items is independent of the presence of a processing task.

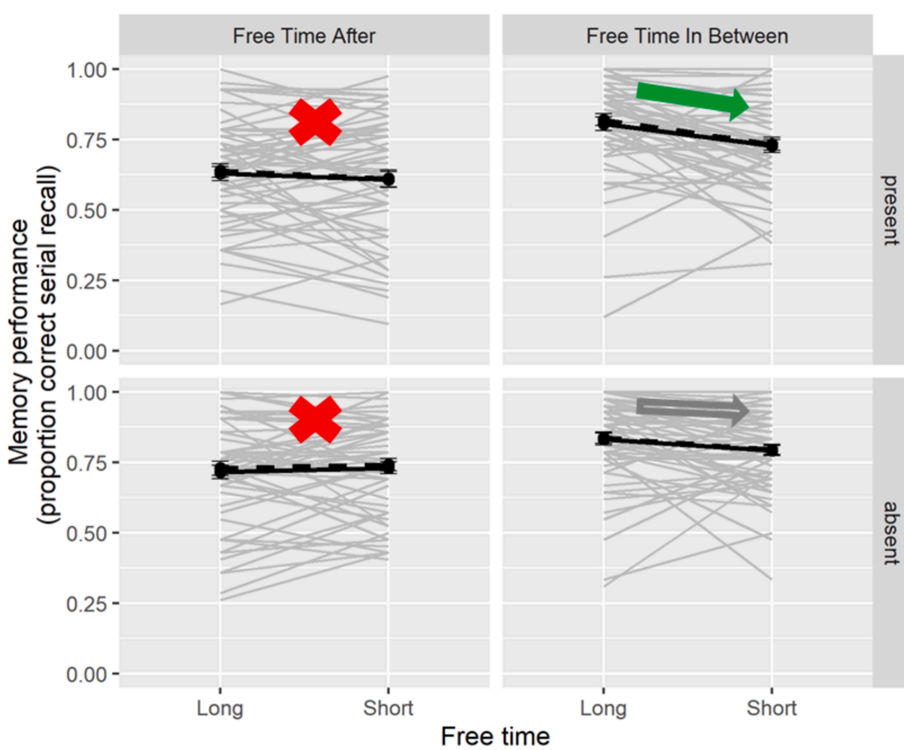

Fig. 6. Mean memory performance observed in Experiment 3, as a function of the Duration of Free Time (Long vs. short), the Position of Free Time (After vs. In Between), and the Presence of the processing task (present vs. absent). Dotted lines correspond to the strict exclusion criterion while full lines correspond to the lenient exclusion criterion. Error bars represent the errors of the mean. The grey lines represent the individual scores of all participants who passed the lenient exclusion criterion. An arrow indicates evidence in favor of a cognitive load effect, while a cross indicates evidence against a cognitive load effect. Filled symbols (green arrow or red cross in the color version) indicate a BF≥3, with a green arrow indicating evidence in favor and a red cross indicating evidence against the effect. Unfilled symbols (grey in the color version) indicate 1 < BF<3, with a grey arrow indicating evidence in favor of the effect. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Bayes Factors for each fixed effect from the general logistic regression in Experiment 3.

Effect	BF in favor of fixed effect (according to the strict / lenient criterion)
Duration Free Time*Position Free Time	4.1 / 7.0
Duration Free Time*Presence Processing Task	.073 /.058
Position Free Time * Presence Processing Task	1.0 /.30
Duration Free Time * Position Free Time*Presence Processing Task	.029 /.027
Duration Free Time	9386 / 208
Position Free Time	$9.4*10^{11}$ / $1.1*10^{12}$
Presence Processing Task	$1.8*10^{5}$/ $2.8*10^{6}$

Experiment 3 specifically aimed to test the role of the processing task on the free time effect. The logistic regression analysis showed strong evidence against an interaction between the Duration of Free Time and the Presence of the Processing Task ($BF_{01} = 14$ and 17 for the strict and the lenient criterion, respectively), suggesting that the effect of free time is not dependent on a processing demand within the task context.

Discussion

The conditions in Experiment 3 with a processing task replicate the observations of Experiments 1 and 2. Clear and consistent evidence for a cognitive load effect was only found for complex span tasks, not for Brown-Peterson tasks. Using a different manipulation of the cognitive load effect showed the robustness of this observation. In conditions without a processing task, a similar pattern of results is observed. The beneficial effect of free time when given in between the memory items appeared smaller than in the presence of a processing task, but the statistical analysis speaks against such a difference. By contrast, the beneficial effect of free time when given after the presentation of the memory items is again absent. The overall conclusion that can be drawn from these results is that the free time effect is larger when free time is given in between the presentation of the memory items than when given after the presentations of the memory items, and that this seems to be the case independently of the presence of a processing task.

