Year: 2019

Is Rehearsal an Effective Maintenance Strategy for Working Memory?

Oberauer, Klaus

Abstract: A common assumption in theories of working memory is that a maintenance process – broadly referred to as rehearsal – is involved in keeping novel information available. This review evaluates the effectiveness of three forms of rehearsal: articulatory rehearsal, attention-based refreshing, and elaborative rehearsal. Evidence for the effectiveness of these strategies is surprisingly weak. Experimental manipulations of articulatory rehearsal have yielded working memory benefits in children, but not in adults; experimentally induced refreshing prioritizes the refreshed information, but yields little benefit compared to a baseline without induced refreshing; and elaborative rehearsal improves episodic long-term memory but has little effect on working memory. Thus, although adults spontaneously use some of these strategies, rehearsal might not play a causal role in keeping information in working memory.

DOI: https://doi.org/10.1016/j.tics.2019.06.002

Originally published at:
Oberauer, Klaus (2019). Is Rehearsal an Effective Maintenance Strategy for Working Memory? Trends in Cognitive Sciences, 23(9):798-809.
DOI: https://doi.org/10.1016/j.tics.2019.06.002

Is Rehearsal an Effective Maintenance Strategy for Working Memory?

Klaus Oberauer, University of Zurich

Oberauer, K. (2019). Is rehearsal an effective maintenance strategy for working memory? *Trends in Cognitive Sciences*. doi:10.1016/j.tics.2019.06.002

Address for correspondence: Klaus Oberauer, Department of Psychology, University of Zurich,

Binzmühlestrasse 14/22, 8050 Zürich, Switzerland. Email: k.oberauer@psychologie.uzh.ch

Key words: Rehearsal, short-term memory, working memory, refreshing, elaboration.

Abstract

A common assumption in theories of working memory is that some maintenance process – broadly referred to as rehearsal – is involved in keeping novel information available. This review evaluates the effectiveness of three forms of rehearsal: Articulatory rehearsal, attention-based refreshing, and elaborative rehearsal. Experimental manipulations of articulatory rehearsal have yielded benefits for tests of working memory in children, but not in adults. Refreshing is difficult to measure, and it is unclear whether people use it spontaneously. When refreshing is experimentally induced, it prioritizes the refreshed information, but yields little benefit compared to a baseline without induced refreshing. Elaborative rehearsal improves episodic long-term memory, but has little effect on working memory. Maintenance processes might not play a causal role in keeping information in working memory.

Varieties of Rehearsal Proposed as Memory Maintenance Strategies

People often need to hold information briefly in mind – for instance a question from the audience that a speaker wants to respond to, or the constellation of pieces on a chess board that results from mentally simulating a series of moves. Our ability for holding information temporarily available for processing is referred to as short-term or working memory (Box 1). Many theories assume that some form of rehearsal plays an important role in maintaining information in working memory. Rehearsal, broadly understood, means to revisit the current contents of working memory with the aim to maintain or improve their memorability. This review is concerned with two questions: First, which rehearsal processes do people spontaneously engage in when confronted with a demand on working memory? Second, do these processes causally contribute to maintenance in typical working-memory tasks (Box 1)?

In the tradition of research on verbal working memory, the focus has been primarily on **articulatory rehearsal** (see Glossary) as a strategy for maintaining verbal materials over time intervals in the order of seconds or tens of seconds. Articulatory rehearsal consists in (usually silently) speaking the items of a memory list to oneself. It is the maintenance process people report most frequently when asked about their strategies in verbal working-memory tasks (Morrison, Rosenbaum, Fair, & Chein, 2016). For several decades, researchers took for granted that articulatory rehearsal is a useful, and perhaps necessary strategy for maintaining verbal information in working memory. Recent computational modelling work (see Box 2) and empirical research has begun to cast doubt on this assumption. One aim of this review is to assess the evidence concerning the effectiveness of articulatory rehearsal as a short-term maintenance strategy.

A relatively novel addition to the hypothetical set of maintenance processes is **refreshing**, defined as directing attention to individual items in working memory (Barrouillet, Bernardin, & Camos, 2004; Raye, Johnson, Mitchell, Greene, & Johnson, 2007). Refreshing has been postulated as a maintenance strategy because it helps to explain the effect of **cognitive load** in working-memory tests: When a distractor task to be carried out during memory maintenance (e.g., mental arithmetic) is demanded at a slower pace (i.e., lower cognitive load), memory is better (Barrouillet, Portrat, & Camos, 2011). In a computational modelling work, refreshing has been identified as an effective maintenance process (see Box 2). Yet, refreshing is rarely, if ever, mentioned as a strategy in people's self-reports, so we need to ask whether people engage in it spontaneously during a working-memory test. I will review evidence speaking to that question, and also evidence on whether refreshing, if it is used, is beneficial for working memory.

In recent years, working-memory researchers have become interested also in a third form of rehearsal, **elaborative rehearsal**. Elaborative rehearsal (or short: elaboration) refers to enriching representation of the to-be-remembered stimuli through additional meaning. Elaboration of words in a memory list could consist, for instance, in creating visual images of the word's referents, or of combining several words into a sentence. Elaboration has long been known to improve episodic long-term memory (Box 1). But what is the role of elaboration in a typical test of working memory? In self-report studies a sizeable minority reports using elaboration in a verbal working-memory test, and these individuals tend to do the task better than those reporting other strategies (Bailey, Dunlosky, & Kane, 2008; Dunlosky & Kane, 2007; Morrison et al., 2016). I will review emerging experimental evidence on the effectiveness of elaboration in working-memory tests.

Articulatory Rehearsal

There is no question that many people spontaneously engage in articulatory rehearsal: It is the most prevalent self-reported strategy people use when asked to remember a verbal list for immediate serial recall; among adults about half of the respondents report using it (Dunlosky & Kane, 2007; Morrison et al., 2016). Overt-rehearsal studies (Box 3) show that most people try to use **cumulative rehearsal**, although when list items are presented at the most commonly used rate of one per second, they rarely manage to rehearse more than the just-presented item (Tan & Ward, 2008).

Most of the evidence for the effectiveness of articulatory rehearsal as a maintenance strategy comes from three sources. First, immediate serial recall of verbal lists is influenced by some linguistic variables – most notably word length – that can be expected to influence how fast the list can be rehearsed (Baddeley, Thomson, & Buchanan, 1975; Mueller, Seymour, Kieras, & Meyer, 2003). However, the interpretation of such correlations between memory performance and naturally varying characteristics of the materials is problematic because many such variables affect immediate serial recall, and they are often correlated (Lewandowsky & Oberauer, 2008). Recent experiments revealed one such confounding variable: Lists of longer words are harder to recall not because of word length per se but because longer words tend to have fewer orthographic neighbors (i.e., other words in the language that are written in a similar way), and neighborhood size affects immediate serial recall (Guitard, Gabel, Saint-Aubin, Surprenant, & Neath, 2018; Jalbert, Neath, Bireta, & Surprenant, 2011).

