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„The Cognitive Load Effect in the Complex-Span Paradigm and the Brown-Peterson Paradigm"

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Table of Contents

Introduction

“If it rains on Saturday, I will go to the zoo, if my friend has time to accompany me, and to the cinema, if my friend has no time to accompany me, but if it does not rain on Saturday, I will go to the swimming pool, if the ice cream shop is open by then, and to the zoo, if the ice cream shop is not open by then.” In order to store all this information accurately in mind after having read this sentence once, we rely on working memory (WM). For most of us, the amount of information contained in this sentence is the maximum amount we are able of processing at once. But why is the capacity of WM restricted at all? There is an ongoing scientific debate on the capacity limit of WM. One popular approach explaining WM capacity, the time-based resource-sharing model, assumes that encoded memory items underly temporal decay unless they are actively maintained. In the present study, we tested predictions derived from this model in order to find out more about the mechanisms responsible for WM capacity.

Theoretical background

Working memory

Working memory is a relatively young concept in cognitive psychology. In 1974, Baddeley and Hitch first presented evidence for the hypothesis of a distinct common system underlying reasoning, comprehension and learning (Baddeley & Hitch, 1974). They described WM as a multi-component system with the *executive control* as a control system limiting storage and processing. Since, the conceptualisation of WM has been theoretically and empirically elaborated by different research groups, and nowadays, WM has reached the state of a well-established concept in the scientific community within and beyond memory research. However, to date there is no common definition of WM. Instead, there are at least nine definitions differing in how they explain WM functioning (Cowan, 2017). For example, WM has been defined as a multicomponent system (Baddeley, 2012; Baddeley & Hitch, 1974), as storage-and-processing system (Daneman & Carpenter, 1980) and as attention-control (e.g., Engle, 2002). According to Cowan (2017), these differences in WM definitions arose, because researchers adapted their definitions to their theoretical needs and thereby confused their assumptions on how WM fulfils its functions with the description of which function WM fulfils.

Although it seems difficult to agree on a common theoretical framework of the processes of WM seems difficult, the paradigms used to measure WM and the phenomena they reveal are quite consistent (Oberauer, 2016). For example, WM span tasks are widely used to study WM. They reveal consistent phenomena, such as the limited amount of information people can hold in mind, and that the amount is further restricted by completing a processing task simultaneously. Moreover, performance in these tasks correlates highly across individuals, suggesting that the tasks measure one common WM factor. These tasks mostly measure complex cognitive processes involving generating and manipulating representations (Halford, Wilson, & Phillips, 1998; Klaus Oberauer, Süß, Wilhelm, & Sander, 2008).

Therefore, this study’s definition of WM does not rely on beliefs how working memory functions. Rather, we use WM in a “generic” term (Cowan, 2017, p. 1163), by defining it in terms of its functions while remaining cautious about the underlying mechanisms. Accordingly, we regard WM as an ensemble of components or mechanisms temporarily holding a limited amount of information in a state of heightened accessibility for processing (Klaus Oberauer, 2009). This retained information can be of any domain. One advantage of this generic definition is that it can be used by authors of different theoretical approaches, because it does not imply assumptions on processes. Another advantage of the generic definition is that it is in line with an individual-differences approach of WM capacity. Individual WM task performance showed to account well for individual differences in general intelligence (Conway, Cowan, Bunting, & Therriault, 2002; Conway et al., 2005; Kane, Conway, Hambrick, & Engle, 2007; Kane et al., 2004), even when the WM task did not involve a processing component (Cowan, 2017). By contrast, WM definitions that understand WM as active only in the presence of a simultaneously present processing component (e.g., the storage-and-processing definition of WM) have difficulties accounting for these findings (Cowan, 2017; Oberauer, 2009).

Working memory capacity

A core finding in the WM literature as well as in everyday life is that WM has limited capacity (e.g., Just & Carpenter, 1992; Oberauer et al., 2007; Turner & Engle, 1989; Unsworth & Engle, 2007). Some authors described the capacity limit in numbers. For example, Cowan (2010) argues that the WM is limited to dealing with a maximum of about four elements. Other authors pointed out that it is difficult to determine how many elements WM can hold in mind, because this number varies depending on several aspects. For example, recall performance differs depending on the nature of the memoranda (e.g., words or letters) and on the features of the memoranda (e.g., word length, word complexity, similarity among words in list, familiarity of words). Moreover, recall performance differs depending on secondary processing and the features of the material processed.

Measuring WM capacity

The paradigm most commonly used to measure WM capacity is testing how much of encoded material participants can remember after a RI of some seconds (Conway, Jarrold, Kane, Miyake & Towse, 2007; Conway et al., 2005). In the *complex-span paradigm* (Daneman & Carpenter, 1980), sequentially presented memoranda are to be encoded for recall in serial order. The presentation of memoranda (e.g., letters) is interleaved with an RI filled with a distractor task. The distractor task can be, for example, reading sentences in a reading-span task, or digit counting in a counting-span task, adding values to a root value (e.g. "7 /+1 /-1 /+1") in an operation-span task, or making yes/no-judgements on the truth-value of sentences (e.g., "Cows eat milk.") or on a perceptual rule (e.g. deciding if two letters show joint features of symmetry). Performance in complex-span tasks is usually measured by assessing the working memory span (i.e., the number of serially recalled items until the first mistake is made) or by the total number of items recalled in their correct position.

Complex-span tasks are a widely used in studying WM capacity, because they most likely elicit the mechanisms that constrain WM capacity. They reliably predict performance in higher cognitive tasks as well as academic achievement (e.g., Conway, Kane & Engle, 2003; Unsworth, Schrock & Engle, 2004; for reviews see Conway, Jarrold, Kane, Miyake & Towse, 2007; Oberauer et al., 2007). WM capacity has been shown to correlate across different tasks and domains (e.g., Kane et al., 2004; Oberauer, Süß, Schulze, Wilhelm & Wittmann, 2000). Furthermore, many features of the complex-span task resemble features of other WM tasks (Oberauer, 2009). Accordingly, different kinds of complex-span tasks correlate not only highly with each other, but also with other measures of WM capacity (e.g., Oberauer et al., 2000).

Thus, understanding why WM is capacity-limited would help us understand, first, why individuals differ in higher order cognitive abilities, and in intelligence in general. It would help us, second, to see which theories might capture WM better than others, and thus to further develop valid theories of WM.

Approaches explaining WM capacity

There have been three approaches explaining the detrimental effect of distractor processing in WM tasks differently: the approach of limited resource, of temporal decay and of interference.

The first approach, resource theories of WM, assume that WM is generally a resource-limited system, and that maintaining as well as processing information demands this resource (Kahnemann, 1973; Ma, Husain, & Bays, 2014; Miller, 1956). Depending on the amount of resource needed at a time, the resource is shared among tasks (e.g., among simultaneous maintenance and processing), which takes the form of alternating of the resource between the demanding tasks. Performance is poorer in the task that is currently not provided by the resource. Most of these WM models assume that the limited resource is attention (Conway & Engle, 1994; LaRocque, Lewis-Peacock, & Postle, 2014; Ricker, Vergauwe, & Cowan, 2016). If the resource of attention was endlessly available, we were able to manipulate countless elements simultaneously, so the assumption.

The second approach, decay theories, explains the capacity limit by assuming that representations in WM quickly decay over time unless they are actively maintained by rehearsal or refreshing (Barrouillet et al., 2004). These mechanisms can serve to prevent memory traces from decay (Barrouillet, Bernardin, & Camos, 2004; Barrouillet, Portrat, & Camos, 2011; Towse, Hitch, & Hutton, 2002). Both these maintenance mechanisms are attention-based and reactivate memory traces held in memory. However, whereas rehearsal maintains only verbal information, refreshing is not limited to a specific domain (Valérie Camos et al., 2018).

The third approach explains the capacity limit by interference between representations. Interference theories of WM assume that items hold in memory interfere with representations of irrelevant encoded contents (Lewandowsky & Farrell, 2008; Nairne, 2002; Klaus Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012; Saito & Miyake, 2004).

Whereas resource and decay theories have been popular accounts in WM literature, the focus of the debate has recently been shifted towards interference theories. According to these theories, information that has been encoded and now is irrelevant superimposes memory items, creating interference. Indeed, the interfering of distractor representations with memoranda representations has received large support in the literature (Lewandowsky, Geiger, & Oberauer, 2008; Klaus Oberauer, Lewandowsky, et al., 2012), so that most researchers accept a detrimental role of distractor interference on memory in WM tasks. However, researchers do not agree on the role of temporal decay in WM. Both proponents and critics can claim support from the literature for their views. In the following, we will look at one model of WM capacity in more detail.

The time-based resource-sharing model

The *time-based resource-sharing model* (*TBRS model*; Barrouillet, 2004, 2007; Barrouillet & Camos, 2007) has been the most successful model proposing temporal decay of memory items. In recent years, a large body of research has been generated testing the model's assumptions. It is further one of two models of WM that have been implemented computationally (TBRS*, Oberauer & Lewandowsky, 2011).

A decay-and-refresh-account of WM capacity.

