Forgetting at short term: When do event-based interference and temporal factors have an effect?

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Forgetting at short term: When do event-based interference and temporal factors have an effect? ☆

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ABSTRACT

Memory tasks combining storage and distracting tasks performed at either encoding or retrieval have provided divergent results pointing towards accounts of forgetting in terms of either temporal decay or event-based interference respectively. The aim of this study was to shed light on the possible sources of such a divergence that could rely on methodological aspects or deeper differences in the memory traces elicited by the different paradigms used. Methodological issues were explored in a first series of experiments by introducing at retrieval computer-paced distracting tasks that involved articulatory suppression, attentional demand, or both. A second series of experiments that used a similar design was intended to induce differences in the nature of memory traces by increasing the time allowed for encoding the to-be-remembered items. Although the introduction of computer-paced distracting tasks allowed for a strict control of temporal parameters, the first series of experiments replicated the effects usually attributed to event-based interference. However, deeper encoding abolished these effects while time-related effects remained unchanged. These findings suggest that the interplay between temporal factors and event-based interference in forgetting at short term is more complex than expected and could depend on the nature of memory traces.

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1. Introduction

Forgetting in the short term is a ubiquitous and pervasive phenomenon that led psychologists to coin the concept of short-term memory (STM) as opposed to a more stable long-term memory (LTM). The limitations of this STM are exemplified in tasks known as immediate serial recall tasks in which individuals are asked to recall series of digits, letters, or words immediately after their presentation. The maximum number of items that can be maintained and recalled under these conditions proved surprisingly low, about 7 plus or minus 2 according to a venerable tradition (Miller, 1956), demonstrating that information rapidly vanishes. After about a century of enquiry, two causes of forgetting in the short term have been evoked. While some theoreticians have argued for a temporal decay of memory traces (Brown, Neath, & Chater, 2007; Burgess & Hitch, 1999; Page & Norris, 1998), others have denied it and favored an event-based interference account (Lewandowsky,

Oberauer, & Brown, 2009; Nairne, 1990; Oberauer & Kliegl, 2006; Oberauer & Lewandowsky, 2008; Waugh & Norman, 1965). Indeed, memory failure could result from a lack of distinctiveness between the memory target and competitors, to an overwriting of their common features, or to a superposition of memory traces of relevant items and competitors into a common weight matrix that would have the same effect of distorting memory traces (Oberauer, Farrell, Jarrold, Pasiecznik, & Greaves, 2012). Recent studies that explored the sources of forgetting in the short term led to a rather mixed picture. Though some studies reported very little loss of information over time (Berman, Jonides, & Lewis, 2009; Cowan et al., 2006; Lewandowsky, Duncan, & Brown, 2004; for a synthesis, see Lewandowsky et al., 2009), the temporal decay hypothesis received recent empirical support (Barrouillet, De Paepe, & Langerock, 2012; Cowan & AuBuchon, 2008; Ricker & Cowan, 2010), indicating that further studies are needed to decipher the puzzle of forgetting in the short term.

Interestingly, emphasis in one of the factors seems to depend on the paradigm that researchers favor. Several recent studies using complex span paradigm in which participants are asked to memorize a list of items for further recall while processing intervening distractors after encoding each memory item point toward a role for temporal factors (for a review, Barrouillet, Portrat, & Camos, 2011a). By contrast, memory tasks in which intervening activities do not take place at encoding but at retrieval (participants are presented with a list of items for immediate serial recall and process distractors between retrievals) bring evidence for event-based interference (e.g., Lewandowsky, Geiger, & Oberauer,

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2008). The present study intended to clarify these apparently inconsistent results by exploring the methodological and theoretical issues that could underlie them. Are these discrepancies resulting from differences in the way these tasks are designed, or from deeper differences in the memory processes the two paradigms elicit?

1.1. Forgetting in complex span tasks

In order to investigate the role of time in short term forgetting, we designed computer-paced complex span tasks in which temporal factors are carefully controlled. For example, Barrouillet, Bernardin, and Camos (2004) designed a reading digit span task in which participants were presented with lists of letters for further recall while reading series of digits successively displayed on screen at a fixed pace after each letter. We manipulated both the number of digits to be read between two successive letters and the time allowed to read them (i.e., the inter-letter interval). The results revealed that recall performance did not depend either on the total time elapsed between encoding and recall or on the number of distractors to process in the inter-letter intervals, but on the ratio between these two factors. More precisely, memory spans proved to be a linear function of the ratio between the number of digits to be read and the time allowed to read them, with more distractors processed per unit of time resulting in poorer recall performance.

The TBRS model was designed to account for this relationship. Barrouillet et al. (2004) hypothesized that, in complex span tasks, memory traces of the items to be recalled suffer from a time related decay as long as attention is occupied by the intervening task, but that this memory traces can be reactivated by attentional focusing as soon as attention is available. For this purpose, attention is rapidly and continuously switched back and forth from processing to storage to avoid a complete loss of memory traces, this switching occurring during short pauses that can be freed while performing the processing component of the task. The main prediction of this model is that recall performance should be a function of the proportion of time during which the processing component of the task occupies attention, thus impeding attentional refreshing to counteract time-related forgetting. This proportion of time is called cognitive load. Increasing the pace at which the digits appeared on screen increased cognitive load and resulted in poorer recall of the letters, an effect that has been extensively replicated with a variety of memoranda and intervening tasks, in adults (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Barrouillet, Portrat, Vergauwe, Diependaele, & Camos, 2011b; Lépine, Barrouillet, & Camos, 2005a; Lépine, Bernardin, & Barrouillet, 2005b; Vergauwe, Barrouillet, & Camos, 2009, 2010) as well as in children (Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009; Camos & Barrouillet, 2011; Gavens & Barrouillet, 2004; Portrat, Camos, & Barrouillet, 2009). It is worth to note that the crucial factor for the TBRS model is not the absolute duration of the delay between encoding and retrieval, but the balance between processing time during which memory traces decay and the time available to restore them, this balance determining the number of memory items that can be sufficiently refreshed during free time to survive decay during processing time. Thus, as long as this balance remains unchanged, that is when distractors are performed at a constant pace, the TBRS model does not predict any effect of the number of distractors, a prediction that was empirically verified in several studies (Barrouillet et al., 2004; Barrouillet et al., 2011b; Plancher & Barrouillet, in press).

We recently extended our TBRS model by adding to the attentional refreshing the rehearsal mechanism described by Baddeley (1986) in his phonological loop model (Barrouillet & Camos, 2010). While phonological information suffers from a time-related decay, a covert articulatory process serves to refresh the decaying representations. Camos, Lagner, and Barrouillet (2009) investigated the existence of these two mechanisms of maintenance and their relationships by manipulating

both the cognitive load and the level of articulatory suppression involved by the processing component of a complex span task. Increasing this cognitive load was intended to disrupt attentional refreshing whereas the articulatory suppression was intended to block the rehearsal mechanism. The results revealed that both a higher cognitive load and a concurrent articulation had a detrimental effect on recall, but these two effects were additive, suggesting that attentional refreshing and verbal rehearsal are two independent mechanisms that can work jointly to maintain verbal information (for congruent findings, see Hudjetz & Oberauer, 2007). Moreover, the results also revealed that in the same way as increasing the pace of the distracting task had a detrimental effect on spans, increasing the pace of the articulatory suppression disrupted concurrent maintenance. Thus, the efficiency of the two mechanisms of maintenance seems to be constrained by temporal factors.

1.2. Moving distracting tasks from encoding to retrieval

With the same objective of investigating the effect of time on forgetting in short term memory, Lewandowsky et al. (2004) introduced a paradigm in which participants were presented with a list of letters for immediate serial recall but asked to repeat aloud an irrelevant word (*super*) before each retrieval. This concurrent articulation was intended to prevent rehearsal and to deconfound time and amount of interference: increasing the number of repetitions of *super* increases the delay between encoding and retrieval while repeating the same distractor leaves unchanged the amount of event-based interference. As noted by Oberauer and Lewandowsky (2008), there are similarities between this paradigm and the complex span task: in the complex span task, the intervening process alternates with encoding of to-be-remembered items, whereas Lewandowsky et al.'s paradigm intersperses articulatory suppression with retrieval. This paradigm was subsequently amended by Oberauer and Lewandowsky (2008) who noted that the articulatory suppression involved by continuously repeating *super* was unlikely to prevent any form of active maintenance. People might indeed be able to maintain active memory traces through attentional refreshing. Thus, they designed a new task in which they manipulated the delay between encoding and retrieval while preventing both rehearsal and refreshing using two distractor tasks: the repeated pronunciation of *super* and a speeded choice task known to disrupt attentional refreshing.

Another variant was introduced by Lewandowsky et al. (2008) to test their SOB model, which assumes that forgetting results from interference created by the obligatory encoding of the distractors that are processed. According to this model, memoranda and distractors are represented by vectors of features associated to a positional marker and superimposed onto a common weight matrix (Farrell & Lewandowsky, 2002). The main tenet of the model is that encoding is energy gated or novelty sensitive. The encoding strength of an item is a function of its novelty or dissimilarity with the current content of STM, with novel items being encoded with a large encoding weight, whereas those that resemble already-encoded information receive smaller encoding strength. Thus, repeated items would result in negligible encoding weight and would not create further interference. Lewandowsky et al. (2008) manipulated the similarity of the distractors by comparing bursts uttered before each retrieval that contained repeated distractors (for example, saying "office, office, office") with bursts containing changing distractors ("office, summer, table").

The results of these different studies showed that increasing the number of utterances of same distractor had no effect on recall performance (Lewandowsky et al., 2004), even when these utterances were accompanied by an attentional demanding task like a speeded choice task (Oberauer & Lewandowsky, 2008). This could echo the observations issued from the complex span paradigm in which the number of distractors has no effect provided that these distractors

are processed at a constant pace. However, and contrary to what is observed in complex span tasks, Lewandowsky et al. (2008) observed that increasing the number of changing distractors has a detrimental effect on recall performance, lending support to the hypothesis of event-based interference[1].