Second, the extent to which people rehearse correlates with how well they do on an immediate serial recall test (Kroll & Kellicutt, 1972; Tan & Ward, 2008). This correlation, however, could also reflect the fact that one needs good memory of a list to be able to rehearse it.

Third, concurrent articulation of irrelevant material (e.g., repeating aloud "ba-bi-bu") during maintenance of a verbal list strongly impairs memory compared to a silent control condition. Concurrent articulation undoubtedly impairs articulatory rehearsal, but it also does other things. For instance, it introduces additional irrelevant material into working memory that interferes with the memory list. Simulations with a computational model of serial recall show that interference alone is sufficient to explain the effect of concurrent articulation (Lewandowsky & Oberauer, 2015). To conclude, all three kinds of evidence are not entirely convincing.

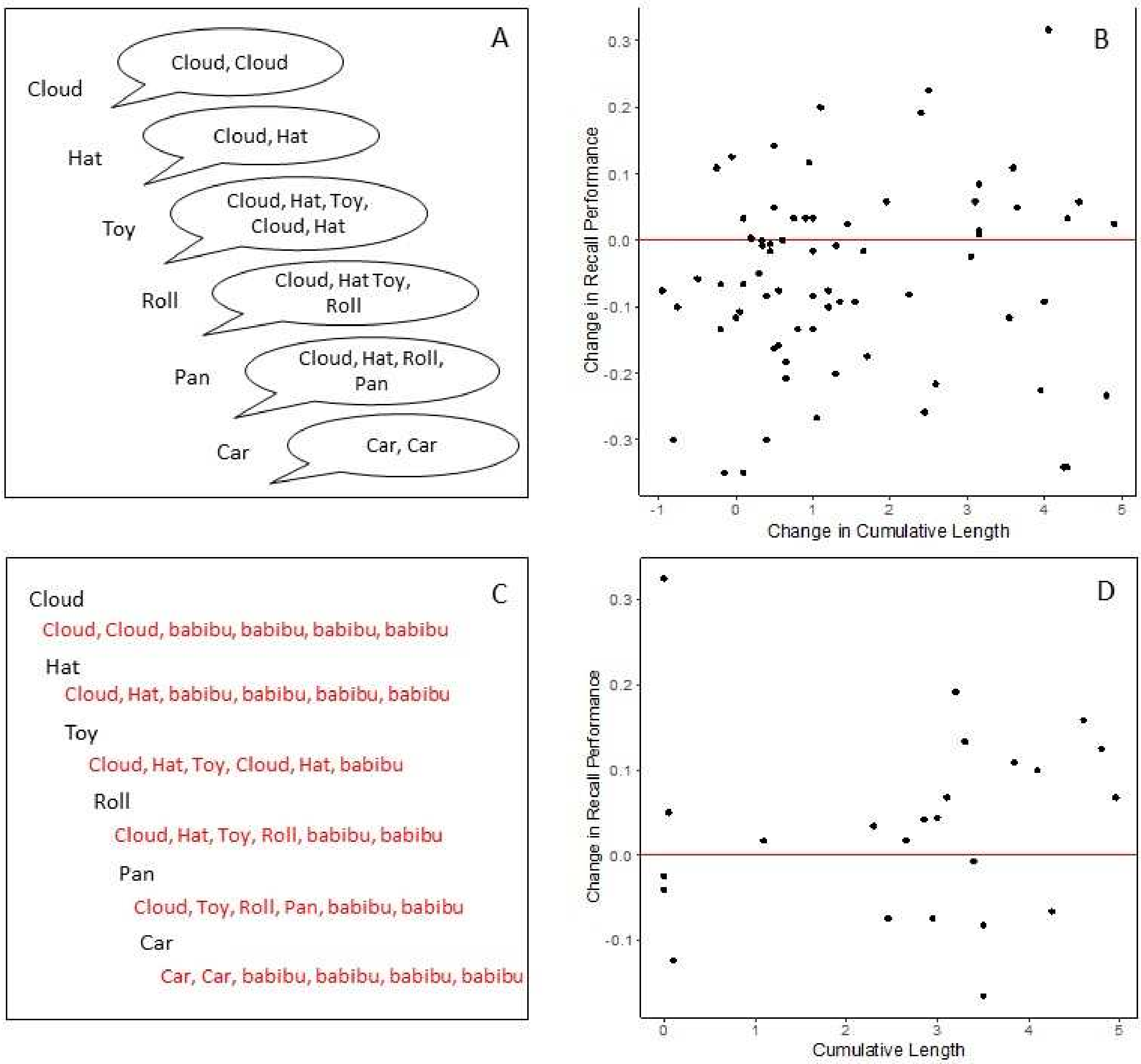
Better evidence comes from studies experimentally inducing rehearsal through instruction or training. Studies with children have shown that such interventions improve immediate serial recall (Bebko, 1979; Miller, McCulloch, & Jarrold, 2015; Peng & Fuchs, 2017). For instance, one research team trained a group of 5-6 year olds and a group of 8-9 year olds in a cumulative rehearsal strategy.

In the short training phase, participants were presented lists of memory items – pictures of familiar objects – and listened to a voice that cumulatively rehearsed the items in between successive pictures. After watching this for one trial, participants were encouraged to use the same strategy during two further practice trials. In the control condition, instead of cumulative rehearsal the voice merely repeated the name of the one most recently presented picture. Subsequently, memory for lists of pictures was tested in a Brown-Peterson procedure: Between list presentation and recall, participants had to work on two trials of a simple distractor task. Regardless of age, the group with cumulative rehearsal practice performed better than the control group (Miller et al., 2015).

Studies with young adults present a different picture. One early study tested the effect of practicing cumulative articulatory rehearsal on performance in a complex-span procedure, in which encoding of memory items alternates with brief periods of distractor activity (Turley-Ames & Whitfield, 2003). The trained group showed better performance when encoding was self-paced, but this was due to them taking more time for encoding the items. When the time to encode each item was controlled by the experimenter, the advantage of the trained group disappeared.

In another study, researchers asked participants to remember between 2 and 6 letters, and to subvocally rehearse them during a 45 s retention interval in sync with a visual metronome. With increasing metronome speed the BOLD signal in several brain areas – among them the premotor cortex – increased, providing evidence that participants followed the instruction. Yet, memory performance was unaffected by metronome speed, suggesting that faster rehearsal does not yield a benefit over slow rehearsal (Fegen, Buchsbaum, & D'Esposito, 2015).

