On some of the main criticisms of the modal model: Reappraisal from a TBRs perspective

Gaëlen Plancher¹ · Pierre Barrouillet²

Published online: 22 October 2019
© The Psychonomic Society, Inc. 2019

Abstract

The model developed by Atkinson and Shiffrin describes memory as a flow of information that enters and leaves a short-term storage and that in some cases consolidates into a long-term store. Their model has stimulated 50 years of memory research and, like every model, has also received several criticisms. It has been argued that a single short-term store in charge of both maintaining memory items and processing other cognitive tasks is not plausible. Some authors have evaluated the proposal of a rehearsal process as the unique way to transfer information into long-term memory as not being likely. Finally, the idea that information decays from the short-term store in the absence of rehearsal maintaining the memory traces has been and is still debated in the working memory literature. In this article, we reconsider these criticisms and show why they are not totally legitimate. We describe a recent working memory model, the time-based resource-sharing (TBRs) model (Barrouillet, P., & Camos, V. (2015). *Working memory: Loss and reconstruction*. Hove, UK: Psychology Press), that shares several theoretical assumptions with the model initially proposed by Atkinson and Shiffrin, assumptions supported by empirical findings. Consequently, the model proposed by Atkinson and Shiffrin in 1968 may be far from outdated and still provide an inspiring framework for memory study.

Keywords Working memory · Short-term memory · Modal model · TBRs model

In the chapter entitled “Human Memory: A Proposed System and Its Control Processes,” Richard Shiffrin and Richard Atkinson proposed in 1968 a new memory model. This model represented a turning point in the evolution of memory theory because it gathered the concepts and results proposed since the start of psychology and formalized them in a general theoretical framework. The “modal model” is one of the name given to this model, which was also referred as the “two-store model.” In the present article, we have chosen to name it the “modal model.” The impact of Atkinson and Shiffrin’s model has been immense. It has served as a template and as a source of creativity for 50 years of research. Probably one of the reasons why the theory has resisted the passage of time is that its components are intuitive and easy to appreciate. George Box noted that all

models and theories are wrong, but nonetheless are useful in many ways (Box & Draper, 1987). No doubt the modal model has been, and is still, useful for research in psychology. The theory has served as a starting point for the development of alternative models, though many subsequent memory models still include ideas developed in Atkinson and Shiffrin’s chapter. The modal model has also elicited several criticisms about the way its components and their relationships were designed.

In the present study, we will first give a cursory presentation of the modal model, focusing on the so-called short-term store (STS) component and its control processes, because they have been found to be central to governing the flow of information in the memory system. Second, we will demonstrate how several criticisms that have been raised against the modal model can be reconsidered, by describing recent research that has assumed memory processes compatible with those in the model initially proposed by Atkinson and Shiffrin.

This paper was originally to be part of the special issue commemorating the 50th anniversary of Atkinson and Shiffrin, edited by K. Malmberg, J. G. W. Raaijmakers, and R. M. Shiffrin, but was not included due to technical issues.

✉ Gaëlen Plancher
gaen.plancher@univ-lyon2.fr

¹ Université Lyon 2, Lyon, France

² Université de Genève, Geneva, Switzerland

The modal model

The modal model assumed that memory is composed of three structural components—a sensory register (SR), an STS, and a long-term store (LTS)—along with control processes. The incoming sensory information first enters the SR within the

appropriate sensory dimensions (e.g., visual), where it stays for a very brief period of time (several hundred milliseconds). The second component, the STS (also called the auditory–verbal–linguistic [a-v-l] STS), which constitutes the core of the system, receives inputs from both the SR and the LTS.¹ Information entering the STS is assumed to decay, and to completely disappear after a delay of 15–30 s, unless it is actively maintained. Importantly, the nature of the information in the STS does not necessarily depend on the form of the sensory input. For example, a word presented visually may be encoded from the visual SR into what Atkinson and Shiffrin called an a-v-l store. Later in the chapter, they mention that the terms *STS* and *a-v-l STS* are synonymous, while also saying that they do not imply that there are not other short-term memories with similar properties.

Overall, these structural components of the model are viewed as permanent features of memory, whereas the control processes are transient phenomena under a subject's control. Because these processes are related to the permanent memory structures, different control processes are described for SR, STS, and LTS. For example, when simultaneous inputs come from several sensory channels, individuals can decide to which SR to attend, and they can also decide where and what to scan within the register. In the LTS, different control processes are also investigated. One example is the strategy adopted to code the information (called *coding*). Another example is the search process in the LTS, a process that typically fails in the tip-of-the-tongue phenomenon.

The most important control processes are those operating on the STS. One of these processes is the search process, typically involved in a recall task. According to Atkinson and Shiffrin, such a process is not as elaborate as those in LTS, because the amount of information to be searched is reduced in the STS, but the process must act quickly, because memory traces decay rapidly. On the basis of Sternberg's (1966) observations that response latencies in a short-term recognition task increase linearly with set size, Atkinson and Shiffrin proposed an exhaustive and fast search process in STS: exhaustive because the search does not stop when a match is discovered, and fast because it scans items at a rate of 40 ms per item. Another control process is rehearsal, the overt or covert articulatory repetition of information, which either increases the strength of memory traces or delays its loss. This control process is separate from the search process because the fast rate of the scanning in the search process appears incompatible with a process of rehearsal that should take more time. Rehearsal has for its role to keep information in the STS and to build up memory traces in the LTS, this construction being a function of both the time during which information is kept in STS and the coding made on that information. The coding process requires access to LTS because

the information in STS is transformed as a result of a search in LTS. Most of the time, coding relies on strong associations previously stored in long-term memory. For the authors, any kind of operation on a memory trace in the STS (e.g., coding) can be viewed as a form of rehearsal, but they finally reserved the latter term for the process that involves articulatory repetition of verbal memoranda.

Later, Atkinson and Shiffrin (1971) offered to the STS a central position, as the memory system was described in terms of the flow of information that goes into and out of STS thanks to processes controlled by the subject. In this new version of the model, the STS was viewed as temporary activation of some portion of the LTS, an idea that remains central in several contemporary models of working memory (WM), such as the embedded-processes model of Cowan (1988, 2005), Engle's (Engle, Tuholski, Laughlin, & Conway, 1999) model, or Oberauer's (2002) model. For Atkinson and Shiffrin, STS is similar to consciousness, and they eventually considered STS as a form of WM, because control processes are centered in STS and act through it. WM is considered a system where decisions can be made and problems can be solved, and to which information flow is directed.