1.3. Accounting for discrepancies between paradigms

The divergence in results between the two paradigms, and more precisely the effect of the number of changing distractors on recall performance, could result from at least two causes. The first relies on some methodological aspects that differ from one paradigm to the other and that could produce apparently divergent results. The second concerns the very nature of the memory traces elicited by the two paradigms that could differ in such a way that they would be affected by different factors leading to their forgetting.

As far as methodological aspects are concerned, the main difference between the two methodologies is the use of self-paced distracting tasks by Lewandowsky and colleagues whereas the complex span tasks we used always constrain the rate at which to-be-processed items are displayed on screen. These temporal constraints are necessary to control for the cognitive load involved by the intervening task. For example, Lewandowsky et al. (2008) asked participants to read one or three distractors before recalling each item of five-consonant lists. When participants had read the distracting word(s) and recalled the next memory item, the experimenter recorded this response on keyboard. Entering the recalled letter triggered the display on screen of another set of distractors. Thus, the pace at which the task was performed entirely depended on the rate at which participants read the distractors and produced their recall. This difference in methodology could lead to differences in results. For example, in Lewandowsky et al. (2008), Exp. 2), the mean time to read either one or three distractors and recall a memory item was of 2.38 and 3.42 s respectively. Thus, it seems that the ratio Number of distractors/Time was higher in the three-distractor condition, explaining why it involved lower recall performance.

Beyond methodological differences, it is also possible that the two paradigms elicit the construction of memory traces that differ in nature, as some recent studies suggest. McCabe (2008) compared delay recall of items that had been memorized during simple or complex span tasks. Though immediate recall performance was higher in simple span task (i.e., word span), McCabe observed a delayed recall advantage for items memorized during complex span task (i.e., operation span). He interpreted this finding within a covert retrieval model assuming that participants maintain items in complex span tasks by covertly retrieving them from long-term memory during the processing phases of the task. These recurrent retrievals that occur in complex but not in simple span tasks would provide cues for delayed recall. This finding suggests that the constraints inherent to the tasks can lead to memory traces that differ in nature, explaining why the two paradigms described above lead to divergent results. For example, memory traces in simple span tasks, which do not need to be recursively retrieved and refreshed to survive processing episodes during encoding, could be more fragile and prone to event-based interference than memory traces constructed during complex span tasks. This could explain why the number of distractors has an effect when presented at retrieval but not at encoding, because in the first case memory items are

presented as in a simple span task (i.e., in immediate succession without any interruption) and thus probably encoded in the same way.

1.4. The present study

The aim of the present study was to shed light on the divergent results observed in memory tasks that combine storage and distracting tasks performed either at encoding or at retrieval. Are the different results due to methodological aspects or deeper differences in memory traces?

To answer the first part of this question, we ran a first series of experiments in which participants were presented with lists of 5 letters for serial recall with a disturbing task to be performed at retrieval (Fig. 1). For this purpose, each retrieval was prompted by a question mark that was preceded by a series of distractors successively displayed on screen. However, contrary to Lewandowsky et al. (2008), these distractors were displayed on screen at fixed paces. We varied the number of distractors (1 to 3 or 4), the pace at which they were displayed (one distractor every 500 ms, 1000 ms or 2000 ms), and their nature (repeating the same word, performing a speeded choice task, or reading changing digits) depending on the mechanism of maintenance we intended to hinder (articulatory rehearsal, attentional refreshing, or both; see Table 1). Both the effects of articulatory suppression and attentional demand, as well as their combination, have been studied on complex span tasks (e.g., Camos et al., 2009) and can be compared with the effects of distracting tasks performed at retrieval.

If the differences in recall performance between the two paradigms are due to methodological divergences, they should vanish with the introduction of computer-paced distracting tasks. Thus, as in complex span tasks, we should not observe any effect of the number of distractors, but an effect of the pace at which they are displayed and processed, with faster paces resulting in poorer recall. As in complex span tasks, this effect should be observed with distractors involving articulatory suppression, attentional capture, or both. However, the difference in recall performance between the two paradigms could result not from methodological differences, but from the fact that the constraints inherent to the complex span tasks lead to strengthened memory traces that better resist event-based interference. To test this hypothesis, the same series of experiments was replicated, but by presenting memory items at a slow rate of one letter every 5 s, instead of 500 ms in the first series. We reasoned that this slow rate of presentation with several seconds between the presentation of two successive memory items would permit participants to achieve a deeper encoding resulting in memory traces akin to those resulting from the recurrent process of retrieval occurring in complex span tasks. If the difference in recall performance discussed above is due to differences in the nature of the memory traces, the peculiarities related with the presentation of distractors at retrieval such as the effect of the number of distractors should disappear when memory items are presented at a slow rate, turning recall performance similar to what is observed in complex span tasks.

2. Experiment 1

The aim of this first experiment was to assess the impact of a computer-paced distracting task involving articulatory suppression when performed at retrieval. For this purpose, participants were presented with series of 5 letters for further recall and asked then to repeat aloud the same digit "2" before recall. This digit was displayed on screen either 1, 2, or 4 times before each retrieval at a slow, medium, or fast pace, defining nine experimental conditions in a within-subject design. Several studies reported no effect of the number of repetitions of same distractor at retrieval (Lewandowsky et al., 2008; Oberauer & Lewandowsky, 2008), but variations in the pace of these repetitions have not yet been investigated.

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[1] It should be noted that Lewandowsky, Geiger, Morrell, and Oberauer (2010) attempted to extend this method to complex span tasks by presenting distractors at encoding after the presentation of each memory item. They reported that increasing the number of changing distractors after each memory item had a deleterious effect on memory while repeating distractors had no effect. However, Plancher and Barrouillet (in press) demonstrated that, when temporal and attentional factors are controlled, the effect of the number of changing distractors totally disappears and the novelty of distractors has no effect on recall performance.
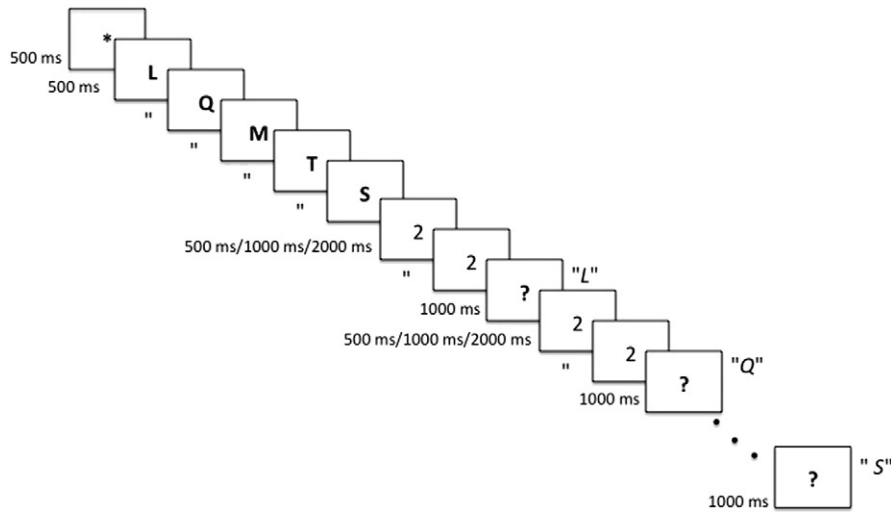
Fig. 1. Depiction of the paradigm used in Experiment 1 with distractors interspersed between retrieval episodes.

2.1. Method

2.1.1. Participants

Twenty-seven undergraduate psychology students (2 males; 25 females; mean age = 22.1 years; SD = 4.7 years) at the University of Geneva received a partial course credit for participating.

2.1.2. Materials and procedure

We created 36 different lists of five consonants randomly extracted without replacement from a pool of 19 consonants (all the consonants of the alphabet except W), avoiding acronyms and alphabetically ordered strings. These 36 lists were grouped into nine blocks of four lists assigned to the nine experimental conditions using a Latin square, with three participants assigned to each mapping. The distractor was the digit "2" displayed, as the letters, in black on a white ground (size 36 in Courier New font).

Trials began with an asterisk centrally displayed for 500 ms, followed by a 100 ms delay and then a list of five consonants successively displayed on screen at a rate of 500 ms per item (400 ms on and 100 ms off). After the last consonant, sets of distractors consisting in the digit "2" alternated with question marks. For a given trial, these sets contained a fixed number of distractors (either 1, 2, or 4) displayed at a pace of either 500 ms (400 ms on and 100 ms off), 1000 ms (800 ms on and 200 ms off), or 2000 ms (1600 ms on and 400 ms off) per stimulus for the fast, medium, and slow paces respectively. After each set of distractors (i.e., either 1, 2, or 4 "two"), a question mark appeared that remained on screen for 1 s. Participants were asked to read the consonants aloud as well as each digit "2" and to orally recall the consonants in correct order at a rate of one consonant per

question mark (Fig. 1). Participants were instructed to remain silent for the forgotten consonants. Before the 36 experimental trials, participants performed nine training trials corresponding to each of the nine experimental conditions.

2.2. Results and discussion

The data were analyzed through an analysis of variance (ANOVA) on the rate of letters recalled in correct position with serial position, pace (slow, medium, or fast), and number of distractors (1, 2, or 4) as within-subject factors. The results of this ANOVA are summarized in Table 2. Apart from the usual effect of serial position, the analysis revealed that slower pace resulted in better recall (44%, 49%, and 51% of correct recall for the fast, medium, and slow pace respectively), an effect that interacted with serial position, with steeper position curves for faster pace (Fig. 2). Newman–Keuls pairwise comparisons revealed that only the difference between fast and medium pace reached significance, but not the comparison between medium and slow pace. No other effect reached significance, including the number of distractors that had hardly any effect on recall performance (48%, 48%, and 49% correct for 1, 2, and 4 distractors respectively).