The TBRS model regards WM as a system "dedicated to the maintenance of information in face of any distracting events" (Camos, Lagner, & Barrouillet, 2009, p. 457). This view lines up with the research strand defining WM as storage-and-processing (Baddeley & Hitch, 1974; Kane et al., 2004). Because involving storage as well as processing components, the complex-span paradigm has been used for developing the TBRS model (Barrouillet & Camos, 2007). The model merges the decay and the resource approach to WM capacity. It assumes that memory traces decay over time, if they are not attentionally prevented from doing so. More specifically, the model bases on the following main assumptions (Barrouillet & Camos, 2007):

First, the TBRS model assumes that memory traces in short-term memory naturally decay over time. This is true for memoranda as well as for distractor representations.

Second, the only way to prevent memory traces from temporal decay is to shift attention towards maintaining them. By receiving attention, the memory traces are refreshed. If not being attentionally refreshed, memory traces would irreversibly fade away. Refreshing supports the maintenance of memory items by retrieving previously presented information from long-term memory. Thus, refreshing lifts a WM representation into a state of heightened accessibility. Although there is currently no consensus on the time course of refreshing, computational modelling indicated that the item with the lowest activation is probably refreshed first (Lemaire, Pageot, Plancher, & Portrat, 2018). The mechanism then might proceed operating on one item at a time (Garavan, 1998; Klaus Oberauer, 2005) or, cumulatively, on several items at once (Loaiza & McCabe, 2012; Vergauwe, Camos, &

Barrouillet, 2014). Refreshing a single item seems to last 40-50 ms (Jarrold, Tam, Baddeley, & Harvey, 2010; Vergauwe et al., 2014).

Third, storage and processing rely on the same attentional resource. To maintain the memory items, the resource is allocated to the memoranda representations in order to refresh them and thus prevent them from decay. To process the distractor task, attention is needed for driving higher order cognitions such as planning and maintaining intermediate solutions, as well as for retrieving processing-relevant information from long-term memory. Thus, attention is needed for both maintenance and processing in a WM task. Fourth, attention is a limited resource, because a bottleneck constrains any central process. While the central attentional bottleneck is occupied by a secondary task, memory traces cannot be maintained, and vice versa. Fifth, and finally, the model assumes that the attentional focussing switches rapidly between processing the secondary task and refreshing the memory traces, in order to share the limited attentional resource among the two task components. In a nutshell, the TBRS model assumes that attention is needed for a mechanism that refreshes decaying memory traces in a WM span task. Because attention is a limited resource, it needs to be shared between this refreshing and the concurrent processing task. This sharing takes the form of rapid switching between refreshing and processing the distractor task. Thus, recall performance is a function of the time dedicated to processing and refreshing, respectively.

Cognitive load.

According to these assumptions, memory representations decay during the time in which attention is captured by distractor task processing and are restored during the time in which attention is freely available. Within the complex-span paradigm, time is freely available after a distractor task has been completed and before the following distractor task or the following letter are presented. During this short interval of free time, attention can rapidly shift from distractor task processing to the items held in memory. The longer this free time lasts, the more the items can be refreshed. Conversely, the longer the processing time lasts, the less the items in memory can be refreshed.

Thus, according to the TBRS model, the main factor influencing recall performance in complex-span tasks is the ratio of the time dedicated to processing to the total duration of the RI. This ratio of processing time to total time has been termed the *cognitive load (CL)* of the

RI (Figure 1). Specifically, CL is defined as the ratio of the time during which a distractor tasks effectively captures central attention to the total duration of the RI.

$$CL = \frac{processing\ time\ for\ one\ distractor * number\ of\ distractors\ within\ the\ RI}{total\ duration\ of\ the\ RI}$$

Figure 1. Cognitive load is defined as the ratio of processing time to total duration within the RI.

If the total duration of the RI is kept constant, but the time for distractor task processing is increased, CL increases. Conversely, if the total time of the RI is increased, but the number of distractors is kept constant, the ratio, CL, decreases (Figure 2). Therefore, high CL would cause poorer recall performance, because most of the time during the RI is used for distractor processing, while little time is spent on restoring the decaying memory traces. Conversely, low CL would result in better recall performance, because most of the time during the RI is used for refreshing, while little time is spent on distractor processing.

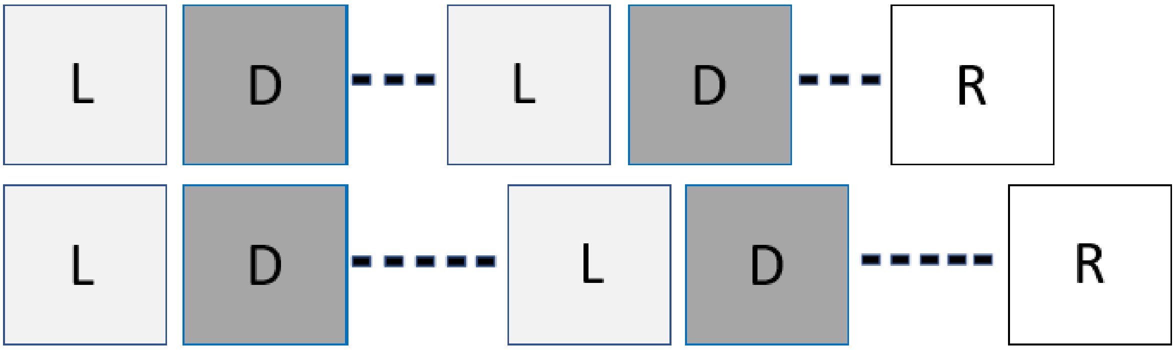

Figure 2. The sequences represent two trials of a complex-task with two memoranda followed by a RI each. Encoding letters (L) alternates with RIs. Within each RI, one distractor task (D) is processed. After the distractor task is completed, a short period of free time remains until the next letter is presented. The upper trial has a high level of CL, because the ratio of processing time to the total duration of the RI is high. The lower trial has a low level of CL, because the ratio of processing time to the total duration of the RI is low.

Empirical evidence on the role of cognitive load in the complex-span paradigm.

To investigate the role of CL, Barrouillet and his colleagues developed a computer-paced version of the complex-span paradigm (Barrouillet et al., 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007). This version allows the experimenter to control the amount of time a participant has for different processing steps in the complex-span task. Thus, the level of CL can be varied systematically. Either, CL can be increased by shortening the period of free time or by prolonging the period of distractor task processing, while keeping the total duration of the RI constant.

Applying computer-paced complex-span tasks, several studies have observed an effect of CL. Thereby, reducing the CL on trial level improved recall performance, and increasing the CL diminished recall performance (Barrouillet et al., 2004, 2007; Barrouillet, Portrat, Vergauwe, Diependaele, & Camos, 2011; Barrouillet & Camos, 2012; Hudjetz & Oberauer, 2007; Oberauer & Lewandowsky, 2014a; Plancher & Barrouillet, 2013; Vergauwe, Barrouillet, & Camos, 2010). In specific, when processing time was increased by increasing the number of distractors, while the total duration of the RI was kept constant, recall decreased (Barrouillet et al., 2004; Barrouillet & Camos, 2001; Gavens & Barrouillet, 2004; Lépine, Barrouillet, & Camos, 2005). Moreover, when the number of distractors was kept constant and the total duration of the RI reduced, recall decreased (Lépine et al., 2005). The effect of CL was consistent across domains (Vergauwe, Dewaele, Langerock, & Barrouillet, 2012).

Thus, the negative effect of CL was observed irrespective of the total duration of the RIs (e.g., Barrouillet et al., 2004), ruling out the hypothesis that the duration of the RI per se negatively effects recall performance (Towse et al., 2002), and instead supporting the assumption that CL is the driving factor for recall performance in complex-span tasks. Furthermore, these findings also suggested that the effect of task difficulty is not an effect of difficulty itself, but of the longer time which is needed to process more difficult tasks. This is also supported by the replication of the CL-effect with relatively simple distractor tasks (Barrouillet & Camos, 2001). This latter finding supports the TBRS model, since it proposes that processing tasks in WM tasks would not require to be difficult to fulfil their function, as long as they capture attention.

The authors further suggested that the number of distractors in a RI negatively affected recall performance only to the extend to that more distractors captured attention longer than fewer distractors (Barrouillet & Camos, 2007). Indeed, the number of homogeneous distractors did not affect recall as long as the ratio of processing time to total time was kept constant (Barrouillet et al., 2004; Oberauer & Lewandowsky, 2008).

This and further evidence also suggested that distractor processing does not need to involve retrieval in order to capture attention, supporting the assumption that this attention is needed by all central processes, instead of being restricted to specific processes such as retrieval (Rohrer & Pashler, 2003). Furthermore, individuals seem to be able to attend to only one process in WM at a time, supporting the assumption of a bottleneck of this central attention (Garavan, 1998; Oberauer, 2003). According to Vergauwe and colleagues (Vergauwe, Barrouillet, & Camos, 2009), the processing task involving the highest CL causes the largest disruptive effect on recall performance, regardless of the nature of the items included. They assume similarity-based interference (because similar distractors evoke higher CL), whereas they do not assume domain-specific interference.