Criticisms of the Atkinson and Shiffrin model

The modal model quickly became a reference and dominated the field of memory for several years. However, in the seventies, several criticisms were raised, about this model and alternative theories were presented that were supposed to handle the new findings. Three postulates of the modal model, in particular, have been criticized and are still today a matter of debate.

First, the idea of a single, unique STS system in charge of maintaining memory items and processing other cognitive tasks was judged to be implausible. The fact that patient K.F. had a lower short-term memory capacity but preserved performance in learning, memory, or comprehension (Shallice & Warrington, 1970; Warrington & Shallice, 1969) led Baddeley and Hitch (1974) to examine whether, in healthy subjects, a common WM system might be shared by storage functions and processes like reasoning, language, or comprehension. They reasoned that if this were the case, limiting the capacity of short-term memory by a memory load should have a detrimental effect on these concurrent cognitive processes. Baddeley and Hitch observed that a process like verbal reasoning was disrupted by a concurrent memory load, but this disruption was far from massive, even when memory load approached the subjects' span. These findings were taken as contradicting the modal model, which predicted that a difficult

¹ In later versions of the model, the SR was combined with the STS into a single component (Atkinson & Shiffrin, 1971; Shiffrin, 1975).

reasoning task and the concurrent maintenance of digit sequences at span should have disastrous reciprocal effects. These observations were the basis for the development of the well-known multiple-component model of WM (Baddeley, 1986), in which a controlling central system is in charge of implementing and supervising processing activities, whereas storage is carried out by separate slave systems. Thus, the way that Baddeley and Hitch interpreted their results has had a robust and durable impact on cognitive psychology, by introducing a separation between the WM functions of processing and storage.

Second, the modal model has been criticized because it suggests that rehearsal is the sole mechanism for transfer to LTS. In particular, Craik and Lockhart (1972) offered a new theoretical framework of memory showing that long-term memory depends on the level (rather than the duration) of processing of the to-be-remembered material. They showed that keeping information in an active state has no effect on further memory performance, but that the probability of delayed recall of information is influenced by the nature of the processing, with deeper processing resulting in better recall performance than shallow processing.

Finally, the modal model assumes that information decays from the STS in the absence of rehearsal for maintaining the memory traces. However, the existence of temporal decay of memory traces has been, and is still, a matter of intense debate in the literature (Oberauer, Farrell, Jarrold, & Lewandowsky, 2016), with some models arguing in favor of decay, and others claiming that only interference accounts for forgetting in WM.

In the following discussion, we will argue that these criticisms against the modal model are not totally justified. The empirical evidence on which the strongest criticisms were based has been shown to be less conclusive than was initially assumed, and WM models have integrated several of the key assumptions of the modal model while avoiding most of the problems it encountered. In particular, a recent WM model, the time-based resource-sharing model (TBRS; Barrouillet, Bernardin, & Camos, 2004; Barrouillet & Camos, 2015; Barrouillet, Portrat, & Camos, 2011) will be presented that includes several principles that were already present in the modal model, such as a common system for processing and storage, the temporal decay of WM traces, and various control systems that have differential effects on the transfer of information from STS to LTS.²

² The assumption of separate short- and long-term memories (named STS and LTS in the modal model) has also been, and is still, strongly criticized. Nonetheless, we decided not to address this criticism in the present review, because it has already been discussed within the TBRS model approach (Barrouillet & Camos, 2015, pp. 184–188) and has recently been the subject of an extensive discussion and refutation by Norris (2017).

A unique WM system with storage and processing sharing resources

The findings on which Baddeley (1986; Baddeley & Logie, 1999) based his multicomponent model and the separation between storage and processing systems, and particularly Baddeley and Hitch's (1974) observations, could have received alternative interpretations more compatible with the modal model. Contrary to the assumptions of the multicomponent model, subsequent empirical work has offered support for the view that processing and maintenance activities share a common resource (e.g., Anderson, Reder, & Lebière, 1996; Barrouillet et al., 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Barrouillet & Camos, 2015; Barrouillet et al., 2011; Vergauwe, Barrouillet, & Camos, 2010; Vergauwe, Camos, & Barrouillet, 2014). Consequently, alternative models have then privileged the hypothesis of a unitary short-term memory system, as in the modal model.

One of the most prominent of these theories is the TBRS model (Barrouillet & Camos, 2012; Barrouillet et al., 2011). This model assumes that processing and storage compete for a unique resource shared within a unitary system, resulting in a perfect trade-off between the two functions. The TBRS model relies on three main assumptions that account for how storage and processing interplay in WM. First, the model assumes that storage and processing need an attentional resource. Importantly, because this resource is limited, it has to be shared between the two functions. Second, because a central bottleneck constrains cognition so that only one elementary cognitive step can take place at a time (Pashler, 1998), processing and maintenance take place in a sequential manner. The third assumption of the TBRS model is that WM traces suffer from temporal decay and interference as soon as attention is switched away. Thus, when attention is occupied by processing, memory traces that can no longer be maintained decay, and when attention is occupied by maintenance activities, concurrent processing must be postponed. Consequently, to avoid memory loss, attention has to be frequently redirected to memory traces for their restoration during short pauses that would be freed while concurrent processing is running, and from storage to processing when items must be processed. This results in a rapid switching between processing and storage that operates through an *executive loop* that allows for constructing, restoring, and transforming representations in WM. It is worth to note that the role of attention is central in several models of WM that conceive the attentional process of restoration as a covert retrieval (Cowan, 1992; McCabe, 2008; Unsworth & Engle, 2007), an attentional refreshing (Raye, Johnson, Mitchell, Greene, & Johnson, 2007), a scanning of the content of WM (Vergauwe & Cowan, 2014, 2015), or a reconstruction of WM representations (Barrouillet & Camos, 2015).

The principles of the TBRS model account for a very robust empirical result, the cognitive load (*CL*) effect, typically observed in complex span tasks in which to-be-remembered items (e.g., letters, digits, spatial locations) are presented for further serial recall, each of these items being followed by a series of to-be-processed distractors that constitute an intervening task (e.g., digits for a parity task, squares for a spatial judgment). It has been observed in many studies that recall performance is a function of the ratio between the time during which processing these distractors occupies attention and the total time allowed to process them, this proportion being referred to as *CL* (Barrouillet et al., 2004; Barrouillet et al., 2007; Barrouillet & Camos, 2014). Because maintenance activities are prevented when the processing component of the task occupies attention, the higher the *CL* of the intervening task, the lower the recall performance. Concretely, in a complex span task, the *CL* of the intervening task can be operationalized in different ways. It increases with the number of distractors to be processed in a fixed interval, so that reduced time is allowed to process a fixed number of distractors, and with the time taken to process each distractor when their number and the time allowed for processing them are kept constant. Typically, the mean response time for processing distractors is used as a raw estimate of the duration of attentional capture. The *CL* of the intervening task is given by the following formula:

$$CL = Nt/T,$$

where *N* is the number of distractors, *t* is the time during which attention is occupied when processing each of them, and *T* is the total time allowed to process them. It is worth noting that even simple activities, such as reading digits or response selection, can efficiently block attention for prolonged periods of time if they are performed under time constraints.