In a recent study, Souza and Oberauer (2018) instructed participants to use cumulative rehearsal during presentation of a six-word list for immediate serial recall. Words were presented at a slow pace – one word every five seconds – because slow presentation provides ample opportunity for articulatory rehearsal, and most people spontaneously use articulatory rehearsal at this pace (Tan & Ward, 2008). In the control condition, participants were free to use any strategy they wanted, but if they chose to engage in articulatory rehearsal, they were instructed to do it aloud. In the cumulative-rehearsal condition, they were instructed to use each inter-word interval to repeat the current list in a cumulative fashion as far and as often as possible, and to do so aloud. This instruction substantially increased the amount of cumulative rehearsal, but it had no beneficial effect on serial-recall performance (Figure 1, A and B).



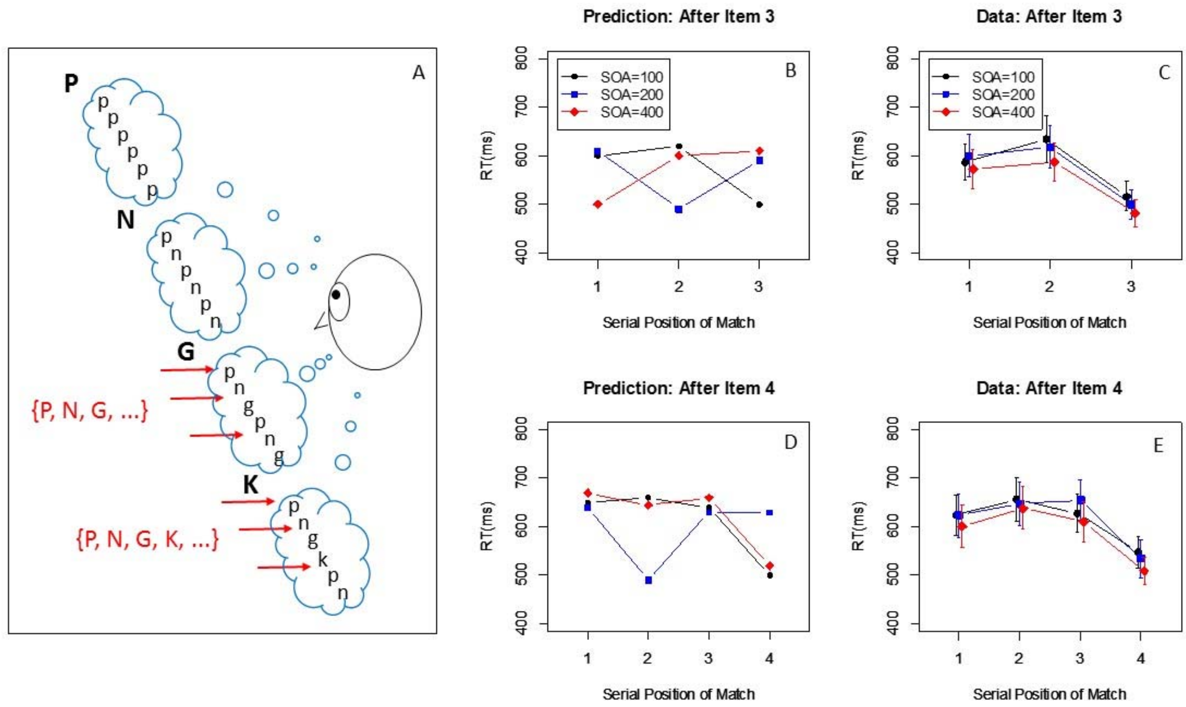
A further experiment tested the hypothesis that participants' spontaneous articulatory rehearsal is already optimal (Souza & Oberauer, 2018). Participants were given lists of six words to remember at a pace of one word every 5 seconds. In the inter-word intervals, they were asked to read additional text off the screen aloud. In the control condition, this text consisted of six repetitions of the syllable sequence "ba-bi-bu". Articulating this sequence served to prevent participants from using articulatory rehearsal. In the rehearsal condition, each participant received the overt-rehearsal record of one participant from a previous experiment to read off the screen; the remainder of the inter-word intervals was filled with "ba-bi-bu" (Figure 1C). These rehearsal records were taken from the control condition in which people were free to use any strategy they wanted, on the assumption that people choose an optimal rehearsal strategy. Memory performance in the rehearsal condition was not better than in the control condition in which articulatory rehearsal was prevented through concurrent articulation (Figure 1D). Taken together this series of experiments implies that neither maximal cumulative rehearsal nor the articulatory-rehearsal schedule spontaneously chosen by participants effectively improves memory in an immediate serial-recall test for young adults.

Why might children benefit from articulatory rehearsal whereas adults don't? One possibility is that children, whose cognitive control is less developed, are easily distracted during the retention interval by environmental stimuli or emerging thoughts that enter working memory and interfere with the to-be-remembered material. Continuous cumulative rehearsal ensures that the child's attention remains focused on the memory items – including earlier encoded items – and does not stray to other, task-irrelevant contents. In adults, a task goal representation is more robustly in place, which in turn controls the gate into working memory, preventing task-irrelevant materials from intruding, and therefore articulatory rehearsal becomes unnecessary (see Outstanding Questions).

Refreshing

Refreshing is an elusive control process which, unlike articulatory rehearsal, cannot be observed directly as a form of behavior (see Box 3). The empirical motivation for postulating refreshing as a maintenance process was the observation that performance in complex-span tests is closely related to the opportunities for refreshing: As the distractor processing component of the complex-span procedure is demanded at a slower pace, leaving more free time in between individual operations on the distractor task, memory gets better (Barrouillet et al., 2011). This *cognitive-load* effect, however, is open to several alternative interpretations, because people could use free time in several ways to improve memory. One possibility is that they use it to remove interfering distractor representations from working memory (Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012). Another possibility is that free time is used for elaboration of the memory materials – although this possibility appears unlikely in light of recent evidence on the effectiveness of elaboration, reviewed below. To confirm a role of refreshing as a maintenance process for working memory, evidence for two conjectures is needed: (a) Participants engage in refreshing spontaneously during a working-memory task, and (b) refreshing effectively improves memory for the refreshed representations.

Vergauwe and colleagues developed a method for gauging people's spontaneous refreshing during presentation of a list (Vergauwe et al., 2016; Vergauwe, Langerock, & Cowan, 2018). Their probe-span procedure builds on two assumptions: (1) Refreshing consists of directing the focus of attention in working memory to one list item at a time, in forward order, and (2) items in the focus of attention are particularly quickly available for comparison with a probe in a recognition task. The first assumption is part of a common definition of refreshing, and the second assumption is supported by evidence showing particularly fast access to the last-processed item in working memory (Garavan, 1998; McElree, 2006), and more directly by research on guided refreshing, discussed in the next section (Vergauwe & Langerock, 2017). In the probe-span procedure, lists of to-be-remembered letters were presented at a leisurely pace. In between letters, participants had to respond to a recognition probe, indicating as quickly as possible whether that probe was an element of the list encoded so far. The time between presentation of the last list letter and the probe was varied over several steps. If participants use the inter-letter intervals to cumulatively refresh the letters, then their focus of attention should switch from the last-presented letter back to the first letter, then to the second, and so on (Figure 2A). Therefore, at different points in time after encoding the last letter, successive letters of the list should be recognized particularly quickly (Figure 2, B & D). This turned out not to be the case: Regardless of when the probe was presented, recognition of the last-encoded letter was always the fastest (Figure 2, C & E). If fast recognition is an indicator for which item is in the focus of attention, these results imply that the focus stays on the last-presented letter until the next letter is presented. Vergauwe and colleagues concluded that people probably do not refresh all list items spontaneously in their test procedure (Vergauwe et al., 2018).