General discussion

Across the three experiments reported here, we observed that (1) the cognitive load / free time effect is consistently larger in the complex span task than in the Brown-Peterson task, and that (2) the effect is mostly absent in the Brown-Peterson task, apart from one exception (when using an unusually long processing phase of more than 30 sec). Overall, this suggests that processes occurring during free time while the list is being presented occur less, or are less beneficial for memory after the entire memory list has been presented. In Experiment 3, the difference in the beneficial effect of free time between the complex span task and the Brown-Peterson task seems to persist in task variants without a processing component, although the statistical evidence is ambiguous in these latter conditions: On the one hand, we found only weak evidence for a beneficial effect of free time in the absence of distractors; on the other hand, we found strong evidence against the interaction of the free time effect with the presence vs. absence of a processing task, and against the 3-way interaction. This ambiguity makes it difficult to determine to what extent the processes occurring during free time are indeed restoring damage caused by processing or mainly boosting memory performance independently of damage caused.

Together, our findings provide evidence for the conclusion that manipulations of cognitive load / free time have different effects depending on whether they occur during or after list presentation. This goes against the current theoretical accounts of the cognitive load effect.

Implications for the TBRS and the SOB-CS Model

So far, two accounts for the Cognitive Load effect have been proposed: the TBRS (Barrouillet, et al., 2007; Barrouillet et al., 2004) and the SOB-CS model (Oberauer et al., 2012). Neither of these accounts adequately explains the larger cognitive load / free time effect in the complex span compared to the Brown-Peterson task. Both models struggle to adapt or specify their postulates to account for the current results. In the following paragraphs, we discuss possible adaptations and specifications, as well as their limitations.

The TBRS model claims that maintenance of memory items and the processing of distractors compete for central attention. In both complex span and Brown-Peterson tasks, attention is taken away from maintenance activities when a processing operation is required, resulting in the decay of memory items. This decay can then be counteracted by refreshing as soon as attention becomes available again. For the TBRS model to account for the difference in the cognitive load effect between the complex span task and the Brown-Peterson task, additional assumptions should be made (and tested). So far, the TBRS model suggests refreshing takes place whenever time allows it and memory items have decayed to some extent. In the complex span and Brown-Peterson tasks, this implies refreshing after every processing step that diverts attention away from the memory items, allowing decay to occur. Since decay occurs both during and after list presentation, refreshing should a priori be equally necessary and effective for restoring partially decayed traces in both the complex span and the Brown Peterson tasks, resulting in comparable effects of cognitive load.

In a recent study (Barrouillet et al., in press), the authors of the TBRS model suggested that the Brown-Peterson task relies less on active maintenance processes than the complex span task. This conclusion was based on a direct comparison between a complex span task and a Brown-Peterson task, both executed at participant's maximum memory span and maximum processing capacity, which had been individually titrated using single-task performance. In the complex span and the Brown-Peterson tasks, participants were instructed to prioritize either the memory task or the processing task. The authors were interested in the residual performance of the unprioritized component, when the prioritized component was performed perfectly. Of interest here is the residual memory performance when the processing task was prioritized. This residual performance should be close to zero, as all working memory resources are taken up by the prioritized processing component. In the complex span task, residual memory performance was indeed close to zero (0.56 memory items). In the Brown-Peterson task, it was about two (1.80 memory items), hence much larger than in the complex span task. The authors suggested that the Brown-Peterson task likely involves additional, memory mechanisms beyond working memory, such as episodic memory. The authors propose that the structure of the Brown-Peterson task facilitates grouping memory items into smaller sequences, which could easily be retrieved from episodic memory after 12 s without active maintenance.

This suggestion of less active maintenance in the Brown-Peterson compared to the complex span task had been proposed before. Jarrold et al. (2011) presented participants with both tasks, with increasing list lengths in both. The processing task was self-paced, allowing participants to delay execution when other attention-demanding processes such as refreshing are running. In the complex span task, processing times were delayed as a function of the memory load throughout the entire processing phase. In the Brown-Peterson task, only the processing time before the first processing item was delayed as a function of memory load, likely reflecting task switching or consolidation, rather than refreshing. This observation supports the idea of more active maintenance in the complex span task as compared to the Brown-Peterson task.