Other studies have tried to further define the processes important to TBRS. As such, attentional refreshing was specified as cumulative restoration of the items in memory, proceeding sequentially from the first list item to the last list item (Loaiza & McCabe, 2012; McCabe, 2008). Furthermore, the authors of the TBRS model have stressed that the model additionally allows for interference created by the environment or by irrelevant long-term-memory information (Barrouillet & Camos, 2007; Barrouillet, Uittenhove, Lucidi & Langerock, 2017). However, in contrast to other models of WM capacity (Oberauer, Farrell, Jarrold, Pasiecznik, & Greaves, 2012; Oberauer & Kliegl, 2006; Oberauer & Lewandowsky, 2008), the TBRS-model does regard interference not as the only factor constraining WM capacity, but as an additional factor besides temporal decay.

Although several studies revealed findings that are in line with assumptions of TBRS, there are difficulties the model faces. First, most of the supporting findings listed above can also be explained by other models (e.g., SOB-CS, Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012). Second, the TBRS model has problems in explaining other evidence from complex-span research. For example, novel distractors disrupt memory performance more than constant distractors (Lewandowsky et al., 2008; Saito & Miyake, 2004), Also, when distractors were heterogeneous and unpredictable, the number of distractors negatively affected recall performance (Lewandowsky, Geiger, Morrell, & Oberauer, 2010). Furthermore, the detrimental effect of distractors on memory performance was larger when distractors and items shared the same domain (Bayliss, Jarrold, Gunn, & Baddeley, 2003; Chein, Moore, & Conway, 2011; Conway et al., 2007; Jarrold, Tam, Baddeley, & Harvey, 2010). These findings challenge the assumptions of the TBRS model, because the nature and number of distractors should not be of relevance for decay and refreshing.

Facing the ambiguous evidence in support of the TBRS model, we aimed to bring more clarity into the debate on the factors limiting WM capacity with the present study. In specific, we tested predictions derived from the TBRS model that concern the model's core assumption: cognitive load.

Alternative accounts to the TBRS model

Interference of irrelevant memory content has been widely accepted. An interference model for performance in complex-span tasks is the *serial-order-in-a-box model for complex-span* (*SOB-CS* model; Oberauer, Lewandowsky, et al., 2012).

The SOB-CS model is a computational implementation of its precursor models SOB (Farrell & Lewandowsky, 2002) and C-SOB (Farrell, 2006), tailored to modelling performance in complex-span tasks. According to SOB-CS, memory items are encoded into a neural network weight matrix that connects the position layer and the item layer. In the position layer, position information, i.e., the context of an item, is stored, and in the item layer, the items representations are stored. During processing, neural units are activated within the distributed network. Because items and distractors are encoded into the same matrix, they superimpose each other, creating interference. More similar items create more interference, because their features overlap in the weight matrix. Interference can be reduced by a removal process active during free time. The removal mechanism dissolves the binding between the distractor and the position marker during free time. Hence, the SOB-CS model can account for the CL-effect on recall performance in complex-span tasks by removal. Importantly, in the SOB-CS model recall performance is only a function of free-time-duration, since more interference can be reduced during longer intervals of free time. However, for the SOB-CS model the duration of processing time per se is of no relevance for recall.

Thus, the core theoretical difference between the TBRS model and the SOB-CS model is that the TBRS model assumes an automatic decay of memory traces, resulting in bad recall, requiring active maintenance. Contrary, the SOB-Cs model assumes an automatic maintenance of memory traces, resulting in bad recall (because they interfere with each other), requiring active removal of memory traces.

The Brown-Peterson task

Besides complex-span tasks, another common task paradigm to study WM is the *Brown-Peterson task*. A first version was designed and applied by Brown (1958) and by Peterson and Peterson (1959). It has been used primarily in clinical neuropsychological assessments (Morrow & Ryan, 2002). As the complex-span paradigm, the Brown-Peterson task presents a list of to-be-remembered items for recall after a short RI during which distractor tasks are to be processed. However, Brown-Peterson tasks differ from complex-span tasks in task structure: Here, all list items of a trial are presented first. Then, after the whole list has been presented, all distractor tasks of a trial are presented sequentially. Therefore, whereas in the complex-span task the RIs interleave list presentation, the RI in the Brown-Peterson paradigm succeed list presentation. Usually, recall in the complex-span is better than recall in the Brown-Peterson task (Tehan, Hendry, & Kocinski, 2001).

Several studies suggest that the Brown-Peterson task and different WM span tasks share the common underlying construct of a unitary WM capacity (Geurten, Vincent, Van der Linden, Coyette, & Meulemans, 2016; Oberauer et al., 2000; Klaus Oberauer, Süß, Wilhelm, & Wittman, 2003). For example, Brown-Peterson and complex-span tasks both show word length and similarity effects, which was interpreted as common process and storage mechanisms involved in both tasks (Tehan et al., 2001). According to Conway and colleagues (Conway et al., 2005), the crucial properties for tasks measuring WM capacity are list presentation, list retention and list recall, while processing an interfering task.

A large body of research has investigated the effect of the duration of the RI in the Brown-Peterson task. Already the first studies using the paradigm observed decreasing recall performance after longer RIs filled with a distractor task (Brown, 1958; Peterson & Peterson, 1959). These studies used steady distractor processing such as counting backwards at a constant rate. Thus, importantly, CL was naturally held constant, because longer RIs implied longer processing and free time at the same ratio.

Since, several studies replicated the negative effect of RI-duration on recall performance in the Brown-Peterson task (Floden, Stuss, & Craik, 2000; Geurten et al., 2016; Glanzer, Gianutsos, & Dubin, 1969; Vaz, Cordeiro, Macedo, & Lukasova, 2010). These studies used different memoranda (e.g., letters, words) and distractor material (e.g., counting, reading, or digits repeating), suggesting that the effect persists across domains.

Usually, when memory content is retrieved immediately after list encoding, recall is very good (Baddeley, Lewis & Vallar, 1984; Tan & Ward, 2008). Thus, at least some item representations must still be available at the start of the RI. For these representations, it should make a difference if they are refreshed much (as in case of low CL) or little (as in case of high CL) in the following RI. Therefore, according to the TBRS model, lower CL in the RI of the Brown-Peterson task should benefit recall, whereas higher CL should impair recall. Moreover, because only the CL but not the total duration of the RI is assumed to effect recall performance, the total duration effect should vanish according to TBRS. Thus, in the Brown-Peterson task, RIs of high CL should evoke poorer recall than RIs of low CL, just as in the complex-span paradigm.

One study investigated the effect of CL on recall performance in the Brown-Peterson task (Conrad & Hull, 1966). The authors varied the number of distractors to be processed and thus the processing time in relation to free time, while keeping the total duration of the RI constant. They observed a negative effect of CL, which they interpreted as support for the decay-and-rehearse-view of WM capacity. However, this interpretation is problematic, since the study confounded processing time with the number of distractors: Longer processing times (i.e., higher CL) implied a higher number of digits to be processed. This negative effect of the number of distractors on recall performance is explicitly predicted by interference models.

In the present study, we solved this confound by investigating the effect of CL in the Brown-Peterson task while keeping the number of distractors constant.

The simple-span paradigm

A commonly used paradigm to test memory performance over several seconds or minutes is the *simple-span task*. Simple-span tasks differ from complex-span tasks in that they do not contain a processing component. Memoranda are sequentially encoded. After list end, serial recall occurs either immediately or after a short delay.

Usually, recall in the simple-span task is much better than recall in the complex-span task (Lewandowsky, Geiger, Morrell, & Oberauer, 2010; Tehan et al., 2001; Unsworth & Engle, 2007), which is explained by the disruptive effect of the distractor processing on memory in complex-span. Another frequently observed finding is the increase in recall performance with slower item presentation. That is, longer intervals of free time between the list items have a more beneficial effect on immediate serial recall than shorter intervals of free time (Bhatarah, Ward, Smith, & Hayes, 2009; Mackworth, 1962; Murray & Roberts, 1968; Tan & Ward, 2008; Warrington & Shallice, 1969, for contrary findings see Conrad, Baddeley, & Hull, 1966; Frensch & Miner, 1994).

While longer intervals of free time interleaving the list-items seem to benefit recall, longer intervals of free time succeeding the list items seem not to benefit recall equally. By contrast, increasing delays in the order of seconds seem to harm recall performance instead (e.g., Peterson & Peterson, 1959).

If memory traces decay during processing, and if attention refreshes them during free time, then these mechanisms should be active irrespective of the task structure. In simple-span tasks, attention is mostly free to prevent item representations from decay. Hence, longer free time between the presentation of two items allows for more refreshing. Accordingly, the TBRS model would expect longer free time between the memoranda, i.e., a slower presentation rate of the memoranda, to have a beneficial effect on recall performance. As we have seen, this assumption is supported by the simple-span literature. However, if this effect of presentation rate in the simple-span paradigm and the effect of CL in the complex-span paradigm rely on the same mechanisms, i.e., decay and refreshing, then these effects should be equal in size. A difference in these effects would, instead, suggest that refreshing is not the only mechanism at work. Even though the literature supports the negative effect of presentation rate in simple-span tasks on the one hand and the negative effect of CL in complex-span tasks on the other hand, there are no studies to date that directly compare the size of these effects. We fill this gap by measuring the two effects in a joint design.