Evidence more consistent with spontaneous refreshing comes from a study using the same rationale with a different procedure (Vergauwe & Langerock, 2017). Memory for five-letter lists was tested with a single recognition probe presented at varying intervals after offset of the last list letter. At probe delays shorter than 1 s, recognition responses were fastest for matches to the last item; at longer delays this last-item benefit disappeared. Apparently the focus of attention did not dwell long on the last-presented item in this task – this could mean that participants use an extended retention interval following the entire list to switch attention back to earlier list items, refreshing them in turn.

A different approach was taken by Jafarpour and colleagues (Jafarpour, Penny, Barnes, Knight, & Duzel, 2017). They asked participants to remember three pictures of three different object categories in working memory, and decoded the individual objects from the MEG signal during the retention interval. In each trial a single object from the memory set was predominantly decodable, and that tended to be the object that, according to a separate neural signal, had received the least attention at encoding. These results converge with those of Vergauwe et al. (2018) in that participants spontaneously attend to only one item in the current memory set rather than refreshing all items in turn, but in the study of Jafarpour and colleagues, this was not necessarily the last-presented item.

What are the consequences of refreshing individual items in working memory for the memorability of these items? This can be investigated with the *guided-refreshing* procedure (Souza, Rerko, & Oberauer, 2015). This procedure was initially developed for visual memory contents. Participants tried to remember an array of six colors. During the retention interval of several seconds, a sequence of four arrows, each pointing to the location of one color in the (no longer visible) array, is presented. Participants are instructed to "think of" the color that they remember to be at the location each arrow points to. In this way, their attention is guided to some array items once, to one of them twice, and to some others not at all. In a subsequent test in which they had to reproduce a randomly selected color on a color wheel, the precision of reproduction increased with the number of times an item had been refreshed. Hence, directing attention to an item in working memory during the retention interval improves its memorability, and attending to it twice helps even more. Further experiments with the guided-refreshing method showed benefits of refreshing individual items for visual, spatial and verbal working-memory contents, although the effects were smaller for verbal than for visual-spatial representations (Souza, Vergauwe, & Oberauer, 2018).

Refreshed items are remembered better than not-refreshed items from the same memory set – but does refreshing improve memory in comparison to a condition without guided refreshing? One guided-refreshing experiment with colors showed that twice-refreshed items are reproduced from memory better than items in a control condition in which no refreshing cues were given during an equally long retention interval (Souza et al., 2015). In contrast, with guided refreshing of spatial locations, performance in the control condition was better than once-refreshed, and even somewhat better than twice-refreshed locations (Souza et al., 2018). With verbal memory items, two studies showed a trend for refreshed items to be recalled better than in the control condition, but in both cases the effect was very small and statistically ambiguous (Bartsch, Singmann, & Oberauer, 2018; Souza et al., 2018).

Guided refreshing has also been used to show that just-refreshed items can be accessed particularly quickly (Vergauwe & Langerock, 2017). In these experiments participants initially encoded a list of four letters, presented in clockwise order across a 2x2 matrix of frames. During the retention interval individual frames were highlighted for one second each in clockwise order, and participants were instructed to "think of" the letter they remembered for that box. This continued for a variable number of one to five boxes, so that the last-refreshed letter could be any list letter. Immediately afterwards memory was tested with a recognition probe. Recognition was particularly fast when the probe matched the last-refreshed item. Hence, when people follow the instruction to think of a particular item in working memory, then that item is arguably in the focus of attention, and this translates into relatively fast access for a recognition decision.

To conclude, instructing participants to selectively attend to individual items in working memory during the retention interval improves memory for these items relative to memory for the not-attended items in the same memory set. In comparison to a control condition without guided refreshing, however, there is no compelling evidence that refreshing improves memory. One could argue that in the control condition participants spontaneously refresh all items, so that memory should be expected to be equally good as for refreshed items in the guided-refreshing condition. However, we do not know whether participants spontaneously refresh multiple items during the retention interval of a working-memory task. The evidence so far suggests that they often do not (see Outstanding Questions).