While more active maintenance in the complex span task than in the Brown-Peterson task could account for the larger cognitive load / free time effect in the complex span task compared to the Brown-Peterson task, there are some inconsistencies with this suggestion. For example, Vergauwe, Camos, et al. (2014) observed delayed processing times in the Brown-Peterson task with increased memory load (at least for a large part of the processing task, see also Camos et al., 2019; Fanuel et al. 2018). This latter observation does not replicate the results of Jarrold et al. (2011) and suggests that the Brown-Peterson task relies to a substantial extent on active maintenance anyhow.

How could the SOB-CS model account for the present findings? The SOB-CS model claims that free time is used for removing representations of distractors from working memory, which are introduced through the processing task. Both in complex span and in Brown-Peterson tasks, each distractor needs to be removed during the free time following it in order to prevent these from interfering with the memory items. For the SOB-CS to account for the difference in cognitive load effect between the complex span and the Brown-Peterson task, additional assumptions would need to be made (and put to test).

According to SOB-CS, the strength of encoding of each stimulus increases with its novelty relative to the existing contents of WM. When switching from encoding a memory item to processing a distractor, the novelty of the distractor is initially high; subsequent distractors are relatively similar to the preceding distractors. Hence, the first distractor in a series is predicted to be encoded strongest, causing the largest degree of interference. In the complex-span task, such relatively novel distractors occur after encoding of each memory item, whereas in the Brown-Peterson task a novel distractor occurs only once at the transition from list encoding to distractor processing. This implies stronger interference from distractors in the complex-span than in the Brown-Peterson task, and hence, more to be gained from removing distractor representations from working memory in complex span than in Brown-Peterson. This argument could be used to explain the larger effect of cognitive load in complex span. However, an explanation along these lines has two serious shortcomings. One is that it implies that the effect of distractor processing – compared to no distractor processing – is also larger in the complex-span than the Brown-Peterson task. This is not what we observed. We obtained inconclusive/moderate evidence against the interaction of task with the presence of a processing task in Experiment 3 and descriptively the Brown-Peterson task seemed to be more impacted by the processing task than the complex span task. This is similar to the results of Jarrold et al. (2011), who found stronger effects of distractor processing in Brown-Peterson than complex span tasks. A second downside of this explanation is that the assumption of novelty-dependent encoding strength has recently been questioned through a series of experiments aimed at testing it directly (Oberauer et al., 2022).

To conclude, we currently find no straightforward way to adapt either the TBRS or SOB-CS model to account for the main results of the present study: The cognitive load effect is smaller in the Brown-Peterson task than the complex span task, and in most cases absent in the Brown-Peterson task.

An additional important result of the present study concerns the similarity between the pattern of results in tasks with and without a processing task present. The evidence for that similarity in the present Experiment 3 is not compelling; we nevertheless discuss what implications it would have if it were confirmed by future studies. If free time affects working memory performance similarly in tasks with and without a processing component, then the cognitive load effect is rather a free time effect instead of a cognitive load effect. This means that the processing task is not important for an explanation of the effect. If that is so, it would contradict both TBRS and SOB-CS, because both models explain the cognitive load effect through the balance between damage to memory representation from distractor processing on the one hand, and restorative processes on the other. When memory representations are not damaged, there is nothing to be gained from restoration.

One way for TBRS and SOB-CS to address this challenge is to assume that even without a processing task there is damage to memory representations that can be restored. In the TBRS theory, time spent encoding new items allows previously encoded items to decay. Subsequent free time can be used to counteract that decay. In the SOB-CS model, interference could be assumed to arise from self-generated thoughts (for example introduced through mind wandering), and free time could be used to remove these interfering representations.

Alternatively, one might assume that the free time effect in the complex span variant without processing task arises from processes boosting memory during this free time, independently of damage caused by distractor processing. The cognitive load effect would then be reduced to a free time effect, as the processing task does not play a direct role in it.

Further explanations for the effects of cognitive load and free time

Assuming the observed effect to be a purely free time effect, which processes could be responsible for boosting memory performance during free time, consistent with the observations in our three experiments? We consider five candidate processes that could take place during free time, in turn: Elaboration, grouping, consolidation, resource replenishment, and reconfiguration of action plans. We only consider how these processes could improve memory during free time, without taking into consideration whether and to what account the memory items might have suffered from the presence of a processing task (as contrasted with the TBRS and SOB-CS accounts).