The present study

The present study tests predictions derived from the assumptions of the TBRS-model. The central assumption of the TBRS-model is that memory traces in short-term memory decay if not provided with attention that refreshes them (Barrouillet & Camos, 2007). However, the studies supporting this theory have only examined CL for complex-span tasks. If, however, memory traces indeed undergo decay and refreshment, then they underly decay and refreshment irrespective of the task structure. Therefore, we investigated the effect of free time for the list-interleaving RIs, list-succeeding RIs and the simple-span task. According to the TBRS model, free time should have the same effect on recall performance across different task structures, as long as all other factors (e.g., amount and nature of task material) are kept constant.

We derived two predictions from the assumption that memory items underlying temporal decay and refreshment (TBRS model, Barrouillet & Camos, 2007; Barrouillet et al., 2017). First, if refreshing is the beneficial mechanism at work during the free time of a RI, then the duration of free time in the list-succeeding RI positively effects recall performance. As previous research shows, immediate recall is usually very good (e.g., Tehan et al., 2001). Thus, it seems that the representations of several items are still active. For these representations, it should make a difference if they are refreshed a lot or only little. However, if free time has an effect in the Brown-Peterson paradigm, we expect this effect to be smaller than in the complex-span paradigm. Looking back at the research with simple-span tasks described above, we know that the effect of free time is stronger when interleaving list presentation than when being available after list presentation (e.g., Peterson & Peterson, 1959). In turn, taking away free time interleaving list presentation should have a more detrimental effect on memory than taking away free time after list presentation. Hence, taking away free time within a RI is more detrimental in the complex-span paradigm than in the Brown-Peterson paradigm. Likewise, adding free time within a RI is more beneficial for memory in the complex-span paradigm than in the Brown-Peterson paradigm. Taken together, varying free time should have a larger effect in the complex-span paradigm than in the Brown-Peterson paradigm. Second, if refreshing is the beneficial mechanism during free time in list-interleaving RIs, then the effect of free time and the effect of presentation rate are the same. Specifically, we predict that, first, the effect of free time in list-interleaving RIs and the effect of presentation rate in simple-span tasks are equal in size, and second, the effect of free time in the Brown-Peterson paradigm and the effect of the duration of the delay in delayed recall tests are equal in size.

Participants were instructed to memorize a list of consonants until being asked to recall them in their order of presentation. We varied variables within participants, thus each participant completed the same tasks, in randomized order. The independent variables were task *structure* (list-interleaving RIs, as in the complex-span task, vs. list-succeeding RIs, as in the Brown-Peterson task), *distractor-presence* (distractors present vs. distractors absent) during the RI, and the *duration* (short vs. long) of free time within a RI.

According to the decay-and-refresh-theory, longer durations of free time should benefit recall performance in all four paradigms, because they allow for longer refreshing. Therefore, longer durations of free time should positively effect recall, irrespective of distractors being present or absent and irrespective of the RIs interleaving list presentation or being administered after list presentation.

This study had two aims: First, we wanted to replicate the positive effect of longer free time in the complex-span paradigm (RIs interleaving, distractors present). We then tested if this effect can also be found in the Brown-Peterson paradigm (RIs after, distractors present). Finally, we aimed to compare the sizes of these two effects. Second, we wanted to compare the effect of longer duration of free time in distractor-present tasks (RIs interleaving, distractors present / RIs after, distractors present) to the effect in distractor-absent tasks (RIs interleaving, distractors absent / RIs after, distractors absent).

Table 1. The expected effects of free time duration depending on the condition.

	distractors absent	distractors present
list-interleaving RI	**+**	**+**
list-succeeding RI	+	+

Note. Free time within the RI is expected to have an effect on recall performance in tasks with list-interleaving RI, and in tasks with list-succeeding RI, even though the latter effect is expected to be smaller (indicated by the weaker plus-symbol). The effect should be of constant size within a specific task structure, irrespective of distractor presence.

Experiment 1

In the first experiment, we aimed to test if the effect of free time can be found in the Brown-Peterson paradigm, and if yes, to compare its size to the effect in list-interleaving RIs.

Methods

Participants and stimuli.

Psychology students (*n* = 32; female = 26) of the University of Zurich participated in exchange for course credits. The experiment was programmed in Matlab R2016a. We used the task materials of Oberauer and Lewandowsky (2014). List memoranda were drawn randomly from a pool of 19 consonants of the German alphabet. The distractor task was a binary decision task with spatial stimuli (Vergauwe, Barrouillet & Camos, 2009, see *Figure 1*). We used this task, because it has formerly been successful in showing an effect of CL on recalling verbal memoranda (Oberauer & Lewandowsky, 2014a; Vergauwe et al., 2009, 2010). A horizontal line and two squares are presented on the screen (Figure 3). The line varied in length (8, 16, 24, 32, 40, or 48 mm), and it deviated from the squares always by 10 pixels. Participants were to decide if the line would fit into the gap.

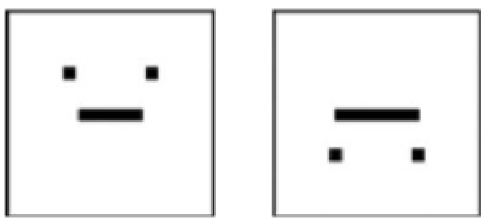

Figure 3. Two examples of distractors. Participants had to decide (yes/no), whether the line fits into the gap between the two squares (Vergauwe et al., 2009, p. 1015).

Design and variables.

The study followed a 2x2x2-within-subject design. The dependent variable was the number of items recalled in their correct position. The three factors were task structure (list-interleaving RIs vs. list-succeeding RIs), duration of free time within an RI (short vs. long) and distractor presence (absent vs. present).

Task structure.

In a task with list-interleaving RIs, each list item is followed by an RI. In a task structure with list-succeeding RI, all list items are presented first, before all RIs follow (Figure 6).

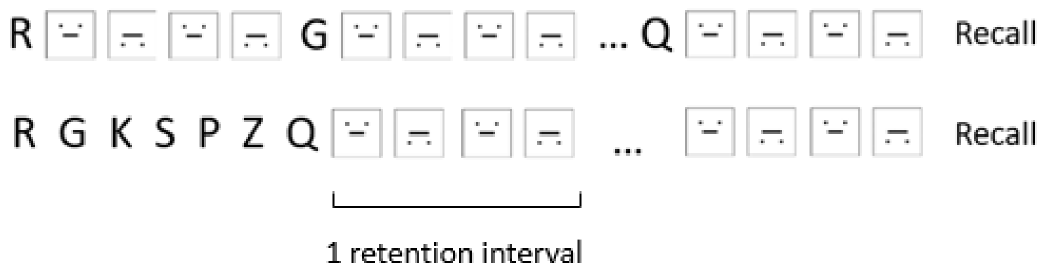

Figure 4. A trial following the task structure with list-interleaving RIs (above) and list-succeeding RIs (below). In the condition of interleaving RIs, each presented consonant is followed by a RI. Within a RI, four distractor-task-screens are subsequently presented. In the condition of succeeding RIs, all consonants are presented first, and afterwards all RIs follow. Here, the 7 x 4 = 28 distractor tasks are completed without interruption.

Distractor presence.

The RIs of one trial could be either filled with distractor tasks or unfilled (Figure 7). In filled RIs, four distractor tasks are subsequently presented. In unfilled RIs, four blank screens are subsequently presented. Filled RIs consisted of time needed to process the distractor task, added by a certain amount of free time. Unfilled RIs only consisted of free time, which was of the same amount as in filled RIs.

Duration of free time.

For the duration of the RIs, we had to determine the available time for the distractor processing (allocated only in filled RIs) and two levels of free time (allocated in filled and unfilled RIs). To determine the available time for the distractor processing, we made use of calculations by Oberauer and Lewandowsky (2014). In one part of their study, participants completed the same spatial-fit-task that we used in the present study, but without memorizing items. Each of the 20 participants responded to 256 spatial-fit-tasks, while reaction times were measured. For each participant, the authors calculated the median RT for each sequential position within the RI. Then, they averaged the median RTs across participants for each sequential position. Thereby, they received the mean amount of time participants need for the distractor task in its respective position within the RT. We used these values to determine the amount of time available for a distractor task in the first, second, third or fourth position within our filled RIs. To determine the two levels of free time, we made use of further calculations by Oberauer and Lewandowsky (2014). As in the present study, they aimed at creating two levels of free time duration within the RI. Set size and memoranda in that experiment were the same as in the present experiment. The authors used each participant's median RT exposed in the distractor task without memory load as a basis for this calculation. Then, they multiplied this value either by 1.5 or by 3, to obtain a shorter and a longer duration (in ms). In a subsequent experiment with the same sample, they applied these two levels of duration to serve as two levels of free time allocated within a RI. They observed that recall of a list of seven consonants while processing the spatial-fit-task was better for trials with RIs containing the longer duration of free time than for trials with RIs containing the shorter duration of free time. These results indicate that the factors 1.5 and 3 are suitable to be multiplied with the average time needed to process a distractor task in order to yield free-time-effects on recall performance. The successful manipulations of free time by Oberauer and Lewandowsky (2014) justify us multiplying the mean RTs across all participants for each distractor task position (0.67635, 0.54775, 0.56135, 0.56375) by the value of 3 and 1.5, in order to receive the amounts of free time allocated in the two conditions of free time (short vs. long) allocated in the RI. The RT for the first distractor of a sequence is notably longer than for the remaining distractors. This longer RT for first items persisted for tasks with memory load, and was assumed to arise from task-switching (Klaus Oberauer & Lewandowsky, 2013, 2014b). In the present case, the participant switches from encoding to processing. In order to account for the task-switching cost, we allocated extra available time (i.e., the elevated mean RT of 0.67635) for all distractor tasks which immediately follow letter presentation. In the complex-span condition, there are more distractor tasks per trial occurring immediately after letter presentation, whereas in the Brown-Peterson condition, there is always just one distractor task per trial that occurs immediately after letter presentation. Hence, the allocated total amount of free time varies between the conditions. However, this is not a problem, because the difference in allocated free time is absorbed by the additional time needed to process these first distractor tasks.