First of all, these results replicated and extended previous findings from Lewandowsky and colleagues. Whatever the pace at which participants articulated the word "two", the number of repetitions had no effect on recall, confirming that the absolute time elapsed between encoding and recall does not cause forgetting in the short term. However, in line with what is observed in complex span tasks, recall performance depended on the pace at which irrelevant material was articulated, something that could not be noticed in previous studies as they did not manipulate this factor. A straightforward interpretation is to assume that increasing the pace of presentation of the distractors reduced the opportunities to rehearse the consonants,

Table 1
Summary of the design and results of the six experiments (Exp.).

Exp.	Encoding time	Distracting task	Main effects		
			Pace	Nb of Dist.	Pace × Nb of Dist.
1	500 ms	Reading same digit 2	*	–	–
2	500 ms	Spatial location judgment	*	**	–
3	500 ms	Reading changing digits	***	***	***
4	5000 ms	Reading same digit 2	***	–	–
5	5000 ms	Spatial location judgment	***	–	–
6	5000 ms	Reading changing digits	***	–	–

Note: Nb of Dist. refers to number of distractors presented before each recall.
* $p < .05$, ** $p < .01$, *** $p < .001$.

Table 2
Summary of analysis of variance results for Experiment 1.

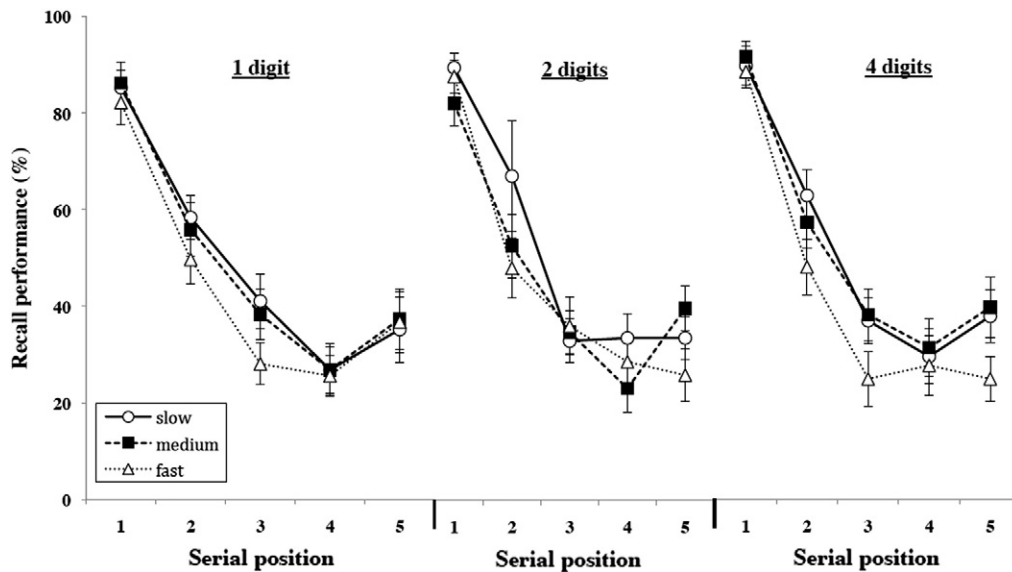| Source	F	p	Partial η^2
Serial position	131.8	<.001	.84
Pace	4.2	<.05	.14
Distractor	0.1	.88	.00
Serial position × pace	2.1	<.05	.07
Serial position × distractor	0.5	.82	.02
Pace × distractor	0.7	.60	.03
Serial position × pace × distractor	0.8	.65	.03

Fig. 2. Mean recall performance (with standard deviations) as a function of pace (slow, medium, fast), number of distractors (digits), and serial position in Experiment 1.

leading to poorer recall. This interpretation could be corroborated by the significant interaction between pace and serial position. Tan and Ward (2008) observed that participants rehearse verbal material in a cumulative forward order. Such a strategy would lead to the Serial Position × Pace interaction because increasing the time available to rehearse the list of consonants before the onset of the following distractor would be more beneficial when progressing through the list up to the more distant position that can be reached and rehearsed within the time allowed. Overall, these results suggested a similarity in the cognitive processes involved in tasks combining processing and storage, either at encoding or at retrieval, with an impact of time-related factors such as the pace at which the secondary task is performed. Experiment 2 extended this investigation to a computer-paced secondary task involving attentional capture rather than concurrent articulation.

3. Experiment 2

In the first experiment, the time-related effects of articulatory suppression were investigated by manipulating the pace of a verbal distracting task. The present experiment focused on the specific effects of impeding attentional refreshing. For this purpose, we used the same task as in Experiment 1, except that the distracting task was a silent speeded choice task requiring a location judgment. Before each question mark, black squares were displayed on screen at a fast, a medium, or a slow pace in one of two possible locations, either in the upper or lower part of the screen. Participants were asked to judge this location by pressing appropriate keys. As far as we know, such a speeded choice distracting task has never been used in isolation at retrieval. We already used this task in a complex span paradigm and observed that recall performance varied with its pace (Barrouillet et al., 2007), but not with the number of distractors (Barrouillet et al., 2011b).

3.1. Method

Forty-two undergraduate psychology students (3 males; 39 females; mean age = 22.8 years; SD = 3.8 years) at the University of Geneva received a partial course credit for participating. None of them took part in the previous experiment. The design of the immediate serial recall task was exactly the same as in Experiment 1, except that the distractors were black squares (side 18 mm subtending 2° of visual angle) located in one of two positions centered in the upper and lower half part of the

screen, 2.8 cm apart from each other. Participants were asked to read and recall the letters aloud and to press either the "p" or the "q" key of the keyboard for the up and down locations respectively.

3.2. Results and discussion

Six participants whose accuracy was below 70% in the square task were removed from the analyses. The remaining 36 participants had a mean accuracy of 88% (SD = 5.6%). An ANOVA with the same design as in Experiment 1 was performed on the rate of correct recall (see summary of the results in Table 3). Apart from the effect of serial position, this analysis revealed an effect of pace with slower pace involving better recall (79%, 82%, and 83% of correct recall for the fast, medium, and slow pace respectively). Nonetheless, this effect was moderate, with no significant difference between the fast and medium pace conditions, $F (1, 35) = 2.27$, $p > .10$, or between the medium and slow paces conditions, $F (1, 35) = 1.02$, $p > .10$, but only a difference between the two extreme conditions, $F (1, 35) = 8.21$, $p < .01$. There was also an effect of the number of distractors, more distractors resulting in poorer recall (84%, 82%, and 79% of correct recall for 1, 2, and 4 squares respectively). Though the effects of pace and number of distractors did not significantly interact, the effect of the number of squares was only significant at the fastest pace, $F (2, 70) = 4.30$, $p < .05$, but not at the medium and slow paces, $Fs < 1$ (Fig. 3). None of the interactions involving serial position reached significance.

The results of this second experiment were somewhat mixed. As in Experiment 1, increasing the pace of the distracting task resulted in poorer recall as it is observed in complex span tasks. However, disrupting attentional refreshing in the present experiment had a far lower effect than disrupting verbal rehearsal in the previous experiment, as the rates of correct recall make clear, and the pace effect was small. It is

Table 3
Summary of analysis of variance results for Experiment 2.

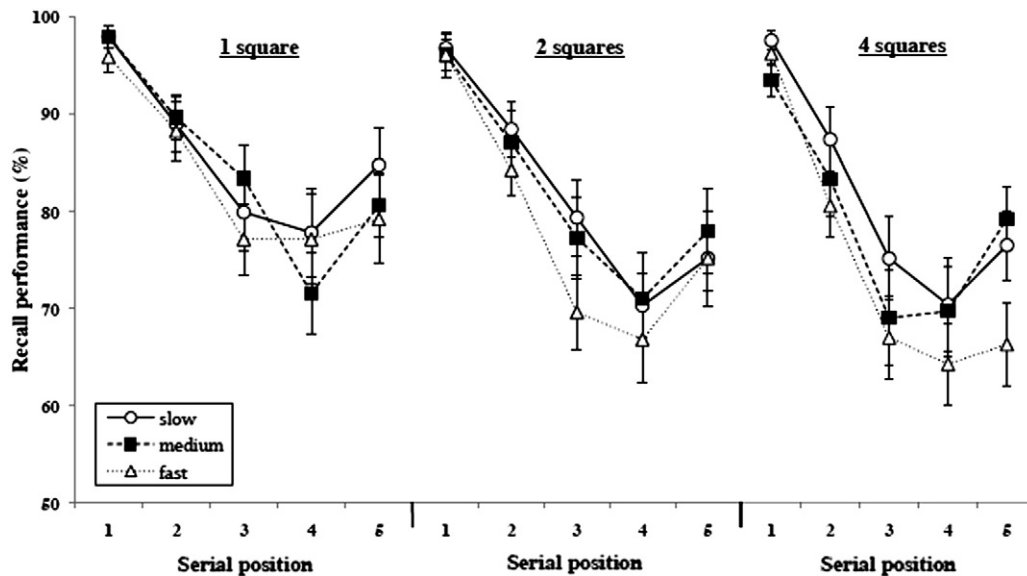| Source	F	p	Partial η^2
Serial position	59.8	<.001	.63
Pace	3.7	<.05	.10
Distractor	6.7	<.01	.16
Serial position × pace	0.9	.52	.03
Serial position × distractor	1.3	.27	.04
Pace × distractor	0.4	.82	.01
Serial position × pace × distractor	1.3	.22	.03

Fig. 3. Mean recall performance (with standard errors) as a function of pace (slow, medium, fast), number of distractors (squares), and serial position in Experiment 2.

possible that this small pace effect was due to the high error rate observed in the square task performed at a fast pace (27%, 5% and 3% of errors in fast, medium and slow pace conditions respectively). It has been suggested that such errors could induce some post-error processing that occupies the attentional bottleneck, thus preventing restorative rehearsal (Lewandowsky & Oberauer, 2009). However, in a series of three experiments, Oberauer and Lewandowsky (in press) found no evidence that errors on the processing component of a complex span task affect memory.