Elaboration

A first process that could occur during free time is elaboration. Participants have reported using this process during both complex span tasks and delayed recall tasks (i.e., Brown-Peterson task without a processing task; Bailey, et al., 2008; Morrison et al., 2016). Although elaboration is typically conceived as adding semantic knowledge to word stimuli, for example by combining words into a meaningful sentence or into a vivid mental image (Craik & Tulving, 1975), in the present context we could imagine participants elaborating on the letters to be remembered by combining some letters into words, which could then be remembered as a sentence or as vivid images. Morrison et al. (2016) showed elaboration to be self-reported as a strategy at approximatively the same degree in complex span and delayed recall tasks. This makes it difficult to explain why elaboration should be beneficial only in complex-span tasks (with or without a processing component). In addition, the effect of elaboration on working memory performance remains yet to be confirmed. Whereas Bailey et al. (2008) showed that in complex span tasks self-reported elaboration correlates positively with performance, Bartsch and Oberauer (2021) as well as Bartsch et al. (in press) found no beneficial effect of instructed elaboration on performance in tasks with free time given in between the memory items. It hence seems unlikely that elaboration can explain the pattern of results of the present study. Additionally, we cannot come up with theoretical reason why people would engage in elaboration in between the presentation of memory items but not after the entire memory list has been presented.

Grouping.

The second process is grouping, referring to the organization of lists into clusters of about three successive items. It is a benchmark finding in short-term and working memory that grouping of items leads to improved recall (Oberauer et al., 2018). This has mainly been demonstrated by experimentally inducing grouping during list presentation by inserting brief temporal gaps between groups. Grouping also occurs spontaneously, as shown by Farrell (2012). For example, when participants have to remember lists of six letters, they tend to remember them in two groups of three items. Morrison et al. (2016) showed that spontaneous grouping of information was reported more often as a strategy in delayed serial recall tasks (corresponding to a Brown-Peterson variant without a processing task) than in complex span tasks. We could speculate that when items are presented one after the other, spontaneous grouping is relatively easy and can already be carried out during list presentation, because the items are presented without interruption. By contrast, when the presentation of letters is separated by free time or a processing task, free time may be necessary to create groups of items that have been presented temporally far apart. If that is the case, free time would be beneficial for complex span tasks (and its variant without a processing task) by facilitating the grouping strategy, but add nothing to the performance in the Brown-Peterson task (and its variant without a processing task) because grouping can be implemented without the need of additional free time. This explanation could however not explain why a cognitive load / free time effect was observed in the Brown-Peterson task with a longer processing task.

Consolidation

Another candidate is consolidation, the process that turns the fragile perceptual representation of a stimulus into a stable working memory representation (Ricker, et al., 2018). It is different from other maintenance processes in that it can only act upon memory representations that have just been encoded. As soon as attention has been diverted to other memory items or processing operations, consolidation stops and cannot be resumed (Bayliss, et al., 2015; Ricker et al., 2018). Bayliss et al. (2015) showed that consolidation time – free time immediately after presentation of a stimulus – has a beneficial effect on working memory performance. De Schrijver and Barrouillet (2017) also showed longer consolidation times to result in better memory performance, although they also showed this free time could be replaced by free time given later on, after attention had already been diverted from the memory item in the meantime.

In the present study, the consolidation time was constant across cognitive load conditions in the complex span task (1000 ms from onset of a memory item to onset of the first distractor to be processed) and in the Brown-Peterson task (1000 ms from onset of a memory item to onset of the next item). Therefore, consolidation cannot explain the cognitive load effect or its interaction with the task used.

Closely linked to the consolidation account, Ricker and Vergauwe (2022) have recently proposed the "enrichment account" to explain the boundary conditions of the cognitive load effect they observed (i.e., the cognitive load effect occurring only under the combination of impoverished consolidation and repeated episodes of concurrent processing). They describe enrichment as a strategic process that reinforces the memory presentations that are too impoverished to optimally execute the memory task. For example, their study showed that a complex span task with shorter presentation times for the memory items results in a more pronounced cognitive load effect compared to longer presentation times. They suggested that, with shorter presentation times, memory items are not sufficiently consolidated and enrichment is invoked during subsequent free time to compensate for this lack. With longer presentation times, enrichment is not necessary. Therefore, longer free time is less beneficial, resulting in a reduced cognitive load effect. If free time occurs after all items have been presented, it is harder for enrichment to act on the representations since they were presented long before. So far, these enrichment processes have not been specified exactly. More conceptual work is needed to define enrichment more precisely, explaining how it is different from elaboration and from refreshing. In its current state, the enrichment account can thus not offer a satisfying explanation of the results observed in the present study.

Replenishment of an Encoding Resource.