The TBRS model accounts for the relationship between WM performance and *CL* in the following way. The way WM items can be maintained and recalled in complex span tasks depends on temporal factors. The first concerns the time during which distracting tasks prevent the refreshing of memory traces, leading to their temporal decay. The longer this time, the greater their decay. The second factor is the time during which attention is free to go back to the memory traces and is available for their refreshing. The longer this time, the higher the number of memory items that can be sufficiently refreshed in order to survive the next processing episode. Increasing *CL* decreases recall performance because it increases the processing time during which memory traces decay, or it reduces the time available to repair the damages of this temporal decay, or both. These predictions were tested by comparing the effects on the maintenance of verbal items of different concurrent tasks that involved various attention-demanding processes (e.g., memory retrieval, response

selection, updating, or inhibition). The ratio of processing times to the total time allowed for performing these tasks was used as a proxy of *CL* (Barrouillet et al., 2011). Whatever the nature of the intervening task, the mean spans proved to be a linear function of *CL*, with WM performance decreasing as *CL* increases. This effect is very strong, as it accounts for more than 90% of the observed variance in memory performance (Barrouillet et al., 2004; Barrouillet et al., 2007; Barrouillet et al., 2011; Plancher & Barrouillet, 2013; Vergauwe, Barrouillet, & Camos, 2009; Vergauwe et al., 2010). In their chapter, Atkinson and Shiffrin (1968) mentioned that the process of decay of information in the STS is difficult to estimate because it is greatly influenced by subject-controlled processes. It is interesting to note that, in the TBRS, the law relating maintenance to processing using the *CL* formula is a way to clarify the relation between decay and refreshing. Indeed, memory decay from STS is a function of the *CL* of the concurrent processing activities.

Let us return to the results of Baddeley and Hitch (1974), who observed no effect of memory load on reasoning performance, but an effect on solution times. How does the TBRS model explain this pattern of results? In this model, items stored in WM do not require a continuous allocation of resources for their maintenance. This thesis is different from the one developed by Baddeley and colleagues, for whom WM is like a continuous allocation of space or resource. That is why Baddeley and Hitch reasoned in terms of the effect of concurrent memory load on reasoning or comprehension. A subject who is loaded to the limit of his span digits would have so little processing capacity remaining that his reasoning performance should collapse. But there is another way to interpret these results. If reasoning performance does not decrease, this is probably because reasoning and storage do not *continuously* share a limited space or energy. If we suppose a sequential functioning of WM, as in the TBRS model (see also the switching model proposed by Towse & Hitch, 1995), any activity related to the storage of memory traces would postpone concurrent processing for a duration proportionate with the amount of information to be maintained in an active state. The results from Baddeley and Hitch reflected this functioning. Because more memory items take longer to be stored and consolidated, they induce a longer postponement of any other activity, resulting in the observed increase in reasoning times with the number of digits. Why did reasoning times not increase with a small memory load? Probably because, with the reasoning task taking only about 2 s, it was not necessary to postpone it when few memory items had to be maintained. This hypothesis also explains why memory load affects only reasoning times, but not accuracy. Indeed, when attention is turned toward processing activities after refreshing activities, its full capacity is available for reasoning processes that have been postponed but are not impacted in their accuracy.

The hypothesis of the postponement of processing by maintenance processes was tested by Vergauwe, Camos, and Barrouillet (2014), who predicted that this postponement should be commensurate with the number of memory items to be maintained but should have a negligible effect on processing accuracy. To test these predictions, using different kinds of memoranda and a Brown–Peterson paradigm, they examined in a series of seven experiments the effect of increasing memory load on different processing tasks. Participants were given a list of items for further recall and asked to perform an intervening task over a fixed retention interval of 12 s prior to recall. They were instructed to perform this intervening activity at their best level, while at the same time they did not forget the memoranda. For example, in one experiment participants were presented with series of zero to seven letters to be remembered and were asked during a 12-s retention interval to judge the parity of as many digits as they could. As predicted, it was shown that processing times increased with the number of memoranda, demonstrating that maintaining information active in WM postpones concurrent processing. However, this effect was observed when the information to be maintained relied on a domain-general attention-based mechanism of maintenance, but not when it could also rely on verbal rehearsal, a domain-specific maintenance mechanism independent from attention. This latter mechanism will be presented later, when the different mechanisms of maintenance in WM will be developed. The results revealed that processing times increased linearly with the number of items to be maintained. The slope of this predicted linear function is indicative of the time it takes to refresh one item through attentional focusing. The slope was estimated to be around 40–50 ms per additional memory item, suggesting a very fast refreshing rate in WM. Interestingly, this estimated refreshing time is consistent with a meta-analysis of response times for processing tasks used in WM paradigms. This analysis indicated a slowing down of response speed depending on the number of to-be-memorized items (Vergauwe & Cowan, 2014). In particular, this estimate of 40–50 ms per item is very close to the time needed to covertly retrieve one item during serial recall (Cowan, Saults, & Elliott, 2002) but also to the memory scanning rate observed by Sternberg (1966). This might be a coincidence, but it might also suggest that the rates of refreshing, covert retrieval, and memory scanning reflect a common limitation, possibly related to the operation of the focus of attention.

Interestingly, Atkinson and Shiffrin estimated, after Sternberg (1966), the rate of scanning in the search process to be 40 ms. It might be assumed that the attentional refreshing hypothesized by the TBRS model would operate through a sequential search process of WM traces, with their retrieval resulting in their reactivation (Barrouillet et al., 2004; Cowan, 1992; Vergauwe & Cowan, 2014, 2015; Sternberg, 2016). Overall, the series of studies developed within the TBRS

framework lend strong support to the hypothesis that the two functions of WM, storage and processing, compete for a unique resource shared in a time-based way, and that processing leading to the postponement of maintenance activities and to lost WM traces, whereas maintenance activities lead to processing postponement. Consequently, the criticism against the modal model formulated by Baddeley and Hitch (1974) appears not to be relevant if we consider STS as a memory system in which the main constraints are temporal in nature. A single STS in charge of maintaining memory items and processing other cognitive tasks, as suggested by Atkinson and Shiffrin's modal model, remains plausible.