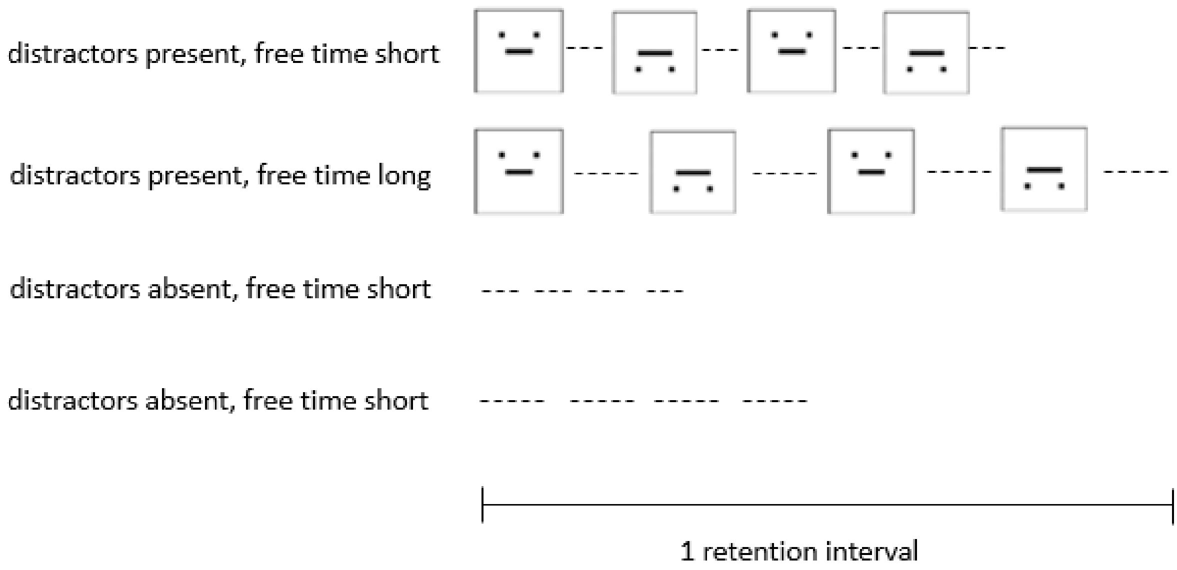

Figure 5. The RI in the four conditions of distractor presence and duration of free time. Dashed lines reflect the duration of free time allocated within the RI.

Procedure.

Participants were seated at a computer desk. After giving written informed consent, all participants received the same written instructions. They completed four training trials before each of the two task structure blocks, covering each of the four combinations of distractor-presence and duration of free time.

The experiment consisted of two blocks, one of which contained 24 trials with list-interleaving RIs, and one of which contained 24 trials with list-succeeding RIs. Distractor-presence and free-time-duration conditions (distractor-absent, short; distractor-absent, long; distractor-present, short; distractor-present, long) were randomly distributed across trials within each task block.

Each trial contained seven letters to be memorized and seven RIs. The RIs varied in combinations of structure (interleaving vs. after), distractor-presence (present vs. absent), and free time (short vs. long).

In the block with interleaving RIs, each trial started with the presentation of a black fixation cross on a white screen for one second. Then, seven consonants were presented subsequently, each consonant followed by one RI. Each consonant was presented capitalised and in red colour for one second. Each RI contained four screens. In distractor present trials, each of the four screens presented a distractor task, resulting in four distractor tasks per RI. For the distractor task, participants had to decide whether the line would fit into the gap between the squares. The stimulus stayed on screen until the time for the respective condition of free time was over. A short interval of 0.2 times the available time of the respective condition is added to the available time for the distractor task, during which the screen was blank, and during which a response was still recorded. In distractor absent trials, the four screens remained blank.

The last RI was followed by a screen indicating the recall of the encoded consonants. Seven underscores serving as prompts subsequently appeared on screen, requesting to type the seven consonants in serial order. When all seven prompts were filled, a fixed delay of 2 s followed, and the next trial began.

In the block with succeeding RIs, the procedure was the same, except one aspect: While in the block with interleaving RIs each consonant presented was followed by a RI, here, all consonants are presented first, and RIs were subsequently presented after the presentation of the last consonant.

Instructions.

For list encoding, participants were instructed to read each letter aloud and to remember all letters in their order of presentation.

For the distractor tasks, they were instructed to use the index finger of their right hand to press the arrow key pointing left if they decided that the line would fit. Further, they should use the middle finger of their right hand to press the arrow key pointing right if they decided that the line would not fit. Moreover, they were instructed to respond as fast as possible, as the available time was limited.

For recall, participants were instructed to type the consonants in their order of presentation. They were instructed to guess, if they were not sure about a consonant at a specific position, and to keep up the correct positions of the remaining consonants. They were not allowed to skip a letter.

Analysis.

Data were analysed using generalized linear mixed-effects models (GLMER) in R (R-Development-Core-Team., 2012). A stepwise backwards reduction of the full model was performed using Bayesian analysis of variance (BANOVA; Rouder, Morey, Speckman, & Province, 2012) to receive Bayes factors (BF) for the model components. We used Bayesian analysis, because we predict no effect in our second prediction. Bayesian statistics allows to assess evidence against an effect, instead of only allowing to either observe or not observe evidence for an effect, as in the classical frequentist statistics.

A BF indicates how much the ratio of the prior probabilities of the two models should be updated in light of the new data. For example, if an alternative model is tested against a null model with equal prior probabilities, and the BF_{10} is above 30, then we obtain very strong evidence for the alternative model (1) compared to the null model (0). By contrast, a $BF_{10} = 0.5$ indicates evidence against the alternative model. In specific, the null model explains the data twice as good as the alternative model. Guides on how to calculate and interpret Bayes factors (e.g., Jarosz & Wiley, 2014) refer to established verbal descriptions of the evidence expressed by the Bayes values (Jeffreys, 1961). According to these, Bayes factors between 1 and 3 are "anecdotal evidence" in favour of the H1; BF_{10} between 3 and 10 are "substantial evidence", BF_{10} between 10 and 30 are "strong evidence", BF_{10} between 30 and 100 are "very strong evidence", and BF_{10} above 100 are "decisive evidence". By contrast, $BF_{10} < 1$ reflect evidence against the effect proposed by the H1.

$$\mathrm{BF10} = \frac{likelihood\ of\ data\ given\ H1}{likelihood\ of\ data\ given\ H0}$$

Figure 6. The Bayes factor in favour of the alternative hypothesis over the null hypothesis (BF_{10}) is the ratio of the likelihood of the data under the assumption of H1 to the likelihood of the data under the assumption of H0.

Results

We excluded three participants from analysis, because their distractor task performance diverged far from the median (77.1%; 67.1%; 64.1%; median: 91%) and one participant, because memory performance was at 10.1 %, whereas the averaged recall performance across all participants was at 69.2%. The diverging of these values from the median suggest that these four participants did not appropriately follow the instructions.

In our analysis, we included task, distractor and free time as well as participant as random factor in our model. We used Bayesian ANOVA to test for the roles of all variables in the overall model. Moreover, we tested our predictions, using Bayesian ANOVA.

We tested the evidence for each effect by comparing a model including that effect together with other effects to a model excluding that effect while keeping all other effects. We first tested the random slopes of the interaction terms, followed by the random slopes of the main effects. We then tested the effects of each interaction term, starting with the three-way-interaction, followed by all two-way-interactions. Then, we tested the main effects of task, distractor and free time separately.

The BF_{10} in favor of a model including free time in the task with distractor-present list-interleaving RIs (complex-span task) indicated very strong evidence for free time. The BF_{10} in favor of a model including free time in the task with distractor-present list-succeeding RIs (Brown-Peterson task) indicated evidence against an effect of free time (Table 2). Thus, we replicated the effect of free time in list-interleaving RIs with distractors but did not find an effect of free time in list-succeeding RIs with distractors (Figure 7).

The BF_{10} in favor of a model including free time in the task with distractor-absent list-interleaving RIs (complex-span task) indicated anecdotal evidence for free time (Table 2).

Thus, the effect of free time was stronger in list-interleaving RIs with distractors than without distractors (Figure 8).