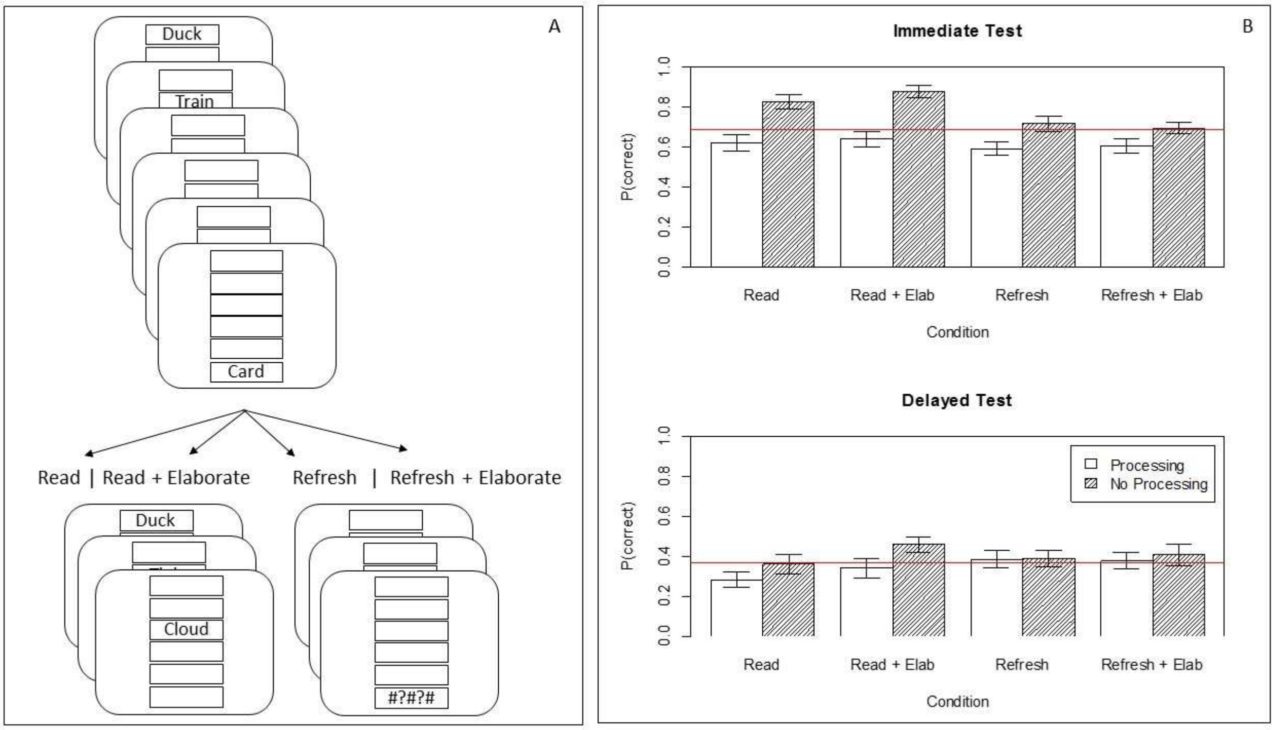
Elaborative Rehearsal

Elaboration means to enrich the representation of a stimulus with associated knowledge from semantic memory. For instance, a list of consonants could be used to form a word by filling in appropriate vowels; a list of words could be enriched through the formation of an image of the word's referents interacting in a scene, or by linking the words into a sentence. In self-report studies, about 15 to 20 percent of young adults report using one of these strategies during verbal working-memory tasks (Bailey et al., 2008; Dunlosky & Kane, 2007; Morrison et al., 2016). These participants tend to show better memory performance. Does this correlation reflect a causal effect of elaboration on working memory?

Elaboration often involves processing the meaning of the memory material, and therefore it is plausible that orienting a person's attention to the meaning of to-be-remembered words encourages elaboration more than orienting them to more superficial features such as the words' spoken sounds or characteristics of their printed form. Several recent studies have investigated whether performance in a working-memory test is improved by an orienting task at encoding that requires processing of the words' meanings compared to one that requires processing of their phonology or printed form (Loaiza & Camos, 2016; Loaiza, McCabe, Youngblood, Rose, & Myerson, 2011; Rose & Craik, 2012; Rose, Myerson, Roediger, & Hale, 2010). The orienting task had the usually observed effect on a delayed memory test – better memory for words processed semantically – but the effect was less consistently found on working-memory tests. Processing a word's meaning is, however, not the same as elaborating on that meaning, and therefore these studies speak only indirectly to the effectiveness of elaborative rehearsal.

A few studies tested the effectiveness of elaboration more directly (Bartsch et al., 2018; Thalmann, Souza, & Oberauer, 2019). Participants were given lists of words to remember, and in one condition asked to elaborate them during encoding (Thalmann et al., 2019), or to elaborate a subset of the list words during the retention interval (Bartsch et al., 2018). Specifically, they were asked to form a mental image in which the referents of the words interacted. For instance, the word list "ball, cloud, flower, hat" could be elaborated by imagining a person with a hat playing ball on a field full of flowers with a cloud overhead. In one study, the instruction to elaborate improved immediate serial recall of the word lists, but only for lists consisting of concrete, highly imageable words, and not (or very little) for words of abstract, difficult to imagine words (Thalmann et al., 2019). In the other study no beneficial effect of elaboration was found for an immediate test of memory regardless of word concreteness, although the usually observed beneficial effect of elaboration for a delayed test was replicated (Bartsch et al., 2018) (see Figure 3).

To summarize, in light of the sparse evidence available so far, the beneficial effect of elaborative rehearsal on working-memory performance is weak and volatile, if it exists at all. When considering the effects of elaboration, we must keep in mind that no test of working memory is process pure. Very likely, in addition to the operation of working memory, episodic long-term memory forms a record of every event during a working-memory test, and at retrieval the person could draw on that record in addition to the information in working memory. Therefore, if elaboration improved only the accessibility of information in episodic long-term memory, that would be sufficient to generate a small advantage for elaborated material in a working-memory test (see Outstanding Questions).



Concluding Remarks

An important role of maintenance processes for keeping information in working memory has long been taken for granted by many memory researchers. Recent evidence suggests that the role of these processes might have been overrated. Instructing children in cumulative articulatory rehearsal helps them maintain verbal materials. In contrast, when the extent of articulatory rehearsal was experimentally manipulated in adults, this had no beneficial effect on memory. Refreshing of a subset of items in a memory set effectively prioritizes these items over others in the set, but it does not do much to elevate memory for the entire memory set. Moreover, there is currently no evidence that participants spontaneously go over all items in working memory in turn to refresh them. They might rather focus attention on only one item throughout the retention interval. Elaborative rehearsal has long been known to improve episodic long-term memory, but the few available studies so far show at best a small effect of elaboration on working memory.

If this emerging picture is consolidated by further evidence, it affords an attractively parsimonious concept of working memory: A limited amount of information can be held in working memory without the need for continuous maintenance processes acting on them. All it takes to keep them is to protect them from intrusions from further input by refraining, as much as possible, from attending to something else than the currently to-be-remembered information.

Glossary

Articulatory Rehearsal: Silently (or sometimes, overtly) repeating a set of verbal memory items to oneself.

Cognitive load: Temporal density of the cognitive demand of a distractor task to be carried out concurrently with memory maintenance. In the Time-Based Resource-Sharing (TBRS) theory, cognitive load is defined as the ratio of the time for which the distractor task requires central attention to the available time for completing the distractor task (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007).

Complex Span Paradigm: A working-memory task paradigm in which presentation of items of a memory list alternates with brief periods of a distractor task (e.g., reading a sentence, solving an arithmetic problem).

Cumulative rehearsal*:* Re-articulation, or refreshing, of all items in a memory list in forward order, cycling through the list repeatedly if time allows.

Elaborative rehearsal*:* Enriching the to-be-remembered stimuli by associated knowledge from long-term memory. For instance, letters in a memory list could be combined into a word; words could be combined into a meaningful sentence or story, or visual images of the word's referents could be created.

Immediate Serial Recall: A common procedure for measuring working memory. Items of a list are presented sequentially, typically at a rate of 1 per second, and the person should repeat them in their order of presentation right after presentation.

Refreshing: Directing the focus of attention to the items in a memory set, one at a time, to increase their memory strength.

Box 1: Working Memory: Definition and Measurement

Theorists of working memory have proposed different definitions of the term (Cowan, 2017), which reflect their diverging theoretical views. They have in common that they conceptualize working memory as a system, or set of processes, that holds information temporarily available for processing (Oberauer, 2018). There has been discussion on whether the concepts short-term memory and working memory ought to be distinguished, but the empirical basis for such a distinction is weak (Unsworth & Engle, 2007), and therefore I don't make one.

There is remarkable consensus among researchers about how to test working memory. Typical tasks require the maintenance of a small number of items (usually between 3 and 8) for a brief retention interval (in the order of seconds or tens of seconds). Some tests involve additional processing demands, requiring cognitive operations on the remembered material, or on unrelated distractor material (for instance, in the **complex-span paradigm**, see Glossary). Tests with verbal material usually require **immediate serial recall**; tests with visual materials most often involve simultaneous presentation of a set of visual objects, followed by a test of a single randomly selected object; tests of spatial working memory use both procedures. Performance is usually measured as the accuracy of memory.