Transfer of information from STS to LTS

As we noted earlier, one of the aspects of the modal model that has received the most criticisms was the idea that maintenance rehearsal is key to the transfer of information from the STS to the LTS. Studying the role of rehearsal in short-term memory, Craik and Watkins (1973) reported that neither the length of the stay of an item in the STS nor the amount of overt rehearsal this item received had an impact on subsequent recall of the item. Craik and Watkins's findings became part of what Lehman and Malmberg (2013) have called the *conventional wisdom* that maintenance rehearsal has no effect on long-term memory. However, it is not clear that this criticism is well founded, for at least two reasons. The first is that Atkinson and Shiffrin (1968) did not assume that maintenance rehearsal was the unique control process for transferring information from the STS to the LTS, and they even suggested that other control processes might be more efficient. Second, contrary to the conventional wisdom, there is ample empirical evidence that maintenance rehearsal does create long-term memory traces.

Let us begin with the first point and recall what Atkinson and Shiffrin (1968, p. 115) wrote about transfer to the LTS:

The important aspect of this transfer, however, is the wide variance in the amount and form of this transferred information that may be induced by control processes. When the subject is concentrating upon rehearsal, the information transferred would be in a relatively weak state and easily subject to interference. On the other hand, the subject may divert his effort from rehearsal to various coding operations which will increase the strength of the stored information.

This makes clear that Atkinson and Shiffrin conceived various control processes with different efficiencies in the transfer process, with verbal rehearsal being less efficient. In line with this idea, considerable evidence has been provided in favor of

two independent mechanisms of maintenance in verbal WM, one having an impact on long-term memory that is stronger than the other. The first mechanism of maintenance is attentional refreshing, and the second one is verbal rehearsal. The attentional refreshing already evoked above is presented as a domain-general type of mechanism relying on attention to keep mental representations active (Barrouillet & Camos, 2015; Camos et al., 2018; Cowan, 1995; Johnson, 1992). This mechanism is acknowledged not only by the TBRS model, but also by the embedded-processes model of Cowan (1992) and by McCabe's (2008) model, which both assume attentional refreshing as a maintenance mechanism for memory traces. As we have seen, in the TBRS model, attentional refreshing is the maintenance mechanism of an executive loop in charge of constructing, maintaining, and transforming mental representations, whatever the nature of these representations (visual, verbal, auditory, spatial, etc.). Some authors have also studied a more deliberate form of refreshing, by giving explicit instructions to participants, such as turning one's conscious attention to an item, thinking of it, or visualizing it (Johnson, 1992; Johnson & Johnson, 2009; Souza, Rerko, & Oberauer, 2015). Note that the way attentional refreshing proceeds remains unclear. It has recently been proposed that it could operate not in a cumulative fashion, as suggested by many models (including the modal model), but rather by refreshing in priority the item that is the most likely to be lost (Lemaire, Pageot, Plancher, & Portrat, 2018).

We explained earlier that the effectiveness of refreshing depends on temporal factors, but it also could result from developmental differences, as children under 7 years old (e.g., Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009) and healthy older adults seem less able to use this mechanism (Johnson, Mitchell, Raye, & Green, 2004; Fanuel, Plancher, Monsaingeon, Tillmann, & Portrat, 2018a; Plancher, Boyer, Lemaire, & Portrat, 2017). Consistent with the fact that refreshing relies on attention, recent studies have suggested that its efficiency could also be enhanced by providing an isochronous rhythm (known to guide attention over time) during the maintenance interval, something that increases memory performance (Fanuel, Portrat, Tillmann, & Plancher, 2018b; Plancher, Lévêque, Fanuel, Piquand, & Tillmann, 2018). It could be argued that theories of the existence of attentional refreshing rely mostly on indirect evidence such as the *CL* effect (see Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012), but Vergauwe and Cowan (2015) provided direct evidence that it consists in reactivating memory traces. They demonstrated that concurrent processing that decreases the proportion of time available for refreshing has no negative effect on recall when this process consists in retrieving the memory items themselves. Another study suggests that refreshing consists in a process of reactivation. Rey, Versace, and Plancher (2018) investigated how the

reactivation of an irrelevant trace (a visual mask) prevents attentional refreshing from taking place. In their study there were two stages. First, the participants performed an association phase in which a visual mask was presented simultaneously with a high-pitched tone, whereas a control stimulus (a gray square) was presented with a low-pitched tone (the reverse association was induced in half the participants). Importantly, the visual mask was created from mixture of the images the participants needed to remember in the second stage. The participants had to judge whether the tone was high-pitched or low-pitched. In the second stage, participants performed a complex span task in which they had to learn images while processing intertwined digits. In a first experiment, the tones previously associated with the mask or the control stimulus were presented during encoding of the images. In a second experiment, the tones were presented during the free time when attentional refreshing was supposed to take place—that is, after each processing episode. The results revealed that in both experiments, the trials in which the tone was associated with the visual mask led to a decrease in recall performance as compared to the trials in which the tone was associated with the control stimulus. The authors suggested, first, that the memory traces created during encoding are sensorial in nature, because they suffer from the reactivation of a visual mask, and second, that refreshing allows for the reactivation of sensorial traces created during encoding. Overall, these findings are consistent with the TBRS framework. When participants reactivated a concurrent trace (i.e., the mask), the attentional refreshing of memory traces was prevented, or at least its efficiency was reduced.

Apart from a process of attentional refreshing, the TBRS model assumes, following Atkinson and Shiffrin (1968), but also Baddeley (1986), the existence of a domain-specific mechanism devoted to the maintenance of verbal information through articulatory or subvocal rehearsal. It has been shown that the two processes have additive effects on WM performance, suggesting that they are independent (Camos, 2015, 2017; Camos, Lagner, & Barrouillet, 2009). Other evidence of their independence is that using verbal rehearsal favors the emergence of phonological effects (i.e., word length and phonological similarity), whereas these effects disappear under the use of refreshing (Camos, Mora, & Barrouillet, 2013; Mora & Camos, 2013), a finding also suggesting that the two maintenance processes might act on memory traces that differ in nature. Subvocal rehearsal would operate on phonological traces by recirculating phonological information into some phonological store, acting like a replay of a just-perceived auditory signal, whereas attentional refreshing would act on multimodal representations through their reconstruction, which involves not only re-creation of the percepts but also knowledge stored in long-term memory (Barrouillet & Camos, 2015). The hypothesis of independence between verbal rehearsal and attentional refreshing has been

corroborated by neurological investigations demonstrating that the two mechanisms involve different neural substrates (e.g., Raye et al., 2007).