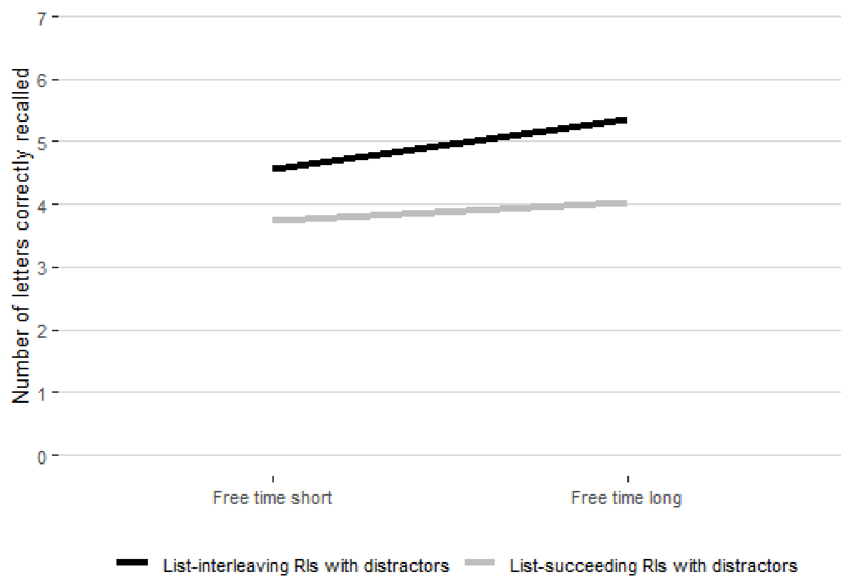

Figure 7. Letters correctly recalled in distractor-present trials, as function of free time and task structure.

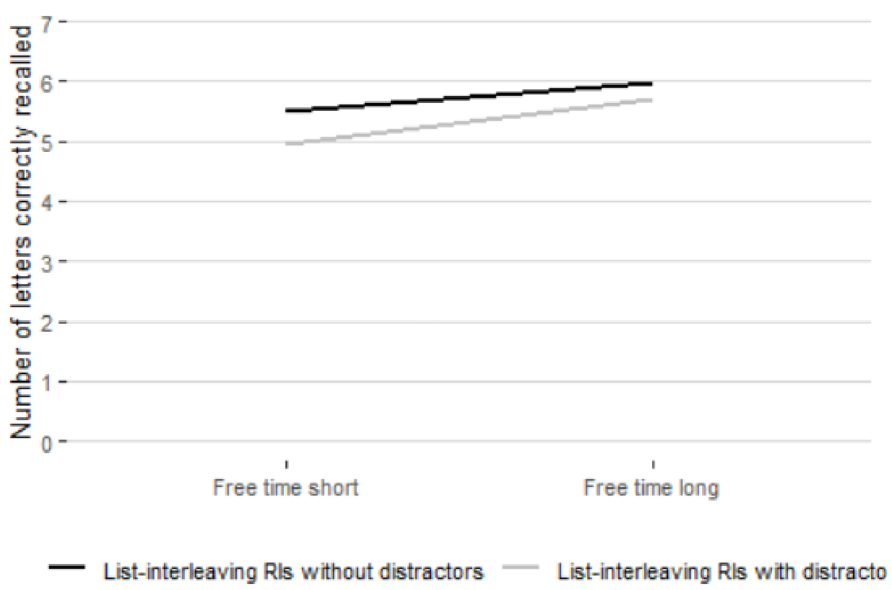

Figure 8. Letters correctly recalled in list-interleaving RIs, as function of free time and distractor-presence.

Table 2. Bayes factors for experiment 1.

Factor	BF_{10}
random interactions	2,94083869176875E-11
random main effects	1,35957536162643E-06
task*distractor*pace	0,211966482419035
task*distractor	1,18673613269816
task*pace	3,35347134487199
distractor*pace	0,803663442251517
task	11450110279,1934
distractor	98047,1053535137
pace	7,79360456068586
pace in complex-span/distr. absent	**2,4624754429869**
pace in complex-span/distr. present	**90,7657071937991**
pace in Brown-P./distr. absent	**0,604484170045666**
pace in Brown-P./distr. present	**0,279282839745024**

Note. Bayes factors (BF_{10}) from model comparisons of experiment 1. All models include participants as random factor.

Discussion

This experiment revealed two important findings. First, we replicated the effect of free time in the complex-span paradigm but did not observe any effect of free time in the Brown-Peterson paradigm. Second, we replicated the effect of free time in the simple-span paradigm. However, contrary to our prediction, this effect was smaller than the effect for list-interleaving RIs. In list-succeeding RIs without distractors, we did not observe an effect of free time.

Both findings do not support the predictions derived from the TBRS model. In the first prediction, we expected a positive effect of free time in list-succeeding RIs, although a smaller effect than the effect for list-interleaving RIs. Contrary to the predictions, we did not observe an effect of free time in list-succeeding RIs with distractors at all, whereas the effect of free time for the list-interleaving RIs with distractors could be replicated. The successful replication shows that the manipulation of free time has worked, and that our task is appropriate to reveal an effect of free time of recall performance. Thus, if WM capacity is based on temporal decay and refreshing, the effect should have also been present in list-succeeding RIs. Because there was no effect of free time in list-succeeding RIs, we can logically infer that WM capacity is not based on the mechanisms of decay and refreshing.

In the second prediction, we expected the effects of free time in the distractor-present conditions and in the distractor-absent conditions to be equal in size. Our results revealed an effect of free time in both the distractor-present and distractor-absent condition of the task with list-interleaving RIs. However, the effect was stronger in the distractor-present condition than in the distractor-absent condition. Our results further revealed no effect of free time in both the distractor-present condition (as reported above) and distractor-absent condition of the task with list-succeeding RIs. The TBRS model hypothesizes that refreshing is the mechanism active during free time, benefitting recall. If the same mechanism (i.e., refreshing) was at work during free time irrespectively of distractor presence, then the effect of free time should be of the same size in these two conditions. Because the effects differ in size in the condition with list-interleaving RIs and were not present at all in the condition with list-succeeding RIs, we can infer that different mechanisms are active during free time in distractor-present and distractor-absent tasks with list-interleaving RIs and that these mechanisms are not active during free time in distractor-present and distractor-absent tasks with list-succeeding RIs. Recall was higher for RIs without distractors than with distractors, irrespectively of the task structure. This is not surprising: in the distractor-present condition there is less free time available. Our results revealed a ceiling effect for the mean number of correctly recalled letters in the slow interleaving task without distractors. This ceiling effect could be responsible for the smaller effect of free time in the distractor-absent condition, because the average distribution is cut off, not allowing for more variance between the free-time-conditions for technical reasons. Hence, it would be helpful to have a more difficult task in the distractor-absent complex-span condition in order to decrease average performance and to investigate the full potential of the effect.

Experiment 2

The second experiment aimed at investigating in more depth the comparison between the effect of free time for list-interleaving RIs with distractors and without distractors. It differed from the first experiment in three aspects. First, we dropped list-succeeding RIs and only administered trials following the complex-span pattern. Second, we reduced the presentation time of the consonants from 1 s (in the first experiment) to 500 ms. This adaption makes the overall task more difficult, and the average recall performance should be lower in all conditions than in the first experiment. By decreasing average task performance, we aim to avoid the ceiling effect of task performance that we had in the task with list-interleaving RIs without distractors in the first experiment. And third, in the condition with distractors, we now presented only five consonants instead of seven. By this reduction of memory load, we aimed to make this condition easier, in order to raise the average performance up to the same level as in the condition without distractors. Having equal levels of average performance in both levels is necessary in order to compare the sizes of the effects of free time at a later point. We assume that effect of free time on performance follows a logit function. On this function, equal changes in the x-variable naturally lead to different changes of the y-variable, depending on the slope of the logit function at the respective position of the x-variable. By contrast, on a linear function, equal changes in the x-variable lead to equal changes of the y-variable throughout the whole function. In the present case, free time has only a weak effect on recall performance when free time is added to a very short or a very long interval of free time. Likewise, free time has a strong effect on recall performance when free time is added to a free-time-interval of medium duration. Thus, if we aim to compare the effect of free time in the distractor-absent and distractor-present condition of the list-interleaving RI, we have to ensure that the overall task difficulty does not differ between these two conditions. Because, the distractor-present tasks are generally more difficult that distractor-absent tasks, as we have seen in the first experiment, we need to reduce difficulty in the distractor-present task or increase difficulty in the distractor-absent task.