Working memory is usually distinguished from episodic long-term memory, although there is debate about how deep that distinction goes (Farrell, 2012). Tests of episodic long-term memory usually involve relatively large sets of items (about 10 to 100) studied at a slow pace (several seconds per item), and tested after an extended delay (in the order of minutes) filled with distractor activity.

Memory for lists of words is often studied with free recall, asking participants to reproduce the words in any order. Although immediate serial recall and free recall yield remarkably similar behavioral phenomena (e.g., Grenfell-Essam & Ward, 2012; Grenfell-Essam, Ward, & Tan, 2017; Ward, Tan, & Grenfell-Essam, 2010), free recall is rarely used to investigate working memory. Research on the role of rehearsal in free recall has used much longer lists, presented more slowly than in typical working-memory tasks (Tan & Ward, 2000). Therefore, this review does not include research on free recall.

Box 2: Computational Modelling of Rehearsal

Models of working memory usually assume the interplay of multiple mechanisms and processes, of which some form of rehearsal can be one. This complexity makes it difficult to derive unambiguous predictions about the effect of rehearsal on memory. Computational implementation of a model can help overcome this difficulty. For instance, the Time-Based Resource-Sharing (TBRS) theory (Barrouillet et al., 2011) has been implemented as a computational model, TBRS* (Oberauer & Lewandowsky, 2011). Simulations with TBRS* revealed that refreshing has to proceed very rapidly – at 80 ms per item or faster – to enable the model to predict memory behavior consistent with experimental data. Subsequent work with TBRS* investigated the effectiveness of articulatory rehearsal and found that, whereas fast refreshing was very effective in protecting memory from decay in the simulations, rehearsal was much less effective (Lewandowsky & Oberauer, 2015). Others have used TBRS* to explore different schedules of refreshing, and found that a refreshing schedule that selects the currently weakest list item to refresh leads to simulated memory behavior most in line with the data (Lemaire, Pageot, Plancher, & Portrat, 2018).

Modelling can reveal unanticipated effects of hypothetical rehearsal mechanisms. For instance, the authors of the TBRS theory have argued that articulatory rehearsal and refreshing operate in parallel, and contribute independently to memory maintenance (Camos, Lagner, & Barrouillet, 2009). On that basis they predicted that experimental manipulations varying the opportunity for using articulatory rehearsal (i.e., concurrent articulation of irrelevant material) and the opportunity for refreshing (i.e., cognitive load) should have additive effects on memory performance. This prediction was confirmed in their experiments. Simulations with TBRS*, in contrast, found that when the relatively slow articulatory-rehearsal and the fast refreshing process operated independently in parallel, memory performance was poorer than with refreshing alone (Lewandowsky & Oberauer, 2015). The predictions from TBRS* therefore do not match the computationally unaided predictions, and also not the experimental findings (Camos et al., 2009). Two parallel and independent maintenance processes do not necessarily have additive effects; a model explaining the additive effects will have to build on different assumptions than the ones incorporated in TBRS*.

Box 3: How to Measure Rehearsal

The most straightforward way to measure articulatory rehearsal is to ask participants to rehearse aloud. This has no discernable effect on their recall behavior compared to a silent condition (Tan & Ward, 2008).

There is no established method yet for measuring refreshing. One approach is to measure which item is in the focus of attention at different time points during the retention interval, building on the empirically well-supported assumption that an item in the focus of attention is accessible faster than other items in the current memory set (Vergauwe et al., 2016; Vergauwe et al., 2018). The drawback of this method is that it adds a second cognitive demand to the primary memory task, thereby potentially altering people's behavior. A less intrusive method could be to decode the content of the focus of attention from neural signals. Because refreshing is assumed to be a fast process, fMRI is too slow for that purpose, but EEG or MEG might yield sufficient temporal resolution for tracking the content of the focus over time (Jafarpour et al., 2017; Johnson, McCarthy, Muller, Brudner, & Johnson, 2015).

There is currently no method for measuring elaboration while it happens, but elaboration can be indirectly assessed through its effect on performance in a delayed test for the memory items from all working-memory trials of an experiment, or of a block in the experiment. Elaboration is known to improve episodic long-term memory, so if an experimental condition intended to increase elaboration during a working-memory task improves delayed memory, that increases confidence that the manipulation was effective (Bartsch et al., 2018).

Researchers have attempted to measure all three forms of rehearsal indirectly through response times – either the times for self-paced encoding of further elements of the memory list (Morey et al., 2018; Poloczek, Henry, Messer, & Büttner, 2019) or the response times to a distractor task during the retention interval (Naveh-Benjamin & Jonides, 1984; Thalmann et al., 2019; Vergauwe, Camos, & Barrouillet, 2014). The underlying assumptions are that rehearsal takes time, and therefore participants postpone other processes until they finished rehearsing, and that they take more time to rehearse longer memory lists. Therefore, rehearsal is inferred from the observation of slower response times at later list positions during encoding, and/or for longer list lengths. One limitation of this method is that it cannot distinguish between different forms of rehearsal: A slow-down of response times with the length of a verbal list could reflect articulatory rehearsal, refreshing, elaboration, or any combination of them. It could also reflect the mere anticipation of a difficult memory task: One study using a complex-span task found that when people knew the list length of the upcoming trial, list length affected already the time they took for encoding and processing the first list item (McCabe, 2010).

Outstanding Questions

* Does articulatory rehearsal serve a function other than maintenance? Possible functions involve keeping attention on the memory materials, turning a visual representation of written material into a phonological-articulatory representation that is more robust against interference, and preparing a speech plan for oral recall.

* If articulatory rehearsal yields no benefit for memory, why do about half of young adults use it as a maintenance strategy? One possibility is that they continue using a strategy that they learned to be helpful when they were children, or because they have a subjective theory of short-term memory according to which information decays unless rehearsed. Another possibility is that holding a verbal list in working memory is tantamount to holding a speech plan in a heightened state of preparation, which tends to induce its execution, if only subvocally.

* What do people spontaneously attend to while holding information in working memory? Do they attend to items in a memory set one by one, and if so, do they refresh them in a cumulative fashion? Alternatively, do they tend to select one item to be attended to constantly, and if so, what determines this selection – is it the last-processed item, or the item most in need of a boost of memory strength?

* Why is elaboration beneficial for episodic long-term memory, and why do the mechanisms responsible for this effect not apply to the same extent to a test of working memory? Could the differential effectiveness of instructed elaboration be used to further illuminate differences in how working memory and episodic long-term memory operate?

References

Baddeley, A. D., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short term memory. *Journal of Verbal Learning and Verbal Behavior, 14*, 575-589.

Bailey, H., Dunlosky, J., & Kane, M. J. (2008). Why does working memory span predict complex cognition? Testing the strategy affordance hypothesis. *Memory & Cognition, 36*, 1383-1390.