Returning to the main point of the present section, another argument in favor of distinct systems operating on different representations is the fact that verbal rehearsal and attentional refreshing have different impacts on long-term storage. Several studies have observed that, in a complex span task, words are recalled better in a subsequent delayed-recall task when they were maintained through attentional refreshing rather than through verbal rehearsal (e.g., Loaiza & McCabe, 2012). Also, when the opportunities to attentionally refresh memory items are increased in a complex span task, either by decreasing the *CL* of the concurrent task or by giving participants more time to do the task, long-term retention improved (Camos & Portrat, 2015; Jarjat et al., 2018; Loaiza & McCabe, 2012; Souza & Oberauer, 2017).

As our quote of Atkinson and Shiffrin (1968) made clear, the existence of distinct mechanisms of maintenance is consistent with the principles of the modal model, which distinguished at least two control processes for keeping information in STS and transferring it to LTS: rehearsal and coding, the latter of which is more efficient than the former. Later, these processes were called *maintenance rehearsal* and *elaborative rehearsal* (Shiffrin, 1975). It is worth noting that the STS was described mainly as an a-v-l store—that is, a store akin to the phonological loop in Baddeley and Hitch's (1974) model and the TBRS model. Bringing together the modal model and the TBRS model, we may assume that the verbal rehearsal of phonological inputs in the TBRS model is akin to the rehearsal of information stored in a-v-l STS in the modal model, and that attentional refreshing in the TBRS model is akin to the more elaborative process of coding. Only the latter process is likely to create strong long-term memory traces, as Atkinson and Shiffrin (1968) surmised and as the studies by Camos and Portrat (2015) and Loaiza and McCabe (2012) demonstrated. In summary, the criticism against the modal model regarding rehearsal as the unique transfer mechanism to LTS (Craig & Lockhart, 1972) is not legitimate, because the theoretical framework proposed by Atkinson and Shiffrin can account for the transfer of information to LTS through other maintenance processes.

Let us now turn to the second point, the fact that, contrary to the conventional wisdom, maintenance rehearsal does create long-term memory traces, as several studies have demonstrated. First, Lehman and Malmberg (2013) pointed out that the results of Craig and Watkins (1973, Exp. 1) actually revealed an effect on delayed recall of the study time of the items—that is, the length of their stay in the STS. The same finding was reported by Darley and Glass (1975), who had participants search lists of 40 words for a target. By varying the location of the targets in the lists (at either their top or

bottom part), Darley and Glass manipulated the length of stay of these targets in STS through maintenance rehearsal. An unexpected recall task at the end of the experiment revealed that recall of targets varied systematically with their location in the lists, with targets that had been searched for a longer time, and that had consequently stayed longer in STS, being recalled better. It has also been shown that the number of repetitions of the items has an effect on long-term memory. Using the phonemic task introduced by Craig and Lockhart (1972; “does the word contain an *r* sound?”), Nelson (1977) varied the number of presentations of the words on which the *r* decision was made. In three successive experiments, he demonstrated that words for which the *r* decision was made twice instead of once were recalled better in an unexpected memory task presented at the end of the experiment after an arithmetic buffer task. By contrast, Glenberg, Smith, and Green (1977) replicated Craig and Watkins (1973, Exp. 3) by showing that the amount of rehearsal of a word has no impact on long-term memory when a minimal amount of capacity is invested in this rehearsal. They asked their participants to memorize four-digit numbers for further recall, while overtly repeating a word over a retention interval of 2, 6, or 18 s (with the word being said 27, 9, or 3 times, respectively). Remembering the numbers was the main task, whereas repeating the word was a mere distraction on which participants were expected to invest a minimal amount of capacity. After several trials and a few minutes of discussion, participants were unexpectedly asked to recall the words they had repeated. The amount of rehearsal had no effect on recall, but the effect did appear when memory for the words was tested through recognition instead of recall.

These findings are in line with the modal model, which predicted that when the subject is concentrating upon rehearsal, as in Glenberg et al. (1977), the information transferred would be in a relatively weak state, hence the absence of an effect in a recall task, but not when memory is tested through recognition. Darley and Glass (1975), who observed an effect of the length of stay of the items in the STS, suggested distinguishing between different types of maintenance rehearsal in order to account for the discrepancy in results between their study and Craig and Watkins's (1973). When maintenance rehearsal consists in what they called *echoing*, a mere repeated utterance, as in Glenberg et al.'s or Craig and Watkins's studies, memory traces are weak and revealed only through recognition, but not recall. When maintenance rehearsal, though remaining nonelaborative, consists in what they call *attending*, the retrievability of the transferred traces is increased and rehearsal affects recall, as in Darley and Glass's or Nelson's studies. This perfectly echoes what Atkinson and Shiffrin (1968) had assumed when suggesting that the important aspect of the transfer from STS to LTS is the wide variance induced by control processes in the amount and form of the transferred information. Overall, Atkinson and Shiffrin's (1968) assumptions about the transfer of

information from the STS to the LTS are not contradicted, and are even supported, by the facts.

Temporal decay as a source of forgetting in WM

The modal model assumes that information decays from the STS in the absence of rehearsal maintaining the memory traces. It is not clear what exactly Atkinson and Shiffrin meant by “decay” at this time. Did they mean “temporal decay” or simply “forgetting” from STS? In the latter case, it would remain unclear whether interference is viewed as a cause of forgetting in STS. However, in their model, although STS was seen as suffering from “decay,” LTS was assumed to suffer from both “decay” and “interference,” implicitly indicating that “decay” is a mechanism distinct from “interference” in the modal model. As we noted earlier, the modal model hypothesis assuming that forgetting in WM is due to decay has been the object of strong criticisms.