There was also an unexpected effect of the number of distractors that is at odds with what is usually observed in tasks combining storage and processing, either at encoding or at retrieval. No effect of the number of distractors was observed by Barrouillet et al. (2011b) who studied the effect of the same secondary task at encoding, and the repeated processing of the same distractor at retrieval should not affect performance according to the event-based interference approach (Oberauer & Lewandowsky, 2008). However, it could also be considered that the distractors in the square task are not only the squares but also the encoding of the response keys and their mapping to the stimuli, which must be retrieved (Oberauer et al., 2012). Thus, when successive squares require different responses, they are not functionally identical and can produce interference. We will discuss the implications of these findings in the further general discussion, but let us turn now to the third experiment, which aimed at investigating the effects of a computer-paced task hindering both attentional refreshing and verbal rehearsal at retrieval.

4. Experiment 3

The effects of articulatory suppression and attentional capture at retrieval were investigated independently in the two previous experiments. The present experiment aimed at investigating these effects when the distracting task involves both an articulatory suppression and a cognitive load. For this purpose, Oberauer and Lewandowsky (2008) associated the repetition of the word *super* with a choice reaction time task. Though this double task has the capacity to hinder both mechanisms of maintenance, its dual nature could have undesired effects and lead participants to perform the two activities sequentially. Thus, we favored a more integrated distracting task in which a unique activity involves both attention allocation and articulatory suppression. We chose a reading digit task in which participants are presented with series of digits successively displayed on screen at a fixed pace and

asked to read them aloud. The retrieval involved in identifying digits occupies the central bottleneck, thus impeding attentional refreshing, while reading them aloud yields the desired concurrent articulation that prevents rehearsal. We already observed that performance in complex span tasks is highly sensitive to the pace at which the reading digit task is performed (Barrouillet et al., 2004, 2009). Experiments 1 and 2 showed that distracting tasks involving either concurrent articulation or attentional demand elicited time-related effects in recall. Thus, a task combining both hindrances should elicit a pace effect with faster pace resulting in poorer recall performance. However, the question of interest was the persistence of the effect of the number of changing distractors observed by Lewandowsky et al. (2008) when the distracting task is computer-paced.

4.1. Method

Twenty-seven undergraduate psychology students (4 males; 23 females; mean age = 21.9 years; SD = 5.4 years) at the University of Geneva received a partial course credit for participating. None of them took part in the previous experiments. The design of this experiment was the same as in Experiment 1, except that the digits to be read differed from each other. Each question mark was preceded by a series of 1, 2, or 3 different digits presented at the same paces as in the previous experiments. Participants were asked to read them aloud before recalling the letters.

4.2. Results and discussion

The same ANOVA as in Experiments 1 and 2 was performed. Its results are summarized in Table 4. As expected, there was a significant effect of pace with slower pace resulting in better recall (44%, 53% and

Table 4
Summary of analysis of variance results for Experiment 3.

Source	F	p	Partial η^2
Serial position	212.8	<.001	.89
Pace	14.6	<.001	.36
Distractor	17.6	<.001	.40
Serial position × pace	0.8	.58	.03
Serial position × distractor	2.03	<.05	.07
Pace × distractor	5.04	<.001	.16
Serial position × pace × distractor	0.5	.94	.01

55% of correct recall for the fast, medium, and slow pace respectively, Fig. 4). As we already observed in Experiment 1, only the difference between the fast and the medium pace was significant, but not the difference between the medium and the slow pace. Interestingly, and in line with Lewandowsky et al.'s (2008) observations, the effect of the number of distractors reached also significance, with more distractors leading to poorer performance (56%, 51%, and 45% correct for 1, 2, and 3 distractors respectively). However, this effect interacted with pace (Fig. 5): It was very strong at the fast pace, F (2, 52) = 23.4, $p < .001$, was less pronounced but still significant at the medium pace, F (2, 52) = 6.5, $p < .01$, and disappeared at the slow pace, $F < 1$. In the other way round, there was a strong effect of pace with three digits, F (2, 52) = 24.0, $p < .001$. However, with two digits, this effect diminished, F (2, 52) = 8.5, $p < .001$, and was only observable between the fast and the medium pace, while it completely disappeared with one digit, $F < 1$. Finally, the effect of number of distractors interacted with the serial position, reading three digits resulting in a steeper serial position curve (Fig. 6).

While manipulating articulatory suppression in Experiment 1 resulted in an effect of pace and manipulating attentional capture in Experiment 2 yielded an effect of the number of distractors and of pace, the reading digit task that combined both manipulations revealed a strong effect of both pace and number of distractors. Interestingly, the latter effect was more pronounced with faster pace, whereas the effect of pace did not appear when only one digit was presented before each question mark. The results of these three experiments will be discussed in the following section.

5. Discussion of Experiments 1–3

This first series of experiments tested the hypothesis of a methodological origin for the discrepant results observed in tasks combining short-term storage with distracting tasks performed either at encoding, such as in the complex span task paradigm, or at retrieval. For this purpose, we studied the effect on recall of 5-consonnant lists of computer-paced secondary tasks involving concurrent articulation or attentional demand, but these computer-paced tasks were interspersed between retrievals instead of being performed at encoding as it is the case in complex span tasks. Two main phenomena arose from this first series of experiments.
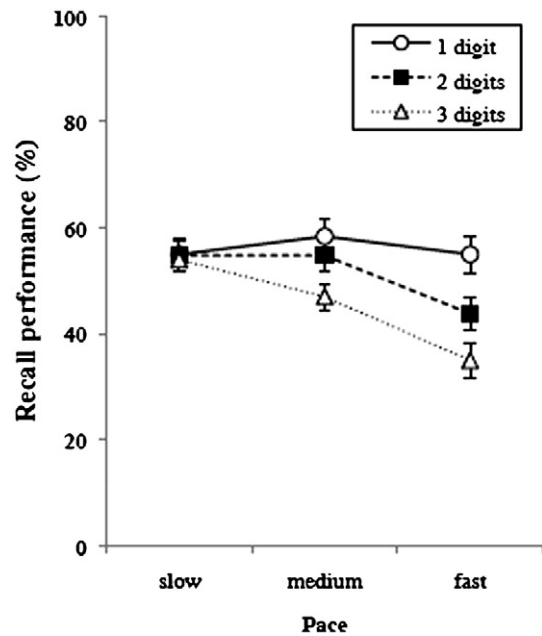

Fig. 5. Mean recall performance (with standard errors) as a function of pace and number of distractors (digits), all serial positions collapsed, in Experiment 3.

First, whatever the nature of the distracting task, its pace had an impact on recall with faster paces resulting in poorer performance as it is observed in complex span tasks (Barrouillet et al., 2004, 2007; Camos et al., 2009; Lépine et al., 2005b). As far as we know, this finding had never been reported before. It extends to the distractors-at-retrieval paradigm the effects observed in complex span tasks. All other things being equal, increasing the rate of articulatory suppression or attentional capture or both results in a more pronounced memory loss. This suggests that, in both paradigms, attention and verbal rehearsal are needed for maintaining memory traces in an active state, and that these maintenance mechanisms are time-constrained. However, the pace effect was less clear than usually observed in complex span tasks. Though the effect of pace was systematically significant, the difference in recall performance between the slow and the medium paces failed to reach significance in the three experiments.
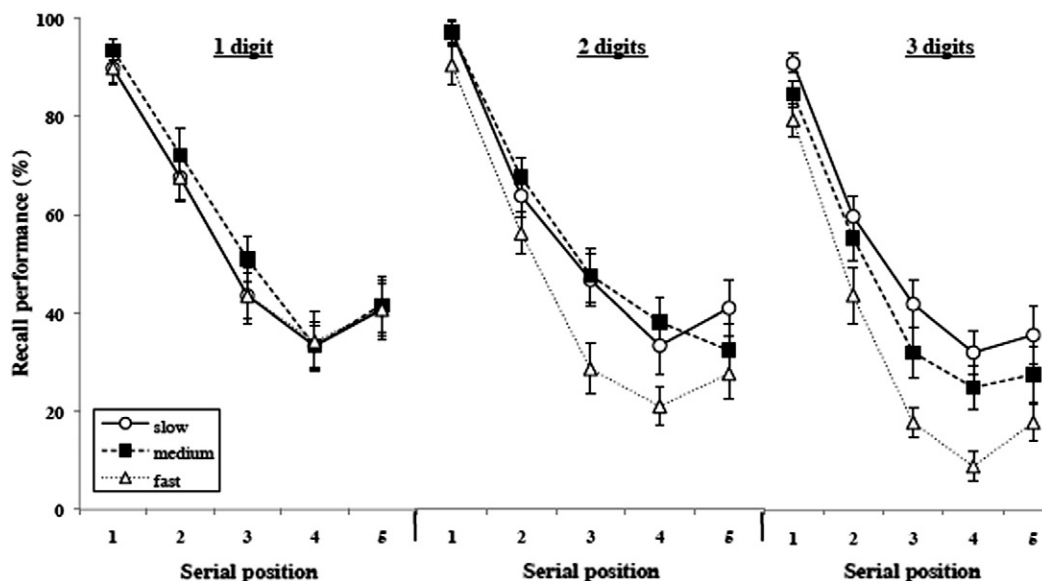

Fig. 4. Mean recall performance (with standard errors) as a function of pace (slow, medium, fast), number of distractors (digits), and serial position in Experiment 3.
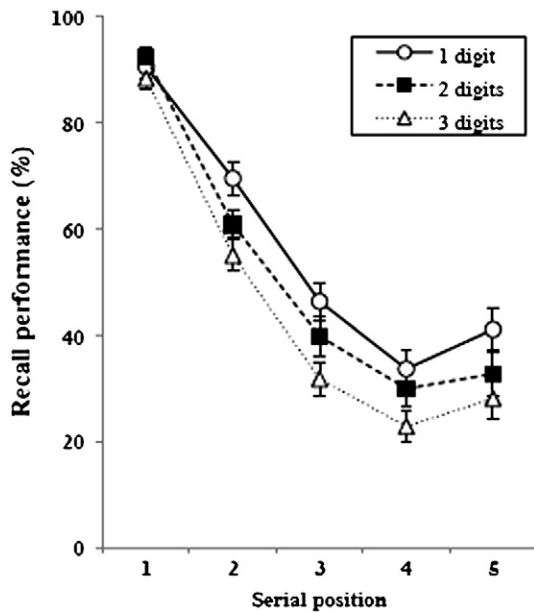
Fig. 6. Mean recall performance (with standard errors) as a function of the number of distractors (digits) and serial position, all paces collapsed, in Experiment 3.