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 & Cognition, 33*, 570-585.

Barrouillet, P., Portrat, S., & Camos, V. (2011). On the law relating processing to storage in working memory. *Psychological Review, 118*, 175-192.

Bartsch, L. M., Singmann, H., & Oberauer, K. (2018). The effects of refreshing and elaboration on working memory performance, and their contributions to long-term memory formation. *Memory & Cognition*. doi:10.3758/s13421-018-0805-9

Bebko, J. M. (1979). Can recall differences among children be attributed to rehearsal effects? *Canadian Journal of Psychology, 33*, 96-105.

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. (2017). The many faces of working memory and short-term storage. *Psychonomic Bulletin & Review, 24*, 1158-1170. doi:10.3758/s13423-016-1191-6

Dunlosky, J., & Kane, M. J. (2007). The contributions of strategy use to working memory span: A comparison of strategy assessment methods. *Quarterly Journal of Experimental Psychology, 60*, 1227-1245.

Farrell, S. (2012). Temporal clustering and sequencing in short-term memory and episodic memory. *Psychological Review, 119*, 223-271.

Fegen, D., Buchsbaum, B. R., & D'Esposito, M. (2015). The effect of rehearsal rate and memory load on verbal working memory. *NeuroImage, 105*, 120-131. doi:10.1016/j.neuroimage.2014.10.034

Garavan, H. (1998). Serial attention within working memory. *Memory & Cognition, 26*, 263-276.

Grenfell-Essam, R., & Ward, G. (2012). Examining the relationship between free recall and immediate serial recall: the role of list length, strategy use, and test expectancy. *Journal of Memory and Language, 67*, 106-148.

Grenfell-Essam, R., Ward, G., & Tan, L. (2017). Common modality effects in immediate free recall and immediate serial recall. *Journal of Experimental Psychology: Learning, Memory and Cognition, 43*, 1909-1933. doi:10.1037/xlm0000430

Guitard, D., Gabel, A. J., Saint-Aubin, J., Surprenant, A. M., & Neath, I. (2018). Word length, set size, and lexical factors: Re-examining what causes the word-length effect. *Journal of Experimental Psychology: Learning, Memory and Cognition, 44*, 1824-1844. doi:10.1037/xlm0000551

Jafarpour, A., Penny, W., Barnes, G., Knight, R. T., & Duzel, E. (2017). Working memory replay prioritizes weakly attended events. *eNeuro, 4*. Retrieved from doi:10.1523/ENEURO.0171-17.2017

Jalbert, A., Neath, I., Bireta, T. J., & Surprenant, A. M. (2011). When does length cause the word length effect? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37*, 338-353.

Johnson, M. R., McCarthy, G., Muller, K. A., Brudner, S. N., & Johnson, M. K. (2015). Electrophysiological correlates of refreshing: Event-relatedpotentials associated with directing reflective attention to face, scene, or word representations. *Journal of Cognitive Neuroscience, 27*, 1823-1839. doi:10.1162/jocn_a_00823

Kroll, N. E. A., & Kellicutt, M. H. (1972). Short-term recall as a function of covert rehearsal and of intervening task. *Journal of Verbal Learning and Verbal Behavior, 11*, 196-204.

Lemaire, B., Pageot, A., Plancher, G., & Portrat, S. (2018). What is the time course of working memory attentional refreshing? *Psychonomic Bulletin & Review, 25*, 370-385. doi:10.3758/s13423-017-1282-z

Lewandowsky, S., & Oberauer, K. (2008). The word-length effect provides no evidence for decay in short-term memory. *Psychonomic Bulletin & Review, 15*(5), 875-888.

Lewandowsky, S., & Oberauer, K. (2015). Rehearsal in serial recall: An unworkable solution to the non-existent problem of decay. *Psychological Review, 122*, 674-699. doi:10.1037/a0039684

Loaiza, V. M., & Camos, V. (2016). Does controlling for temporal parameters change the levels-of-processing effect in working memory? *Advances in Cognitive Psychology, 12*(1), 2-9. doi:10.5709/acp-0182-3

Loaiza, V. M., McCabe, D. P., Youngblood, J. L., Rose, N. S., & Myerson, J. (2011). The influence of levels of processing on recall from working memory and delayed recall tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37*, 1258-1263.

McCabe, D. P. (2010). The influence of complex working memory span task administration methods on prediction of higher level cognition and metacognitive control of response times. *Memory & Cognition, 38*, 868-882.

McElree, B. (2006). Accessing recent events. In B. H. Ross (Ed.), *The Psychology of Learning and Motivation* (Vol. 46, pp. 155-200). San Diego: Academic Press.

Miller, S., McCulloch, S., & Jarrold, C. (2015). The development of memory maintenance strategies: training cumulative rehearsal and interactive imagery in children aged between 5 and 9. *frontiers in Psychology, 6*. Retrieved from doi:10.3389/fpsyg.2015.00524

Morey, C. C., Hadley, L. V., Buttelmann, F., Könen, T., Meaney, J. A., Auyeung, B., . . . Chevalier, N. (2018). The effects of verbal and spatial memory load on children's processing speed. *Annals of the New York Academy of Sciences, 1424*(1), 161-174. doi:10.1111/nyas.13653

Morrison, A. B., Rosenbaum, G. M., Fair, D., & Chein, J. M. (2016). Variation in strategy use across measures of verbal working memory. *Memory & Cognition, 44*, 922-936. doi:10.3758/s13421-016-0608-9

Mueller, S. T., Seymour, T. L., Kieras, D. E., & Meyer, D. E. (2003). Theoretical implications of articulatory duration, phonological similarity, and phonological complexity in verbal working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*, 1353-1380.

Naveh-Benjamin, M., & Jonides, J. (1984). Maintenance rehearsal: A two-component analysis. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 10*, 369-385.

Oberauer, K. (2018). e pluribus unum: Consensus despite diversity. Retrieved from https://featuredcontent.psychonomic.org/whatwm-e-pluribus-unum-consensus-despite-diversity/

Oberauer, K., & Lewandowsky, S. (2011). Modeling working memory: a computational implementation of the Time-Based Resource-Sharing theory. *Psychonomic Bulletin & Review, 18*(1), 10-45.

Oberauer, K., Lewandowsky, S., Farrell, S., Jarrold, C., & Greaves, M. (2012). Modeling working memory: An interference model of complex span. *Psychonomic Bulletin & Review, 19*, 779-819. doi:10.3758/s13423-012-0272-4

Peng, P., & Fuchs, D. (2017). A randomized control trial of working memory training with and without strategy instruction: Effects on young children's working memory and comprehension. *Journal of Learning Disabilities, 50*, 62-80. doi:10.1177/0022219415594609

Poloczek, S., Henry, L. A., Messer, D. J., & Büttner, G. (2019). Do children use different forms of verbal rehearsal in serial picture recall tasks? A multi-method study. *Memory*. doi:10.1080/09658211.2018.1563615

Raye, C. L., Johnson, M. K., Mitchell, K. J., Greene, E. J., & Johnson, M. R. (2007). Refreshing: A minimal executive function. *Cortex, 43*, 135-145.