The causes of forgetting in WM have been, and remain, highly debated in the literature (see Oberauer et al., 2016, for an overview of the causes of WM forgetting). All theoretical models agree that WM is limited, but at least three different hypotheses have been proposed to account for this limit. The first account is that forgetting occurs because WM representations decay over time (Baddeley, 1986; Baddeley, Thomson, & Buchanan, 1975; Barrouillet et al., 2011; Cowan, 1999, 2005; Lovett, Reder, & Lebière, 1999; Page & Norris, 1998; Ricker & Cowan, 2010; Towse & Hitch, 1995). In these models, decay can be prevented by maintenance mechanisms. Already in 1958, Brown proposed a theory of forgetting based on memory traces that lose activation, or decay, with the passage of time (see Ricker, Vergauwe, & Cowan, 2014, for an historic of decay theories). The second hypothesis of forgetting assumes that our ability to hold several representations available at the same time is limited by mutual interference between these representations (Nairne, 1990; Oberauer & Kliegl, 2006; Saito & Miyake, 2004) or by interference produced by distractors (Oberauer et al., 2012). Forgetting in this case is due to compromised accessibility rather than to loss of memory traces. A third hypothesis explains forgetting through a limitation in cognitive resources (Case, Kurland, & Goldberg, 1982; Just & Carpenter, 1992; Ma, Husain, & Bays, 2014). This resource is viewed as either continuous or discrete. For example, the “slot model” includes discrete resources (Cowan, Rouder, Blume, & Saults, 2012). In this view, forgetting in WM is explained by the fact that resources are limited and must be shared between representations held simultaneously available with processes that need to be carried out. Note that these three accounts are not mutually exclusive. For example, the TBRS model assumes that WM traces suffer from temporal decay but also interfere with each

other and with distractors (Barrouillet, Plancher, Guida, & Camos, 2013). It is also possible that the interference created by distractors leads to forgetting that occurs over time, as in the perturbation model (Estes, 1972; Lee & Estes, 1977, 1981). Moreover, forgetting might also occur when memory items are intentionally dropped from WM, a process called *compartmentalization* by Lehman and Malmberg (2009, 2011, 2013). This might be the case in WM tasks when participants prioritize processing over storage and give up on maintaining a part of the memoranda (Doherty et al., 2019).

During the last decade, whether temporal decay or interference is the cause of forgetting has been a matter of intense debate. Two models of working memory, in particular, have been opposed: the TBRS model and the serial order in a box (SOB) model (Farrell & Lewandowsky, 2002), also called the SOB-CS model (Oberauer et al., 2012, with CS standing for *complex span*). As in the modal model, the main cause of forgetting postulated by the TBRS model is temporal decay. As we explained earlier, the TBRS model assumes that this decay occurs when attention is captured by concurrent processing that prevents attentional refreshing. As we have already noted, many studies have demonstrated that recall performance indeed depends on the *CL* of the processing task, with poorer performance being consistently observed at high as compared with low *CL* (Barrouillet et al., 2007; Portrat, Barrouillet, & Camos, 2008; Vergauwe et al., 2010). It is worth noting that although the TBRS model does not deny interference effects in WM, other models refuse to posit decay as a cause of forgetting and tend to explain forgetting through interference only (Lewandowsky, Oberauer, & Brown, 2009; Nairne, 1990; Oberauer & Kliegl, 2006). In this kind of model, there is no need for a maintenance mechanism, as memory traces do not decay. Consequently, the causal role of rehearsal is called into question by interference models (e.g., Lewandowsky, & Oberauer, 2015). In one of the most influential interference models, the SOB-CS model (Oberauer et al., 2012), the greater the number of features shared between memory items and processing items, the poorer the recall performance will be (Lewandowsky, Geiger, Morrell, & Oberauer, 2010). However, interference could also come from distractors that are processed in some intervening task, with the amount of interference being a function of the novelty of the distractors. This is referred to as *novelty-gated encoding* (Oberauer et al., 2012). Using a complex span task, Lewandowsky et al. (2010) observed lower recall performance when the number of distractors and their novelty were increased. These findings led them to conclude that forgetting does not result from temporal decay but from interference due to novelty encoding. However, the method used by Lewandowsky et al. (2010) confounded novelty and attentional demands. In the condition with a low level of novelty, participants were required to process (and then encode, according to the interference model) only one word, whereas

the condition with a high level of novelty involved three different distractor words to be processed after each memorandum. The latter condition might have involved greater interference, but processing three words probably also led to a greater attentional demand than processing a single word.

Controlling for attentional demands and temporal factors of the concurrent task, Plancher and Barrouillet (2013) tested the two main predictions of the SOB-CS model, namely that recall performance will be impeded by increasing the number of distractors to be processed as well as by decreasing the similarity between these distractors, thus increasing their novelty and the strength of their encoding. To disentangle novelty from attentional demands, Plancher and Barrouillet required participants to pay attention to every distractor, even when these distractors were repeated. This is possible if participants cannot anticipate the nature of the forthcoming distractor. In a series of experiments, participants performed a computer-paced complex span task in which the distractors were interspersed between the to-be-remembered items. *CL* was manipulated by varying the pace at which distractors were presented, either slow or fast. The level of interference was manipulated by varying the novelty of the distractor words, which were either repeated (low novelty level) or always differed from each other (high novelty level). The trials in which distractors repeated involved a maximum of two different words that were repeated in an unpredictable way by randomly varying the structure of the trial. In line with the TBRS model, we observed a strong effect of the pace at which distractors were presented. However, none of the predictions of the SOB-CS model were verified. At a constant pace, we observed no effect of the number of distractors and no effect of their level of novelty on recall performance. This suggests that temporal decay is a more likely source of forgetting than novelty-based interference.

More recently, Barrouillet, Uittenhove, Lucidi, and Langerock (2017) examined further whether forgetting from WM is due only to interference or is also caused by temporal decay. One issue for the interference models is to account for the robust *CL* effect. Indeed, for interference theories, it is not clear how low *CL*, resulting from more free time between distractors, would be beneficial for memory. Indeed, with the number and nature of distractors remaining the same, the amount of interference they create would likewise remain the same. One solution would be to view the free time available after processing each distractor as an opportunity to reduce the interference created by this distractor. In the SOB-CS model (Oberauer et al., 2012), this would be achieved by removing the distractors that have been encoded in WM and that interfere with memory traces (Oberauer & Lewandowsky, 2014). Because this removal process is assumed to occupy the attentional bottleneck, it can only take place during the free time following each distractor's processing. According to SOB-CS, longer free times have a beneficial effect on memory

because they allow for more complete distractor removal, thus reducing interference and resulting in better recall performance. In consequence, like the TBRS model, the SOB-CS model predicts a relationship between *CL* and WM span.

Barrouillet et al. (2017) tested the predictions issuing from the temporal decay hypothesis and from the interference-only hypothesis by focusing on two manipulations, the duration of each processing episode and the number of these episodes. The temporal-decay hypothesis predicts an effect of the duration of processing episodes, because longer processing episodes involve longer attentional capture during which memory traces decay, thus resulting in poorer recall. Barrouillet, De Paepe, and Langerock (2012) provided evidence for this phenomenon. The duration of an arithmetic task to be processed after each memorandum was varied by comparing operations written either in word format (three x five = fifteen) or in digit format ($3 \times 5 = 15$), with operations written in words being known to take longer to solve. The free time after each problem solving was kept constant. In line with the predictions of the temporal-decay hypothesis, Barrouillet et al. (2012) observed that longer solution times resulted in poorer memory performance. Concerning the second manipulation, the number of processing episodes, the temporal-decay hypothesis does not predict any effect of this number as long as the pace at which distractors are presented—that is, the *CL* they involve—is kept constant (e.g., Plancher & Barrouillet, 2013).