The second main phenomenon concerns the effect of the number of distractors to be processed before each retrieval episode. Our results replicated what is usually observed when distractors are processed at retrieval (Lewandowsky et al., 2008). When the same distractor was repeated, as in Experiment 1 in which the distracting task consisted in repeating the word "two", the number of repetitions had no effect. However, when the task involved several different distractors, as the digits to be read in Experiment 3, a significant effect of the number of distractors occurred, contrary to what is observed in complex span tasks. An effect of the number of distractors was also observed in Experiment 2. Though the squares did not differ from each other, we have seen that the different responses they elicited and the different stimulus–response mappings they involve could have resulted in representation-based interference. Thus, introducing a strict control of time with computer-paced tasks did not abolish the discrepancy in results observed between tasks involving distractors either at encoding or at retrieval. Moreover, the effect of the number of distractors interacted with pace in Experiment 3. It can be noted that, in Experiments 2 and 3, the effect of the number of distractors was stronger at fast pace. We will address these unexpected findings in the general discussion in light of the findings issued from the second series of experiments.

In summary, it can be concluded that the differences in recall performance related with the presentation of distracting tasks either at encoding or at retrieval in previous studies cannot be entirely attributed to methodological differences in the two paradigms, and more precisely to the way the distracting tasks are administered. Even when these tasks are computer-paced, phenomena related to the number of distractors occur, suggesting the intervention of event-based interference. However, our results indicate that these phenomena only occur when distractors are processed at a fast pace. This last finding could suggest in turn that event-based interference mainly affects fragile memory traces. Processing of distractors at a fast pace could prevent maintenance mechanisms to take place and to consolidate memory traces after their initial encoding, rendering them more prone to degradation through interference.

This leads us to our second hypothesis, which is that the differences observed in previous studies between the two paradigms could result from differences in the strength of the memory traces constructed, with the complex span paradigm eliciting the consolidation of memory traces by their recursive covert retrieval. If this is the

case, these differences and the effects related with the number of distractors should disappear if memory items are presented at such a slow rate that subjects manage to sufficiently consolidate memory traces before engaging in the distracting task. Thus, we ran a second series of experiments with exactly the same distracting tasks performed at the same paces as in the first series, except that memory items were presented at a slower rate. In order to maximize the probability of a consolidation of memory traces, we chose the extreme rate of 5 s per item recently used by Tan and Ward (2008).

6. Experiment 4

The purpose of this experiment was to assess the disruptive effect of an intervening task that blocks verbal rehearsal when to-be-remembered items have benefitted from a long period of consolidation. Participants were presented with series of 5 letters at a rate of one letter every 5 s and then asked to read the digit "2" displayed on screen either 1, 2, or 4 times at slow, medium or fast pace. Complex span tasks that allow consolidation of memory traces revealed an effect of the pace at which distracting tasks are performed, including those that involve a mere concurrent articulation (Barrouillet et al., 2004). Thus we expected, as in Experiment 1, lower recall performance with faster pace and no effect of the number of distractors.

6.1. Method

Twenty-seven undergraduate psychology students (3 males, 24 females, mean age = 22.5 years; $SD = 4.6$ years) at the University of Geneva received a partial course credit for participating. None of them took part to the previous experiments. The material and procedure were identical to Experiment 1 except that the letters were presented at a rate of one letter every 5 s (2000 ms on and 3000 ms off) instead of 500 ms.

6.2. Results and discussion

The same ANOVA as in the previous experiments was performed on recall performance. It yielded a number of expected effects summarized in Table 5. Apart from an effect of serial position, we observed the predicted effect of pace, with slower pace leading to better recall (72%, 78% and 83% of correct recall for the fast, medium, and slow pace respectively). Contrary to what was observed in Experiment 1, planned comparisons showed that there was a significant difference not only between fast and medium pace ($p<.005$), but also between medium and slow pace ($p<.05$). The pace interacted with serial position, revealing steeper serial position curves for faster pace (Fig. 7). The number of distractors did not reach significance (77%, 77%, and 79% correct for 1, 2, and 4 distractors respectively), but interacted with serial position. This interaction was due to a recency effect restricted to the one-distractor condition in which the fifth letter was better recalled than the fourth. We do not have any explanation for this recency effect restricted to this condition. There was also a significant overarching interaction between serial position, number of distractors, and pace in which the recency effect described above probably played an important

Table 5
Summary of analysis of variance results for Experiment 4.

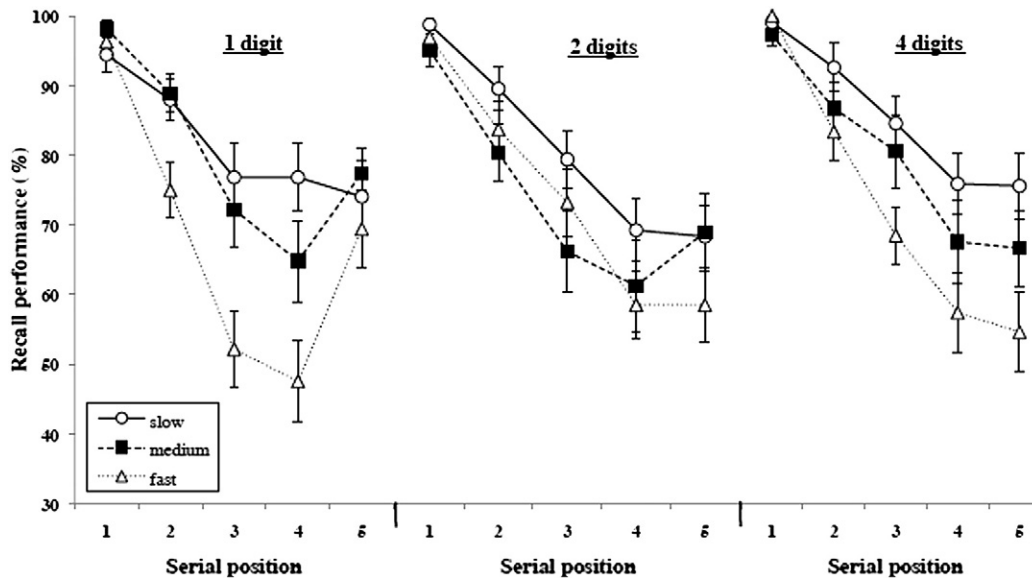| Source	F	p	Partial η²
Serial position	62.8	<.001	.71
Pace	16.7	<.001	.39
Distractor	1.06	.35	.04
Serial position × pace	4.86	<.001	.16
Serial position × distractor	3.42	<.005	.17
Pace × distractor	1.88	.12	.07
Serial position × pace × distractor	1.72	<.05	.06

Fig. 7. Mean recall performance (with standard errors) as a function of pace (slow, medium, or fast), number of distractors (digits), and serial position in Experiment 4.

role because this interaction was no longer significant when restricting the analyses to the first four positions.

Overall, the results of this experiment were in line with our expectations. As it was observed in Experiment 1, the pace of the concurrent articulation had a significant effect whereas the number of words articulated had no effect, confirming that the absolute time elapsed between encoding and recall does not cause forgetting in the short term. Moreover, in line with Tan and Ward's (2008) observation that participants rehearse letters in a cumulative forward order, we observed an interaction between pace and serial position. Longer pace enabled rehearsal of more letters, resulting in flatter serial position curve. However, the slow rate of presentation of the letters involved specific phenomena. First, contrary to Experiment 1, the pace effect extended to the contrast between slow and medium paces. Second, recall performance was far better than in Experiment 1. Whereas the fast rate of 0.5 s per letter led to a mean number of letters recalled of only 2.40, this number was raised to 3.89. These findings suggest that the deeper encoding of the memoranda allowed by a slower rate of presentation increases the number of memory items that can be maintained, but that this maintenance is still dependent on verbal rehearsal, as testified by the clear effect of the pace at which distractors are articulated. Before discussing these findings, we turn now to the exploration of the effects of a non-verbal distracting task involving attentional demand on the recall of letters presented at a slow rate, keeping in mind that an unexpected effect of the number of distractors occurred in the first series of experiments.

7. Experiment 5

In this experiment, we investigated the effect of a distracting task intended to disrupt attentional refreshing on the immediate serial recall of letters presented at a slow rate of one letter every 5 s. As in Experiment 2, participants performed a silent location task on squares that appeared either in the upper or the lower part of the screen. To avoid a possible ceiling effect, seven letters were presented instead of five. In line with what is observed in complex span tasks, we expected a pace effect without any effect of the number of distractors.

7.1. Method

Twenty-eight undergraduate psychology students (4 males, 24 females, mean age = 21.1 years, $SD = 2.8$ years) at the University of

Geneva received a partial course credit for participating. None of them took part in the previous experiments. Participants were presented with 36 series of seven letters each. The procedure was similar to the one used in Experiment 2 except that each letter was presented for 2000 ms and followed by an empty screen of 3000 ms.