Rose, N. S., & Craik, F. I. M. (2012). A processing approach to the working memory/long-term memory distinction: Evidence from the levels-of-processing span task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*, 1019-1029.

Rose, N. S., Myerson, J., Roediger, H. L., & Hale, S. (2010). Similarities and differences between working memory and long-term memory: Evidence from the levels-of-processing span task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*, 471-483.

Souza, A. S., & Oberauer, K. (2018). Does articulatory rehearsal help immediate serial recall? *Cognitive Psychology, 107*, 1-21. doi:10.1016/j.cogpsych.2018.09.002

Souza, A. S., Rerko, L., & Oberauer, K. (2015). Refreshing memory traces: thinking of an item improves retrieval from visual working memory. *Annals of the New York Academy of Sciences, 1339*, 20-31. doi:10.1111/nyas.12603

Souza, A. S., Vergauwe, E., & Oberauer, K. (2018). Where to attend next: guiding refreshing of visual, spatial, and verbal representations in working memory. *Annals of the New York Academy of Science*. doi:10.1111/nyas.13621

Tan, L., & Ward, G. (2000). A recency-based account of the primacy effect in free recall. *Journal of Experimental Psychology: Learning, Memory & Cognition, 26*, 1580-1625.

Tan, L., & Ward, G. (2008). Rehearsal in immediate serial recall. *Psychonomic Bulletin & Review, 15*, 535-542.

Thalmann, M., Souza, A. S., & Oberauer, K. (2019). Revisiting the attentional demands of rehearsal in working-memory tasks. *Journal of Memory and Language, 105*, 1-18. doi:10.1016/j.jml.2018.10.005

Turley-Ames, K. J., & Whitfield, M. M. (2003). Strategy training and working memory task performance. *Journal of Memory and Language, 49*, 446-468.

Unsworth, N., & Engle, R. W. (2007). On the division of short-term and working memory: An examination of simple and complex span and their relation to higher order abilities. *Psychological Bulletin, 133*(1038-1066).

Vergauwe, E., Camos, V., & Barrouillet, P. (2014). The impact of storage on processing: How is information maintained in working memory? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*, 1072-1095.

Vergauwe, E., Hardman, K. O., Rouder, J. N., Roemer, E., McAllaster, S., & Cowan, N. (2016). Searching for serial refreshing in working memory: Using response times to track the content of the focus of attention over time. *Psychonomic Bulletin & Review*. doi:10.3758/s13423-016-1038-1

Vergauwe, E., & Langerock, N. (2017). Attentional refreshing of information in working memory: Increased immediate accessibility of just-refreshed representations. *Journal of Memory and Language, 96*, 23-35. doi:10.1016/j.jml.2017.05.001

Vergauwe, E., Langerock, N., & Cowan, N. (2018). Evidence for spontaneous serial refreshing in verbal working memory? *Psychonomic Bulletin & Review, 2*, 674-680. doi:10.3758/s13423-017-1387-4

Ward, G., Tan, L., & Grenfell-Essam, R. (2010). Examining the relation between free recall and immediate serial recall: The effects of list length and output order. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*, 1207-1241. doi:10.1037/a0020122

Figure Captions

Figure 1: An Experimental Manipulation of Cumulative Articulatory Rehearsal

A: Typical record of overt rehearsal when words are presented at a slow rate, and participants are free to rehearse any way they want (Souza & Oberauer, 2018; Tan & Ward, 2008). B: When instructed to rehearse in cumulative forward order as much as possible, most participants increased their average length of cumulative rehearsal, compared to a condition with free rehearsal. This increase in rehearsal was not accompanied by an increase in serial-recall performance. Data are from Experiments 1a, 1b, and 2 of Souza and Oberauer (2018). C: In Experiment 3 of Souza and Oberauer (2018), participants remembered lists of six words (printed in black), and during the inter-word intervals read six letter strings off the screen (printed in red). In the rehearsal condition, each participant was given the overt-rehearsal records of one participant from another experiment to read. The example shows the rehearsal record from panel A. D: The average length of cumulative rehearsal traces provided to participants in Experiment 3 of Souza and Oberauer (2018) varied between 0 and 4 words, reflecting the variability of spontaneous rehearsal schedules generated by other participants. Compared to a control condition in which rehearsal was prevented by concurrent articulation, reading other people's rehearsal records did not improve memory.

Figure 2: Testing Refreshing with the Probe Span Procedure

A: The probe-span procedure of Vergauwe et al. (2016). Participants tried to remember a list of four letters (printed in large, upper-case letters). During the inter-letter intervals, a recognition probe was presented at a variable stimulus onset asynchrony (SOA) after the last letter, shown by red arrows in the last two inter-letter intervals. If participants refreshed the letters during the inter-letter intervals, their focus of attention would cycle through the letters presented so far, presumably in forward order, as shown by the small lower-case letters in thought bubbles. A probe matching the last-refreshed item should be recognized faster than one matching another list item. B, D: Predicted response times to matching probes at different SOAs during the third (B) and fourth (D) inter-letter interval. At the shortest SOA (100 ms), the just-presented letter – in the currently last list position – should still be in the focus of attention. At longer SOAs, the focus of attention should have switched back to letters in earlier list positions. Therefore, the serial positions at which matches should be detected fastest should vary with SOA, following the assumed sequence in which letters are refreshed. C, E: Observed response times to matching probes. Contrary to the predictions, matches were detected particularly quickly for the last-presented letter regardless of SOA (Vergauwe et al., 2016; Vergauwe et al., 2018).

Figure 3: An Experiment Testing the Effects of Elaborative Rehearsal

A: The procedure of inducing refreshing and elaboration in Bartsch et al. (2018): Six to-be-remembered words are presented from top to bottom across six frames. This is followed by processing of the first three or the last three words according to one of four conditions: In the Read condition, the three to-be-processed words are presented again, one at a time, for 2 s each, to be read silently. In the Read + Elaboration condition, participants were instructed to read the words and to form a vivid mental image of their three referents interacting with each other. In the Refresh condition, a constant string of symbols was presented in the three frames instead of the words. Participants were instructed to "think of" the word in the respective frames. In the Refresh + Elaboration condition, they should in addition form a vivid mental image. B: Memory performance in immediate and delayed tests of memory (Bartsch et al., 2018) for words from the processed and from the not-processed subset of the memory lists. The horizontal red line reflects average performance in a baseline condition in which the processing instruction was replaced by an unfilled interval of 6 s. Immediate memory was improved by reading the to-be-remembered words again, but neither elaboration nor refreshing yielded a benefit over and above reading, compared to baseline. Delayed memory benefited from elaboration but not from refreshing.