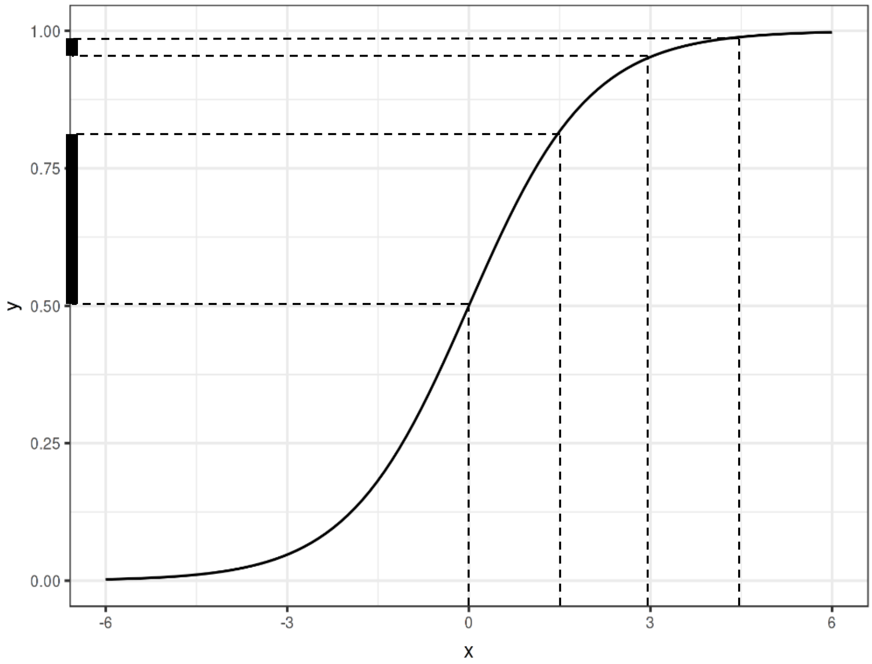

Figure 9. Logit function. On this function, equal changes in the x-variable naturally lead to different changes of the y-variable, depending on the slope of the logit function at the respective position of the x-variable.

https://www.google.com/search?q=logit+function&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjr0f-vzfvhAhWuUhUIHdQfDPEQ_AUIDigB&biw=2304&bih=1051#imgrc=soLjkOy3lV0p-M:

Methods

Participants and stimuli.

Psychology students (*n* = 25; female = 21) of the University of Zurich participated in exchange for course credits. The materials used were the same as in experiment 1.

Design and variables.

This experiment followed a 2x2-within-subject design, with the two independent variables of free time within the RI (short vs. low) and distractors (present vs. absent). The dependent variable is the proportion of consonants recalled in their correct position. The experiment consisted of a total number of 48 trials. Pace and distractor conditions are randomly distributed across all trials. Trials of the distractor-present condition contain seven letters to be memorized and seven RIs, which can be either fast or slow. Trials of the distractor-absent condition contain five letters to be memorized and five RIs interleaving the list. In the distractor-present trials, participants complete four distractor tasks per RI. In the distractor-absent condition, the screen stays blank during the RI. Moreover, in half of the trials, RIs were short, and in the other half of the trials, RIs were long. Before the experiment started, participants pass a training phase. They performed four training trials, one of each of the four trial-conditions.

The manipulations of distractor-presence and of free time were the same as in experiment 1.

Procedure and instructions.

The procedure was the same as in experiment 1, with three exceptions: First, experiment 2 contains only RI-interleaving-tasks. Second, consonants were presented at a rate of 0.5 s. And third, the memory set in the distractor-present condition contained only five consonants, whereas the set in the distractor-absent condition still included seven consonants.

Analysis.

The analysis was the same as in experiment 1.

Results

We excluded two participants from analysis. One participant had a distractor task performance of only 74.2 %, whereas the median across participants was at around 93 %, and a memory performance of only 49.0 %, while the median across participants was at around 79 %. The other participant had an appropriate distractor task performance, however, had a memory performance of only 14.6 %. These low average values suggest that the participants did not follow the instructions appropriately.

In our analysis, we included distractor and free time as well as participant as random factor in our model. We used Bayesian ANOVA to test for the roles of all variables in the overall model. Moreover, we tested our predictions, using Bayesian ANOVA.

We tested the evidence for each effect by comparing a model including that effect together with other effects to a model excluding that effect while keeping all other effects.

We first tested the random slopes of the main effects, followed by the interaction term. We then tested the main effects of distractor and free time. Then, we tested the main effects of task, distractor and free time separately.

The BF_{10} in favor of a model including pace in the task with distractor-absent list-interleaving RIs indicated decisive evidence for the effect of pace. The BF_{10} in favor of a model including pace in the task with distractor-present list-interleaving RIs indicated anecdotal evidence for the effect of pace (Table 3). The large difference in BF_{10} indicates that the effect of free time is larger in the condition with absent than with present distractors.

Table 3. Bayes factors for experiment 2

Factor	**BF10**
random main effects	0,906553784796548
distractor*pace	7,71620565098147
distractor	37,3002598522578
pace	665,345558998301
pace in complex-span/dist. absent	**5346,18911335927**
pace in complex-span/distr. present	**2,58453169572556**

Note. Bayes factors (BF_{10}) from model comparisons of experiment 2. All models include participants as random factor.

Discussion

The results of the second experiment replicated the effect of free time in both the distractor-present and the distractor-absent complex-span paradigm. Moreover, this effect was larger in the distractor-absent condition than in the distractor-present condition. This finding is the opposite of the finding in experiment 1, where the effect of free time was larger in the distractor-present condition than in the distractor-absent condition.

With the second experiment, we aimed to counteract ceiling effects in the slow distractor-absent condition. The manipulation of accelerating letter presentation rate in both conditions was successful in that it led to an overall decrease in average recall performance, preventing the performance distribution in the slow distractor-absent condition from touching ceiling. Moreover, the manipulation of reducing memory set size in the distractor-present condition evoked an increase in average performance only in this condition, thereby lifting the average performance of the two conditions to an equal level on the number scale (but not on the proportion-correct scale). Equal average performance is necessary, if we aim to compare the effect size of free time in the two conditions. Comparing the effect size, we observe a positive effect of RIs including long free time compared to short free time. Moreover, this effect was even stronger in the distractor-absent condition than in the distractor-present condition, suggesting that the effect in experiment 1 was indeed limited by touching ceiling. However, and crucial for our study, the free time effects were not of equal size in the distractor-present and -absent condition. The difference in size suggests that the effects of free time in the two tasks are not caused by the same mechanism.

This finding is problematic for the TBRS model. The model assumes that the decay and refreshing are the mechanisms at work in WM tasks, determining WM capacity. If this was the case, then free time should have equal effects on recall in the task with list-interleaving RI, irrespective of distractor presence. Because the free-time-effects differ, depending on distractor presence, we can infer that the mechanisms active during free time in these conditions differ.

General discussion

We derived predictions on the effect of free time on WM performance from the TBRS model and tested them in two experiments. The first experiment replicated the effect of free time on recall performance in the task with list-interleaving RIs. However, and contrary to the predictions of the TBRS model, it revealed no effect of free time in list-succeeding RIs. Moreover, and again contrary to the predictions of the TBRS model, it revealed different effect sizes for free time in distractor-present and distractor-absent tasks with list-interleaving RIs, with a larger effect in the distractor-present condition. In the second experiment, we only allocated list-interleaving RIs. We accounted for a potential ceiling effect in the condition of distractor-absent tasks with list-interleaving RIs of the first experiment. To increase task difficulty over the whole experiment, we presented the list of consonants at a rate twice as high than in the first experiment (500 ms instead of 1 second). To further serve for equal difficulty across the distractor-absent and distractor-present condition, we reduced task difficulty in the distractor-present condition by reducing the memory set from seven to five items. For analysis, we then used the proportions of correctly recalled items instead of the absolute number as in the first experiment. Results revealed a larger effect of free time on recall performance for the distractor-absent condition compared to the distractor-present condition, suggesting that the opposite effect in the first experiment had indeed been subject to touching ceiling. In the following, the findings will be more deeply assessed from the viewpoint of the TBRS model, and alternative explanations will be discussed.

Our first prediction proposed a positive effect of free time in list-succeeding RIs. First, the twofold replication of the free-time-effect for distractor-present list-interleaving RIs indicates that our test paradigm is in principle capable of revealing effects of free time, and thus, that null-effects in our data most likely represent true null-effects. Second, and contrary to the finding in the complex-span paradigm, free time does not affect memory in list-succeeding RIs. Rather, the null-effect of free time in list-succeeding RIs suggests that the assumption of CL cannot be applied to all WM tasks. Thus, it is unlikely that temporal decay and refreshing are the mechanisms determining WM capacity. Instead, its empirical support is restrained to studies using complex-span tasks. This suggests that different mechanisms are active during processing and during free time, depending on the structure of the task. The present results thus contradict the assumption of decay and refreshing as common processes underlying WM capacity.

We can exclude the possibility that the missing effect stems from touching ceiling or floor in both free time conditions: Rather, the average number of correctly recalled letters was with 4.27 in list-succeeding RIs not conspicuous at all.

To defend the TBRS model in light of the missing effect of free time in the Brown-Peterson paradigm, TBRS proponents could point to the covert retrieval model (Loiza & McCabe, 2012). According to this model, refreshing does not only activate the memory item itself, but also its connection to its context. Hence, refreshing in the complex-span task also refreshes the information of the accompanying distractor stimuli of the respective item. This information serves as beneficial cue when retrieving the memory items (McCabe, 2008). Because in the complex-span task item encoding alternates with distractor processing, many retrieval cues can be created that are beneficial for recalling the encoded items. By contrast, in the Brown-Peterson task, item encoding is completed before distractors are processed. Thus, in the Brown-Peterson task, the distractors are not informative as retrieval cues for the memory items. In line with this assumption, delayed recall was better in a complex-span than in a simple-span task (Loaiza & McCabe, 2012).