7.2. Results and discussion

One participant whose accuracy was below 70% in the square task was removed from the analyses. The remaining 27 participants had a mean accuracy of 85% ($SD = 7.5\%$). As in Experiment 2, the fast pace condition elicited more errors (27%) than the medium and slow pace conditions (9% and 8%, respectively). Recall performance was analyzed in the same way as in the previous experiments. The results of the ANOVA were particularly clear (Table 6), revealing a main effect of serial position reflecting the typical serial position curve with a moderate recency effect (Fig. 8) and, as we predicted, a strong and significant effect of pace (52%, 59%, and 62% letters correctly recalled in the fast, medium, and slow pace conditions, respectively). Recall performance did not vary with the number of squares (57%, 57% and 59% letters correctly recalled with 1, 2, and 4 squares respectively) and no interaction reached significance.

The results of this experiment were straightforward. As we expected, varying the pace of the intervening task had a significant effect on recall performance, with faster pace resulting in poorer recall. By contrast, the number of distractors to process had no effect at all. This last result contrasts with Experiment 2 where increasing the number of distractors disrupted memory performance, especially when these distractors were displayed at a fast pace. The combination of an effect of the pace at which distractors are processed with no effect of the number of these distractors is usually observed in complex

Table 6

Summary of analysis of variance results for Experiment 5.

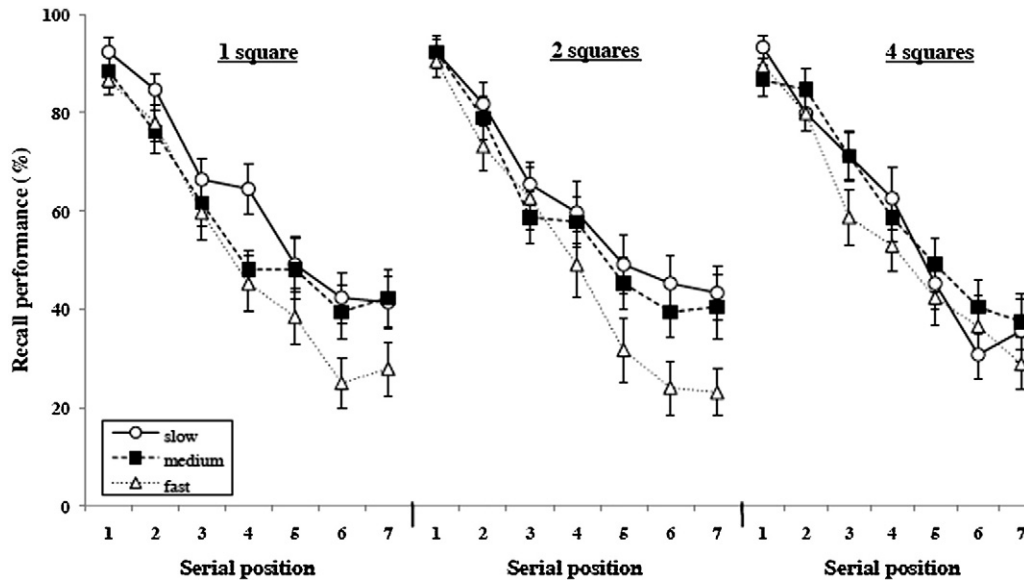| Source	F	p	Partial η^2
Serial position	135.9	<.001	.84
Pace	8.7	<.001	.26
Distractor	0.3	.74	.01
Serial position × pace	1.4	.17	.05
Serial position × distractor	0.9	.57	.04
Pace × distractor	0.9	.44	.04
Serial position × pace × distractor	1.2	.22	.05

Fig. 8. Mean recall performance (with standard errors) as a function of pace (slow, medium, or fast), number of distractors (squares), and serial position in Experiment 5.

span tasks (Barrouillet et al., 2004; Barrouillet et al., 2011b; Plancher & Barrouillet, in press). Thus, the results of the present experiment suggest that memory tasks involving distracting activities at retrieval are affected by the same factors as complex span tasks when memoranda are strongly encoded. The last experiment in which Experiment 3 was reproduced with a slow rate of presentation of the letters was a stringent test of this hypothesis.

8. Experiment 6

This last experiment replicated Experiment 3 with a slower rate of presentation of the letters. Recall that in this previous experiment participants were asked to read either one, two, or three digits presented at a slow, medium, or fast pace before each recall. The results revealed not only an effect of pace, but also an effect of the number of digits to be read and an interaction between the two factors. Following the hypothesis that performance in immediate serial recall is affected by the same factors as those affecting recall performance in complex span tasks when memory traces are strongly encoded, we expected an effect of the pace of the distracting task, but no effect of the number of distractors to process and no interaction, as it is usually observed in complex span tasks.

8.1. Method

Twenty-seven undergraduate psychology students (2 males, 25 females, mean age = 22.0 years, SD = 4.2 years) at the University of Geneva received a partial course credit for participating. None of them took part in the previous experiments. The procedure was the same as in Experiment 3 except that each letter was presented for 2000 ms and followed by an empty screen of 3000 ms.

8.2. Results and discussion

The same ANOVA as in the previous experiments was performed (Table 7). The results were straightforward. As expected, there was a significant effect of pace with slower pace resulting in better recall (51%, 57% and 62% of correct recall for the fast, medium, and slow pace respectively). Contrary to Experiment 3, the difference was significant not only between the fast and the medium paces (p<.005), but also between the medium and the slow paces (p<.05). Interestingly, the effect of the number of distractors no longer reached significance

(58%, 56%, and 55% correct for 1, 2, and 3 distractors respectively), and did not interact with pace (Fig. 9). Contrary to Experiment 3, the pace effect interacted with serial position, faster paces resulting in steeper serial position curves (Fig. 8). As noted by Lewandowsky et al. (2004), this two-way interaction revealing the fanning out of serial position curves is predicted by time-based theories but not by event-based theories. Overall, these results confirmed that when items are presented at a rate that allows their consolidation, recall performance is affected by the same factors as those affecting recall performance in complex span tasks.

9. Discussion of Experiments 4–6

Two main facts arose from this second series of experiments in which the memoranda were presented at the slow rate of one item every 5 s. First, all the experiments revealed a main effect of the pace at which the distracting task was performed. These pace effects tended to be even clearer than in the first series, as revealed by higher partial η^2 values. Importantly, these pace effects no longer interacted with the number of distractors, as it was the case in Experiment 3 when varying the pace of the reading digit task. Second, the effect of the number of distractors never reached significance, whatever the nature of these distractors (Table 1).

These findings confirm the hypothesis that the differences observed in the literature between tasks involving distracting activities at either encoding or retrieval were due to differences in the nature of the memory traces. When items presented for further serial recall benefit from a deeper encoding, recall performance still depends on the pace of intervening tasks involving articulatory suppression, attentional capture, or both, while the effects related to the number of

Table 7
Summary of analysis of variance results for Experiment 6.

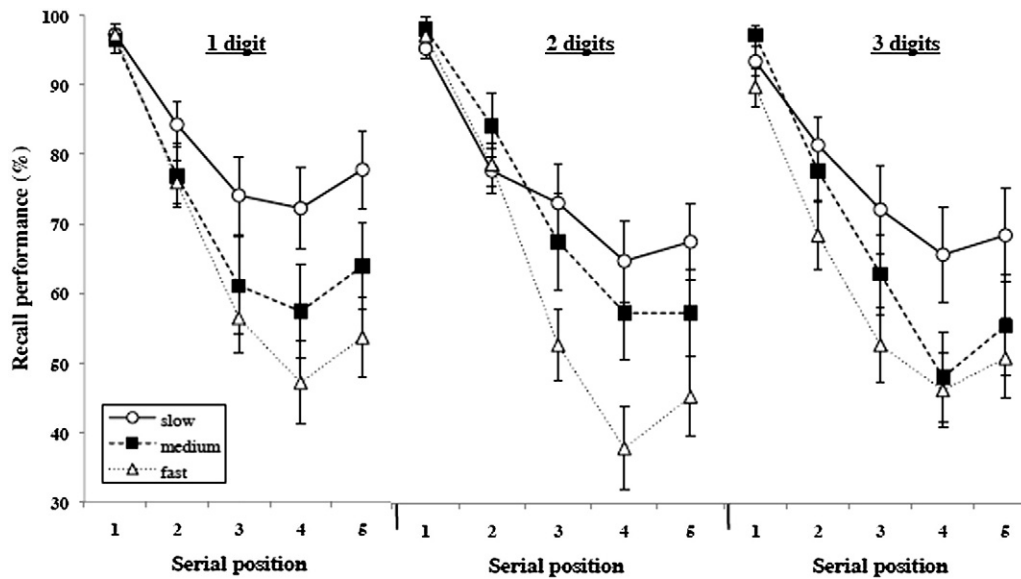| Source	F	p	Partial η^2
Serial position	81.0	<.001	.76
Pace	16.9	<.001	.39
Distractor	1.7	.20	.06
Serial position × pace	7.7	<.001	.23
Serial position × distractor	1.5	.15	.06
Pace × distractor	0.6	.66	.02
Serial position × pace × distractor	0.9	.58	.03

Fig. 9. Mean recall performance (with standard errors) as a function of pace (slow, medium, or fast), number of distractors (digits), and serial position in Experiment 6.

distractors to be processed disappear, exactly as it is observed in complex span tasks. The difference in nature between memory traces resulting from either a fast or a slow presentation of the letters is confirmed by their differential sensitivity to the distracting tasks we used. It can be observed that with a fast presentation, a simple articulatory suppression such as repeating the same word "two" had the same effect on recall performance as an articulatory suppression coupled with the attentional demand involved by reading changing digits (2.40 compared with 2.54 letters recalled in Experiments 1 and 3 respectively). By contrast, memory traces of letters presented at a slow rate proved far less affected by the repetition of the word "two" than by reading changing digits (3.89 and 2.83 letters recalled in Experiments 4 and 6 respectively). This was confirmed by an ANOVA with the type of distracting tasks (repeated vs. changing digits) and the rate of presentation of the letters (fast vs. slow) as between-subject factors on the number of letters recalled in correct position. This analysis revealed that the slow rate of presentation of the letters resulted in their better recall, $F (1, 104) = 59.04$, $p < .001$, $\eta^2 = .36$, that reading changing digits had a stronger effect than repeating "two", $F (1, 104) = 16.00$, $p < .001$, $\eta^2 = .13$, but more importantly, that the two factors interacted, $F (1, 104) = 27.19$, $p < .001$, $\eta^2 = .27$ (Fig. 10). Whereas the two distracting tasks did not differ in their effect on recall performance when letters were presented at a fast rate, $F < 1$, reading changing digits had a far more detrimental effect on recall than repeating "two" when letters were presented at a slow rate, $F (1, 104) = 27.19$, $p < .001$, $\eta^2 = .27$. These findings and those issued from the three first experiments have a series of consequences for our understanding of short-term and working memory that are addressed in the following general discussion.