Interestingly, the interference-only hypothesis makes opposite predictions. Because variations in processing time do not generate additional interfering representations, processing time should have no effect on recall (Oberauer & Lewandowsky, 2013). However, contrary to the temporal-decay hypothesis, the interference-only hypothesis predicts an effect of the number of distractors, with more distractors resulting in a greater amount of interference and poorer recall (Lewandowsky et al., 2010; Lewandowsky, Geiger, & Oberauer, 2008). Across three experiments, Barrouillet et al. (2017) used complex span tasks in which the duration of the processing episodes and their number were orthogonally manipulated while participants maintained series of memory items (either verbal or visuospatial) for further serial recall. Each memory item was followed by either two or four operations, each of them followed by a constant free time. The duration of the processing episodes, short versus long, was manipulated by presenting either matrices of digits or matrices of words. For example, in one experiment, the matrices were composed of two numbers in red and two numbers in black, and participants had to judge whether the sum of the red numbers was the same as the sum of the black numbers. Across three experiments, and in line with the predictions of the TBRS model and its temporal-decay hypothesis, the authors observed that when participants were required to memorize letters, lower memory performance were measured for word than for digit matrices. By contrast, the number of processing

episodes did not significantly affect memory performance. When participants were required to memorize spatial locations, longer processing times also resulted in lower memory performance. However, the effect of the number of processing episodes just failed to reach significance (Exps. 1 and 3) or was significant (Exp. 2), with four processing episodes resulting in lower recall performance than two episodes. For verbal memoranda, the results clearly fit the decay hypothesis, but the effect of the number of distractors when participants had to memorize spatial locations was more in line with the predictions of the interference-only hypothesis. These results suggest that the efficiency of the restorative processes of memoranda described in the TBRS may depend on the nature of these memoranda. The negative effect of the number of distractors on visuospatial maintenance may be due to distracting tasks generating specific visuospatial interference (processing digits involving a mental spatial line; e.g., Dehaene, 1992). This deleterious effect could not be counteracted by a refreshing mechanism and would be added to the detrimental effect of temporal decay. Overall, it seems more reasonable to identify several sources for such a complex phenomenon as WM forgetting, including temporal decay and interference.

Another way to test the predictions of interference-only models is to focus on the fate of distractors in a complex span task. A main prediction of the SOB-CS model is that if free time is available after processing a distractor, participants will use it to remove distractors (Oberauer et al., 2012). As we mentioned earlier, that is how SOB-CS accounts for the robust *CL* effect. Dagry, Vergauwe, and Barrouillet (2017) were interested in the fate of distractors and provided evidence against the hypothesis that distractor removal might be more efficient with longer free time. In a complex span task, participants were required to memorize words and to process distractors that were also words after each memory item, with these distractor words being presented at either a slow or a fast pace. As usual in a complex span task, participants had to recall the memoranda at the end of each trial. The originality of this study was to test participants with delayed recall or recognition of the words previously seen, including the distractors. The reasoning was that if longer free time after each distractor in the slow-pace condition (low *CL*) enables better removal of the distractors, this would result in better immediate recall of the targets (reflecting the well-known *CL* effect), but also in poorer memory of the distractors, which presumably had been removed better. Contrary to this prediction, Dagry and colleagues observed that memory for distractors was not poorer but *better* when participants had longer free time after each processing episode. In that context, the *CL* effect observed in immediate recall of the targets seems difficult to interpret as more efficient use of removal with low *CL*.

In another study, the same authors tested memory for distractors at the end of every trial or during the trial (Dagry & Barrouillet, 2017). Because one may argue that removal is a process more related to short-term than to long-term memory, the removal effect might occur only at immediate recall. In line with their first study, Dagry and Barrouillet observed better memory performance for distractors in unexpected immediate recall when the pace of the concurrent task was slow as compared to fast. In a second experiment, Dagry and Barrouillet inserted a lexical decision task within a complex span task. They were interested in repetition priming, according to which the time to process an item would be reduced if this item had been processed just before. If participants were able to remove distractors at a slow pace, the priming effect should vanish or at least decrease in that condition. Indeed, removing distractors should make them novel again, thus reducing the priming effect. On the contrary, Dagry and Barrouillet observed a stronger repetition-priming effect in the slow-pace trials, testifying to better memory for the distractors. Overall, these results suggest that a mechanism such as removal of distractors for explaining the *CL* effect is far less plausible than the hypothesis that a refreshing mechanism counteracts the deleterious effect of temporal decay of memory traces.

Already in 1968, in line with the researches of Peterson and Peterson (1959) and Brown (1958), Atkinson and Shiffrin included in their model temporal decay as a central cause of forgetting in working memory. In the modal model, both STS and LTS are assumed to suffer from decay, while interference is reserved to LTS. The empirical evidence reported above suggests that the hypothesis of temporal decay of memory traces in short-term or working memory that was endorsed by the modal model cannot be easily dismissed.

Conclusion

Despite having been the object of strong criticisms, the main tenets of the model proposed by Atkinson and Shiffrin in 1968 might still be a reference in the field of memory. The STS can indeed be viewed as WM, because the hypothesis of a unique system in charge of maintaining memory items and processing other cognitive tasks is supported by several recent empirical findings, and consequently is assumed by several current models of WM. In addition, it is still pertinent to propose control processes that enable maintenance and the transfer of information from STS to LTS. Atkinson and Shiffrin (1968) put the emphasis on rehearsal in the first version of their model, but they explicitly said that any kind of operation on a memory trace in the STS can be viewed as a form of rehearsal, including coding, which relies on