To further explain the absence of effect in the Brown-Peterson task, TBRS model proponents could argue that memory traces have already become inactivated over the period of distractor processing in the list-succeeding RI. Thus, free time allocated after distractor processing would come too late for refreshing. Taking a closer look at the processing durations in the Brown-Peterson task, averaged processing durations across participants were approximately 25.2 s for the short-free-time-condition and 50.4 s for the long-free-time-condition.[1] Previous research showed that participants were able to retrieve 40% of the learnt items after one minute of delay while counting backwards (Valérie Camos & Portrat, 2015). Although memory items had been repeatedly encoded and could be freely instead of serially retrieved after the delay, displaying advantages over the memory items of the present study that have only been encoded once before retrieval and further had to be retrieved in serial order. Moreover, memoranda were short words instead of letters, which could have further contributed to encoding the items into long-term memory. Despite of these advantages which memory items in this study had in order to stay active compared to the memory items in the

[1] 0.5 s (RT) x 1.2 (constant) x 1.5 (short free time manipulation) x 4 (distractors/RI) x 7 (RIs) = 25.2 s;

0.5 s (RT) x 1.2 (constant) x 3.0 (long free time manipulation) x 4 (distractors/RI) x 7 (RIs) = 50.4 s present study, it is highly probable that also the memory traces in the present condition with list-succeeding RIs to at least some extend survived the processing time.

In sum, the missing effect of free time on recall performance in the Brown-Peterson task has several implications. First, it suggests that it is not decay and refreshing determining WM capacity. If this was the case, free time should have had a positive effect in the Brown-Peterson task, just as in the complex-span task. Second, it suggests that the mechanisms active during free time allocated after list-presentation is less or not beneficial for recall performance compared to free time interleaving list-presentations. This finding is in line with research with the simple-span paradigm where especially free time interleaving list presentation benefited recall. We can thus infer that the mechanism at work during free time interleaving list presentation is not at work during free time following list presentation. Further, we can infer that this mechanism is not refreshing decaying memory traces.

But what is the mechanism active during free time in complex-span tasks? The SOB-CS model suggests removal of interference as possible mechanism. For example, longer free time in the distractor task in complex-span task could have its positive effect on recall because more time is available to remove interference. The SOB-CS also accounts for other findings initially supporting the TBRS model. For example, the negative effect of processing duration stems from the increase of distractor number that usually accompanies an increase in processing duration. However, the SOB-CS has also difficulties accounting for the present finding. More free time for removal should benefit recall also in the SOB-CS, irrespectively from the task structure. Yet, removal of interference is a very slow process compared to the rapid attentional refreshing (Oberauer, Lewandowsky, et al., 2012), taking 1-2 s to remove one distractor. Therefore, the difference in the duration of free time could have not been large enough in order to allow the removal process to show different effects in recall performance. Future studies could investigate if a larger difference between the conditions of free-time-duration could reveal a positive effect of longer free time that could be interpreted in terms of removal.

Our second prediction concerned the effect of free time on memory in the complex-span and the simple-span task. The TBRS model assumes that decay and refreshing are the common mechanisms determining WM capacity. If this was the case, then they should determine WM capacity irrespective of the task structure. Accordingly, the effect of free time (during which refreshing can counteract decay) should be the same in distractor-absent and distractor-present tasks. However, our data shows the contrary: When controlling for ceiling effects, the effect of free time on recall performance was larger in distractor-absent than in distractor-present tasks. This difference in effect size suggests that there are different mechanisms active during free time in the distractor-absent and in the distractor-present tasks. The mechanisms which are active during free time in the retention interval and which have a beneficial effect on memory thus seem to depend if there was previous distractor processing or not.

These results challenge the TBRS model not only because of the differing effect sizes of free time on distractor-presence, putting the idea of a common refreshing-mechanism into question. To an even greater degree, they challenge the TBRS model because the effect of free time is larger in distractor-absent tasks compared to distractor-present tasks. The TBRS model could have accounted for differing effect sizes if free time would have had a larger effect in distractor-present tasks. After distractor processing, a memory items have been longer subject to decay than when there was no distractor processing. Hence, memory items would profit more from long refreshing periods after distractor processing than immediately after item encoding. However, our results show the opposite: Free time is more beneficial in the absence than in the presence of distractor processing.

The stronger effect of free time in distractor-absent than in distractor-present tasks also questions the covert retrieval model that we suggested to account for the missing effect of free time in list-succeeding RIs (Loiza & McCabe, 2012). If free time was more efficient in the complex-span than in list-succeeding RIs because only the alternating structure of item and distractor presence in the former allows the creation of retrieval cues, then free time should have been also more efficient in the complex-span than in the simple-span because only the former includes distractor stimuli that could serve as retrieval cues. However, we observed the contrary: free time was more efficient in the simple-span than for list-interleaving RIs. This finding contradicts the covert retrieval model, and it rules out one possible decay-and-refresh-explanation of the null-effect of free time in list-succeeding RIs.

Conclusion

In the present study, we have investigated the role of free time within the RI of different tasks involving memory retention over the short-term. Contrary to assumptions of the TBRS model of decay-and-refreshing, the effect of free time could not be replicated when the RI succeeded rather than interleaved list presentation. Moreover, and further challenging the assumptions of the TBRS model, free time had a larger effect in tasks lacking distractor processing compared to tasks including distractor processing, suggesting that different mechanisms are at work in these two conditions. More precisely, decay-and-refresh are most likely not the common mechanisms determining WM capacity.

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List of abbreviations

CL	cognitive load
RI	retention interval
RT	reaction time
WM	working memory

Appendix

Zusammenfassung

Die Abrufleistung für kurze Listen im Arbeitsgedächtnis steigt, je mehr freie Zeit zwischen den Elementen der Listen zur Verfügung gestellt wird. Das Time-Based Resource-Sharing (TBRS) Modell erklärt diesen Befund mit der *kognitiven Last* des Retentionsintervalls (RI): Je mehr Zeit innerhalb des Retentionsintervals für das Bearbeiten von Ablenkaufgaben verwendet wird, und je weniger Zeit frei verfügbar ist, um zerfallende Gedächtnisspuren aufzufrischen, desto schädlicher ist der Effekt auf die Leistung im seriellen Abruf der Listenelemente. Wir leiten daraus zwei Vorhersagen ab: Erstens, unter Konstanthaltung der Bearbeitungszeit von Ablenkaufgaben sollte der positive Effekt von freier Zeit auf die Abrufleistung nicht nur in Aufgaben zu finden sein, in denen sich RI und Listenelemente abwechseln (wie in der kompelxen Spannenaufgabe), sondern auch in Aufgaben, in denen zuerst alle Listenelemente und anschließend alle RIs präsentiert werden (wie in der Brown-Peterson-Aufgabe). Darüber hinaus sollte der Effekt von freier Zeit in Aufgaben mit und ohne Distraktoren gleich groß sein. Die aktuelle Studie untersucht den Effekt von kognitiver Last in einem 2x2x2 Messwiederholungsdesign mit den Variablen Aufgabenstruktur (RIs zwischen Listenelementen vs. RIs nach Listenelementen), Distraktoren (mit vs. ohne) und Dauer der freien Zeit (kurs vs. lang). Die Ergebnisse widersprechen den Vorhersagen des TBRS-Modells: Freie Zeit hatte nur einen Einfluss auf Abrufleistung in Aufgaben mit RIs zwishcen Listenelementen, aber nicht in RIs nach Listenelementen. Weiterhin war der Effekt von freier Zeit in Aufgaben mit RIs zwischen Listenelementen größer in Bedingungen mit als in Bedingungen ohne Distraktoren. Zusammengenommen sprechen die Befunde gegen einen übergreifenden Effekt von kognitiver Last, wie das TBRS-Modell ihn vorhersagt.

Schlüsselwörter: Arbeitsgedächtnis, Kapazitätsbeschränkung, komplexe Spannenaufgaben, Brown-Peterson-Aufgaben, kognitive Last, Time-Based-Resource-Sharing-Modell

Abstact

In working memory tasks with list-interleaving retention intervals, recall performance increases when the amount of free time interleaving the list items is increased. The time-based resource-sharing model (TBRS) explains this finding with the cognitive load (CL) of the RI: The higher the ratio of processing time to free time, the more detrimental is the effect on recall performance. We derive two predictions from the premise of free time determining WM capacity. First, when keeping processing time constant, the positive effect of free time on recall performance should not only be found when the RI interleaves list presentation (as in the complex-span task), but also when it follows list presentation (as in the Brown-Peterson task). Moreover, the effect of free time should be equal in distractor-absent and -present conditions. The current study examines the effect of cognitive load in a 2x2x2 within-subject design, varying task structure (list-interleaving RIs vs. list-succeeding RIs), distractor presence (present vs. absent) and duration of free time within the RI (short vs. long), whereas a common task paradigm was applied to all conditions. Our results contradict the assumptions of TBRS. First, when keeping processing time in the RI constant, free time did not have an effect in the Brown-Peterson task, whereas the effect in the complex-span task was replicated. Second, the effect of free time was larger for unfilled RIs than for distractor-filled RIs interleaving list presentation, suggesting that these tasks differ in the beneficial mechanisms active during free time. The present findings challenge a core assumption of the TBRS model, according to which cognitive load is the common driving factor limiting WM capacity.

key words: working memory capacity, complex-span task, Brown-Peterson task, cognitive load, time-based resource-sharing model