10. General discussion

The aim of the present study was to address the discrepancies in results observed in memory tasks combining storage with distracting tasks performed either at encoding or at retrieval. When performed at encoding, the detrimental effect of the distracting task on recall performance depends on the pace at which distractors are processed but not on their number, with faster pace resulting in poorer performance (for a review, Barrouillet et al., 2011a). By contrast, increasing the number of distractors proved to reduce recall performance when intervening tasks are performed at retrieval (Lewandowsky et al., 2008). A first series of experiments indicated that these discrepancies did

not result from methodological differences. When distracting tasks performed at retrieval were temporally constrained, a pace effect occurred, but the number of distractors still had a significant effect. However, a slower presentation of memory items allowing deeper encoding made the effect of number of distractors disappear, suggesting that the divergences in results between the two streams of research relied on the nature of the memory traces.

The present study sheds light on the nature of the memory traces resulting from the two paradigms. When distracting tasks are presented at retrieval, the uninterrupted fast presentation of the letters followed by the immediate presentation of the first distractor prevents consolidation of memory traces, probably resulting in a superficial phonological
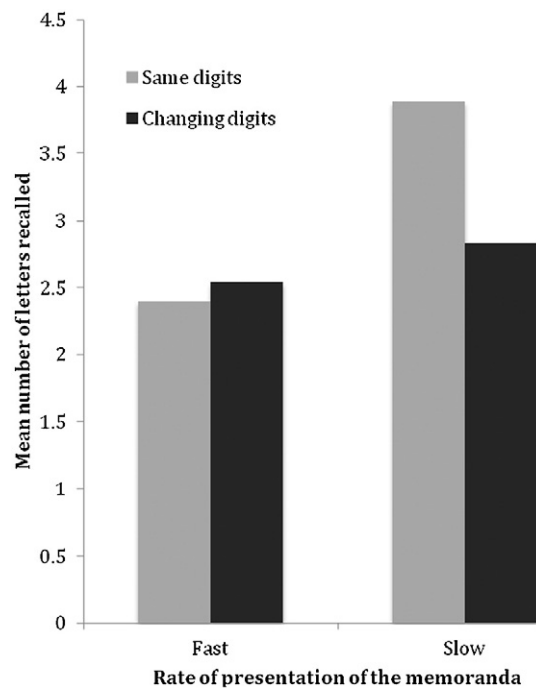

Fig. 10. Mean recall performance (with standard errors) as a function of the nature of the distracting task and the rate of presentation of the memoranda. The "Same digits" condition refers to Experiments 1 and 4 for 0.5 s and 5 s respectively, while the "Different digits" condition refers to Experiments 3 and 6 for 0.5 s and 5 s respectively.

encoding. Accordingly, these superficial memory traces were highly sensitive to articulatory suppression that prevented refreshment of their constitutive phonological features, and prone to event-based interference, as the effect of the number of distractors testified in Experiments 2 and 3. These phenomena evoke storage in some peripheral system of working memory (WM) like the phonological loop described by Baddeley (1986). By contrast, memory traces constructed during complex span tasks or resulting from a slow rate of presentation of the letters as in our second series of experiments proved to be far more resistant to articulatory suppression. It is only the conjunction of articulatory suppression and attentional capture induced by reading changing digits that produced dramatic forgetting (Fig. 10). This suggests that, as long as attention was available to refresh these memory traces, verbal rehearsal was not indispensable for their maintenance. Moreover, these memory traces proved resistant to event-based interference, as testified by the disappearance of any effect of the number of distractors to be processed. These findings evoke a storage in some general WM system like an episodic buffer (Baddeley, 2000; Repovs & Baddeley, 2006). This episodic buffer stores transient representations integrating features of different natures (visual, spatial, verbal, auditory, semantic). The multi-modal nature of these representations makes them more immune from peripheral interference. However, there is overwhelming evidence that the maintenance of such representations is disrupted by the concurrent involvement of executive central processes and that these effects are commensurate with the duration of the concurrent attentional capture (Barrouillet et al., 2011a; Vergauwe, Dewaele, Langerock, & Barrouillet, 2012; Vergauwe et al., 2010). This suggests that, contrary to long-term memory traces, these representations are prone to temporal-decay. To sum up, our results suggest the existence of two different kinds of verbal short-term memory traces. Superficial phonological traces, directly arising from the sensory input, would be maintained in some peripheral buffer like a phonological loop. Prone to temporal decay when their refreshing by verbal rehearsal is prevented, they would also be affected by representation-based interference due to their unimodal nature. When deeper encoding is possible, the sensory input would be enriched by activated knowledge from long-term memory leading to the construction in an episodic buffer of multi-modal representations. These representations would be more immune to interference but still prone to temporal decay when their attentional refreshing is prevented by concurrent attentional demanding tasks.

Although our findings suggest that different memory traces with different characteristics were built depending on the time allowed to their consolidation, it would be simplistic to assume a strict distinction between purely phonological traces on the one hand and multimodal representations on the other. Indeed, though the square task had a far less disruptive effect on recall performance of letters presented at a fast rate than tasks involving articulatory suppression, the attentional capture induced by the spatial location task had nonetheless a detrimental effect on memory (see Table 3 and Fig. 3). Even performed at the slowest pace, the square task resulted in a significantly lower performance than a quiet condition in which there was no distracting task[2]. Of course, it is

possible that the attentional capture involved by the location task hindered the initiation of the verbal rehearsal process, but the detrimental effect of the square task suggests that at least some features of these memory traces could not be preserved through verbal rehearsal and benefitted from attentional refreshing. It is probably more accurate to imagine the difference between the two kinds of memory traces as two locations along a continuum.

Beyond the differential sensitivity to event-based interference of the memory traces induced by the two paradigms, our results revealed a ubiquitous pace effect. Whatever the nature of the distracting task and the time allowed to encode the memoranda, distracting tasks performed at a faster pace resulted in poorer recall. This indicates that the detrimental effect of concurrent activities is time related. As it is observed when distractors are processed at encoding (e.g., Barrouillet et al., 2004, 2007, 2011a, 2011b), cognitive load approximated by the number of distractors processed per second determines recall performance in both series of experiments (Fig. 11). The fact that the same linear trend occurs when distractors are processed at encoding and retrieval strongly suggests that both paradigms are governed by the same mechanisms of forgetting and maintenance. The articulatory suppression resulting from the repetition of a word on the one hand, and the attentional capture induced by a location judgment on the other differ sufficiently from each other in their nature and in the cognitive processes they involve to conclude that their effect does not result from some direct action they could have on memory traces. Instead, their action is probably indirect and consists in hindering mechanisms needed to maintain memory traces until recall. Nonetheless, there are at least two ways to account for the time-related effect of pace. The first is to assume that the mechanisms of restoration counteract a temporal decay of memory traces. All other things being equal, a faster pace results in an unchanged duration of decay, which is coextensive with the time during which processing distractors impedes reactivation mechanisms to take place, but to shorter periods during which these mechanisms are available to reactivate decayed memory traces. This leads to more forgetting and lower recall performance. The second is to assume that the degradation is not time-dependent, but results only from event-based interference created by encoding distractors. In this case, memory performance would still depend on the time during which restoration mechanisms can be used. The shorter periods of restoration resulting
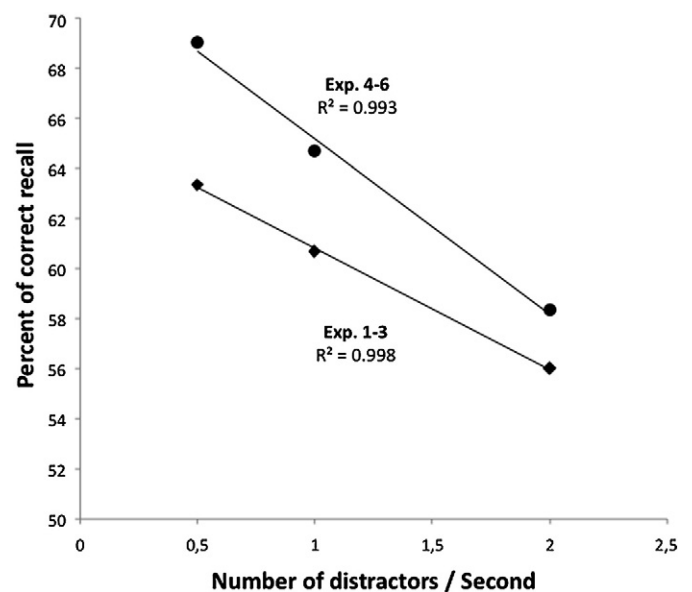
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[2] The quiet condition used the same experimental design as in the first series of experiments (0.5 s per letter) with 25 participants who were presented with three conditions of pace (slow, medium, or fast), and three conditions of distractors that were replaced by blank screens (1, 2, or 4). In the quiet condition, pace and number of blank screens were confounded in a same factor "time", that represented the time elapsed between each retrieval (0.5, 1, 2, 4 or 8 s). The effect of this factor "time" did not reach significance ($F < 1$) (88%, 91%, 92%, 91% and 91% of correct recall for 0.5, 1, 2, 4 or 8 s respectively) while the effect of serial position did ($p < .001$). An analysis of variance on the rate of letters correctly recalled with the kind of concurrent task used (repeating the digit "two" in Experiment 1, judging the location of squares in Experiment 2, reading changing digits in Experiment 3, and the quiet condition) as between-subjects factor indicated a main significant effect of concurrent task with higher recall performance induced by the quiet condition (91% of correct recall) compared with the repetition of the word "two" (47%), the spatial location task (81%), and the reading of changing digits (51%), $F(3, 111) = 107.44$, $p < .001$, $\eta 2 = .74$. Post hoc Tukey tests revealed that the quiet condition significantly differed from each of the three other concurrent tasks, $ps < .01$.