Another candidate is resource replenishment. Popov and Reder (2020) proposed that encoding items into memory results in the depletion of an encoding resource with each new item being encoded. Free time in between the presentation of memory items could be used to replenish this encoding resource. Mızrak and Oberauer (2021) applied this assumption to explain the effect of free time in working memory. They varied the positioning of free time during list presentation in a serial recall task. The benefit of free time was observed exclusively on the memory items presented after the manipulated free time interval. Whereas the attentional processes we have discussed so far should have an effect on the items preceding the free time, the benefit of resources replenishment is expected on the items that follow the free time, as their encoding is benefitting from the replenished resource. This could explain why adding free time in between the presentation of the memory items has a beneficial effect, while adding free time after all memory items have been presented has no effect: free time after list presentation allows replenishment of the encoding resource at a time when it is no longer needed for the current memory list. This replenishment resource can explain most of our findings, with the exception of the cognitive load / free time effect observed in the Brown-Peterson task with a longer processing phase in Experiment 2.

Reconfiguration of motor plans

Recently, Joseph and Morey (2021) have suggested that free time in working memory tasks may be used to reconfigure the memory items into a motor plan for the upcoming recall. As long as new items are added to the memory list, these reconfiguration processes take place right after each item presentation. As soon as no new memory items are added to the list, these reconfiguring processes can stop, and the recall motor plan remains stable in a format ready for output. This could explain why adding free time after the memory list has been presented is not useful. It will in this case not be used for the reconfiguration of motor plans as this process has already been completed. Free time presented in between the presentation of the memory items could be used to continue integrating the last-presented item into the motor plan, resulting in better memory performance. So far, not much research has been done regarding these hypothetical reconfiguration processes, but these seem at first sight to be concordant with the results of the present experiments. That is, motor reconfiguration processes can explain the presence of a free time effect in tasks with free time given in between the presentation of the memory items and the absence of such an effect in tasks with free time given after the presentation of the entire memory list. It is however harder to explain why a Brown-Peterson task with a very long processing phase would result in a free time effect, unless one assumes that a motor plan degrades over time and therefore needs to be renewed after a certain (quite long) time.

At the moment, we need to conclude that none of the candidate processes potentially occurring during free time in working memory task can explain the whole pattern of results. Two of them – replenishment of an encoding resource, and reconfiguration of a recall motor plan – can explain the main pattern of results consistently: Longer free time/lower cognitive load improves memory during list presentation but not after. None of them can explain the one exception to this pattern that we observed in Experiment 2 with the longer processing phase in the Brown-Peterson task.

To further investigate the processes at play during free time in working memory tasks, it is important to first determine their nature: do they restore degraded working memory representations, or do they purely boost intact working memory representations? The present experiments could not give a conclusive answer to that question. The results of Experiment 3 in particular should therefore be replicated and elaborated. Once the nature of these processes is established, a more detailed investigation of their functioning should be undertaken to describe them more precisely and determine under which task conditions they are effective.

Conclusion

To conclude, we repeatedly observed a larger and more consistent cognitive load / free time effect in the complex span task than in the Brown-Peterson task. We did not observe any evidence for a cognitive load / free time effect in the Brown-Peterson task, except once when using an unusually long processing phase. The current explanations of the cognitive load effect cannot account for these observations. Two alternative explanations appear promising: Free time is used for the replenishment of an encoding resource, or free time is used for adding further memory items to a recall motor plan. Both explanations imply a beneficial effect of free time during list presentation but not necessarily after, independently of whether a distractor processing task is present.

Ethics approval

The ethical commission board of the Faculty of Psychology and Educational Sciences at the University of Geneva approved the experiments 1 and 2 included in this article. Experiment 3 was carried out in accordance with the regulations of the ethics committee of the Faculty of Arts and Social Sciences at the University of Zurich; as this experiment involved minimal risk, no formal approval was required.

Author's contributions

Naomi Langerock: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization, Project administration. Elena Throm: Methodology, Software, Investigation, Writing – Review & Editing. Klaus Oberauer: Conceptualization, Methodology, Software, Formal analysis, Writing – Review & Editing, Supervision, Project administration; Funding acquisition.

Evie Vergauwe: Conceptualization, Methodology, Validation, Formal analysis, Resources, Writing – Review & Editing, Supervision, Funding acquisition.

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CRediT authorship contribution statement

Naomi Langerock: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Klaus Oberauer:** Writing – review & editing, Writing – original draft, Supervision, Software, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Elena Throm:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation. **Evie Vergauwe:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

A link to the raw data and the code for the analysis is shared.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jml.2024.104558.

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