Fig. 11. Relationship between percent of correct recall and cognitive load expressed as the number of distractors per second when averaging recall performance across experiments with fast (Experiments 1–3) and slow (Experiments 4–6) presentation of the memoranda.

from a faster pace would lead to more forgetting (Lewandowsky & Oberauer, 2009).

However, our results do not fit very well with this latter hypothesis. If the pace effect was due to the fact that processing the distractors impedes restoration mechanisms to remove the effect of the interference created by these distractors, the pace effect should co-occur with the effects traditionally attributed to event-based interference such as the effect of the number of distractors. However, the slow presentation of the letters made this effect disappear while the effect of pace remained unchanged. This independence of the two effects suggests that the time-related effects we observed are not due to event-based interference, but are more in line with the TBRS hypothesis that forgetting from STM mainly occurs through temporal decay, a decay that can be counteracted by attentional refreshing or rehearsal when verbal information is involved. Hence, memory performance depends on the balance between the periods of decay and reactivation. This account does not exclude the occurrence of event-based interference that adds its deleterious effect to temporal decay. For example, the effect of the number of distractors in Experiment 3 could be explained in this way. However, it could also be due to the high cognitive load created by the fast pace we used. Indeed, effects of the number of distractors in our experiments were only observed at fast paces (Fig. 5). This effect could result from the sustained occupation of the central bottleneck engendered by the reading activity that prevents attention from refreshing memory traces (Barrouillet et al., 2011a), while verbal rehearsal is blocked by reading the digits aloud. In this case, the period of temporal decay tends to become coextensive with the delay between encoding and recall, a delay that increases with the number of distractors. Thus, the effect of the number of distractors could be explained by either the interference or the temporal decay accounts. These accounts are not exclusive and both could be correct. Overall, this study has provided us with clear evidence that immediate serial recall is affected by the same time-related effects that had been observed when studying complex span tasks, suggesting that the same time-based resource-sharing mechanism could be extended to a large range of situations that requires the maintenance of information in the short term.

To conclude, the interplay of temporal factors and event-based interference in short-term forgetting could be more complex than expected. The present study revealed that the relative impact of the two factors varies with the paradigm used, and that divergent results can be reconciled when the nature of memory traces is taken into account. This points towards the need for more integrated approaches using a variety of tasks and methods in an attempt to specify the domain of validity of theoretical proposals.

References

Baddeley, A. D. (1986). *Working memory.* Oxford: Calendron Press.
Baddeley, A. D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*, 4, 417–423.
Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource-sharing in adults' working memory spans. *Journal of Experimental Psychology. General*, 133, 83–100.
Barrouillet, P., Bernardin, S., Portrat, S., Vergauwe, E., & Camos, V. (2007). Time and cognitive load in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 33, 570–585.
Barrouillet, P., & Camos, V. (2010). Working memory and executive control: A time-based resource-sharing account. *Psychologica Belgica*, 50, 353–382.
Barrouillet, P., De Paepe, A., & Langerock, N. (2012). Time causes forgetting from working memory. *Psychonomic Bulletin and Review*, 19, 87–92.
Barrouillet, P., Gavens, N., Vergauwe, E., Gaillard, V., & Camos, V. (2009). Working memory span development: A time-based resource-sharing model account. *Developmental Psychology*, 45(2), 477–490.
Barrouillet, P., Portrat, S., & Camos, V. (2011a). On the law relating processing to storage in working memory. *Psychological Review*, 118, 175–192.
Barrouillet, P., Portrat, S., Vergauwe, E., Diependaele, K., & Camos, V. (2011b). Further evidence for temporal decay in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 37, 1302–1317.

Berman, M. G., Jonides, J., & Lewis, R. L. (2009). In search of decay in verbal short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 35, 317–333.
Brown, G. D. A., Neath, I., & Chater, N. (2007). A temporal ratio model of memory. *Psychological Review*, 114, 539–576.
Burgess, N., & Hitch, G. J. (1999). Memory for serial order: A network model of the phonological loop and its timing. *Psychological Review*, 106, 551–581.
Camos, V., & Barrouillet, P. (2011). Developmental change in working memory strategies: From passive maintenance to active refreshing. *Developmental Psychology*, 47, 898–904.
Camos, V., Lagner, P., & Barrouillet, P. (2009). Two maintenance mechanisms of verbal information in working memory. *Journal of Memory and Language*, 61, 457–469.
Cowan, N., & AuBuchon, A. M. (2008). Short-term memory loss over time without retroactive stimulus interference. *Psychonomic Bulletin & Review*, 15, 230–235.
Cowan, N., Elliott, E. M., Saults, J. S., Nugent, L. D., Bomb, P., & Hismjatullina, A. (2006). Rethinking speed theories of cognitive development: Increasing the rate of recall without affecting accuracy. *Psychological Science*, 17, 67–73.
Farrell, S., & Lewandowsky, S. (2002). An endogenous distributed model of ordering in serial recall. *Psychonomic Bulletin & Review*, 9, 59–79.
Gavens, N., & Barrouillet, P. (2004). Delays of retention, processing efficiency, and attentional resources in working memory span development. *Journal of Memory and Language*, 51, 644–657.
Hudjetz, A., & Oberauer, K. (2007). The effects of processing time and processing rate on forgetting in working memory: Testing four models of the complex span paradigm. *Memory & Cognition*, 35, 1675–1684.
Lépine, R., Barrouillet, P., & Camos, V. (2005a). What makes working memory spans so predictive of high-level cognition? *Psychonomic Bulletin and Review*, 12, 165–170.
Lépine, R., Bernardin, S., & Barrouillet, P. (2005b). Attention switching and working memory spans. *European Journal of Cognitive Psychology*, 17, 329–346.
Lewandowsky, S., Duncan, M., & Brown, G. D. A. (2004). Time does not cause forgetting in short-term serial recall. *Psychonomic Bulletin and Review*, 11, 771–790.
Lewandowsky, S., Geiger, S. M., Morrell, D. B., & Oberauer, K. (2010). Turning simple span into complex span: Time for decay or interference from distractors? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 36, 958–978.
Lewandowsky, S., Geiger, S. M., & Oberauer, K. (2008). Interference-based forgetting in verbal short-term memory. *Journal of Memory and Language*, 59, 200–222.
Lewandowsky, S., & Oberauer, K. (2009). No evidence for temporal decay in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 35, 1545–1551.
Lewandowsky, S., Oberauer, K., & Brown, G. D. A. (2009). No temporal decay in verbal short-term memory. *Trends in Cognitive Sciences*, 13, 120–126.
McCabe, D. P. (2008). The role of covert retrieval in working memory span tasks: Evidence from delayed recall tests. *Journal of Memory and Language*, 58, 480–494.
Miller, G. A. (1956). The magical number seven plus or minor two: Some limits on our capacity for processing information. *Psychological Review*, 63, 81–97.
Nairne, J. S. (1990). A feature model of immediate memory. *Memory & Cognition*, 18, 251–269.
Oberauer, K., Farrell, S., Jarrold, C., Pasiecznik, K., & Greaves, M. (2012). Interference between maintenance and processing in working memory: The effect of item-distractor similarity in complex span. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 38, 665–685.
Oberauer, K., & Kliegl, R. (2006). A formal model of capacity limits in working memory. *Journal of Memory and Language*, 55, 601–626.
Oberauer, K., & Lewandowsky, S. (2008). Forgetting in immediate serial recall: Decay, temporal distinctiveness, or interference? *Psychological Review*, 115, 544–576.
Oberauer, K., & Lewandowsky, S. (in press). Evidence against decay in verbal working memory. *Journal of Experimental Psychology*: *General*. http://dx.doi.org/:10.1037/a0029588.
Page, M. P. A., & Norris, D. (1998). The primacy model: A new model of immediate serial recall. *Psychological Review*, 105, 761–781.
Plancher, G., & Barrouillet, P. (in press). Forgetting from working memory: Does novelty encoding matter? *Journal of Experimental Psychology: Learning, Memory, and Cognition*. http://dx.doi.org/10.1037/a0028475.
Portrat, S., Camos, V., & Barrouillet, P. (2009). Working memory in children: A time-constrained functioning similar to adults. *Journal of Experimental Child Psychology*, 102, 368–374.
Repovs, G., & Baddeley, A. D. (2006). The multi-component model of working memory : Explorations in experimental cognitive psychology. *Neuroscience*, 139, 5–21.
Ricker, T. J., & Cowan, N. (2010). Loss of visual working memory within seconds: The combined use of refreshable and non-refreshable features. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 36, 1355–1368.
Tan, L., & Ward, G. (2008). Rehearsal in immediate serial recall. *Psychonomic Bulletin & Review*, 15, 535–542.
Vergauwe, E., Barrouillet, P., & Camos, V. (2009). Visual and spatial working memory are not that dissociated after all: A time-based resource-sharing account. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 35, 1012–1028.
Vergauwe, E., Barrouillet, P., & Camos, V. (2010). Do mental processes share a domain-general resource? *Psychological Science*, 21, 384–390.
Vergauwe, E., Dewaele, N., Langerock, N., & Barrouillet, P. (2012). Evidence for central pool of general resources in working memory. *Journal of Cognitive Psychology*, 24, 359–366.
Waugh, N., & Norman, D. (1965). Primary memory. *Psychological Review*, 72, 89–104.