strong associations previously stored in long-term memory. In consequence, they had already acknowledged several forms of maintenance of the information stored in the STS, with some forms being more likely than others to transfer information to LTS. However, they proposed that when coding and other strategies of maintenance are used, a trade-off would occur in which the buffer size of rehearsal would be reduced. Contrary to this proposal, we have presented some studies that support independence between verbal rehearsal and attentional refreshing. In the TBRS model, a trade-off between processing and storage or between the storage of two different memory sets occurs only when attention has to be shared. Because verbal articulatory rehearsal is viewed as a mechanism that does not depend on attention, at least after its initiation, its use should have little impact on this trade-off. In the modal model, the role of attention sometimes was unclear. For example, while describing a continuous paired-associate memory task, Atkinson and Shiffrin (1968) assumed that participants' attention was captured by searching memory, and consequently was not available for rehearsal, suggesting at least implicitly that rehearsal needs attention. In the same way, they assumed that a subject "allots to items in the buffer only enough attention to keep them 'alive'" (p. 180). But later they said that the transfer of information to LTS is "passive," the crucial factor being the total time that an item resides in the buffer. This suggests that direct attention to an item in STS might not be necessary for transfer to LTS. By contrast, coding was viewed as an active transfer strategy. We have seen that it seems that maintenance rehearsal has an impact on further recall only when this maintenance involves attending to the items. However, when tested through recognition instead of recall, long-term memory can result from mere articulatory rehearsal, contrary to the conventional wisdom. Finally, Atkinson and Shiffrin (1968) proposed that information in the STS decays completely and is lost when control processes are not available to maintain this information. This view fits with current theories of WM that defend decay as a cause of forgetting, and with empirical evidence.

In conclusion, in light of the empirical facts and recent theorizing we have reported, it is clear that the main tenets of the modal model are far from outdated. This model, and more specifically its conception of the entire memory system as a flow of information between systems, still offers to modern psychologists an inspiring framework. In the present review, we have also aimed at demonstrating that rebuttals of theories are based on empirical evidence that rarely is unequivocal and often is open to divergent interpretations. This seems to be the case of most of the criticisms that have been raised against the modal model. It is often claimed that good

ideas do not die easily. In this respect, Atkinson and Shiffrin's (1968) modal model has been, and is still, a mine of good ideas.

Acknowledgements This research was supported by LABEX grant ANR-11-LABX-0042 from the Université de Lyon, within the program "Investissements d'Avenir" (ANR-11-IDEX-0007) operated by the French National Research Agency (ANR).

References

- Anderson, J. R., Reder, L. M., & Lebière, C. (1996). Working memory: Activation limitations on retrieval. *Cognitive Psychology*, 30, 221–256.
- Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In K. W. Spence & J. T. Spence (Eds.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 2, pp. 89–195). New York, NY: Academic Press.
- Atkinson, R. C., & Shiffrin, R. M. (1971). The control of short-term memory. *Scientific American*, 225(2), 82–90. <https://doi.org/10.1038/scientificamerican0871-82>
- Baddeley, A. (1986). *Working memory*. Oxford, UK: Oxford University Press, Clarendon Press. [https://doi.org/10.1016/S0079-7421\(08\)60452-1](https://doi.org/10.1016/S0079-7421(08)60452-1)
- Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 8, pp. 47–89). New York, NY: Academic Press. [https://doi.org/10.1016/S0079-7421\(08\)60452-1](https://doi.org/10.1016/S0079-7421(08)60452-1)
- Baddeley, A. D., & Logie, R. H. (1999). Working memory: The multiple-component model. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 28–61). Cambridge, UK: Cambridge University Press.
- 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. [https://doi.org/10.1016/S0022-5371\(75\)80045-4](https://doi.org/10.1016/S0022-5371(75)80045-4)
- 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. <https://doi.org/10.1037/0096-3445.133.1.83>
- 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. <https://doi.org/10.1037/0278-7393.33.3.570>
- Barrouillet, P., & Camos, V. (2012). As time goes by: Temporal constraints in working memory. *Current Directions in Psychological Science*, 21, 413–419. <https://doi.org/10.1177/0963721412459513>
- Barrouillet, P., & Camos, V. (2014). On the proper reading of the TBRS model: Reply to Oberauer and Lewandowsky (2014). *Frontiers in Psychology*, 5, 1331. <https://doi.org/10.3389/fpsyg.2014.01331>
- Barrouillet, P., & Camos, V. (2015). *Working memory: Loss and reconstruction*. Hove, UK: Psychology Press.
- Barrouillet, P., De Paepe, A., & Langerock, N. (2012). Time causes forgetting from working memory. *Psychonomic Bulletin & Review*, 19, 87–92. <https://doi.org/10.3758/s13423-011-0192-8>
- 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, 477–490. <https://doi.org/10.1037/a0014615>
- Barrouillet, P., Plancher, G., Guida, A., & Camos, V. (2013). Forgetting at short term: When do event-based interference and temporal factors

- have an effect? *Acta Psychologica*, 142, 155–167. <https://doi.org/10.1016/j.actpsy.2012.12.003>
- Barrouillet, P., Portrat, S., & Camos, V. (2011). On the law relating processing to storage in working memory. *Psychological Review*, 118, 175–192. <https://doi.org/10.1037/a0022324>
- Barrouillet, P., Uittenhove, K., Lucidi, A., & Langerock, N. (2017). On the sources of forgetting in working memory: The test of competing hypotheses. *Quarterly Journal of Experimental Psychology*, 20, 1–46. <https://doi.org/10.1080/17470218.2017.1358293>
- Box, G. E. P., & Draper, N. R. (1987). Empirical model building and response surfaces. New York, NY: Wiley.
- Brown, J. (1958). Some tests of the decay theory of immediate memory. *Quarterly Journal of Experimental Psychology*, 10, 12–21. <https://doi.org/10.1080/17470215808416249>
- Camos, V. (2015). Storing verbal information in working memory. *Current Directions in Psychological Science*, 24, 440–445. <https://doi.org/10.1177/0963721415606630>
- Camos, V. (2017). Domain-specific versus domain-general maintenance in working memory: Reconciliation within the time-based resource sharing model. In B. H. Ross (Ed.), *The psychology of learning and motivation* (Vol. 67, pp. 135–171). San Diego, CA: Elsevier Academic Press. <https://doi.org/10.1016/bs.plm.2017.03.005>
- Camos, V., Johnson, M., Loaiza, V., Portrat, S., Souza, A., & Vergauwe, E. (2018). What is attentional refreshing in working memory? *Annals of the New York Academy of Sciences*, 1424, 19–32. <https://doi.org/10.1111/nyas.13616>
- Camos, V., Lagner, P., & Barrouillet, P. (2009). Two maintenance mechanisms of verbal information in working memory. *Journal of Memory and Language*, 61, 457–469. <https://doi.org/10.1016/j.jml.2009.06.002>
- Camos, V., Mora, G., & Barrouillet, P. (2013). Phonological similarity effect in complex span task. *Quarterly Journal of Experimental Psychology*, 66, 1927–1950. <https://doi.org/10.1080/17470218.2013.768275>
- Camos, V., & Portrat, S. (2015). The impact of cognitive load on delayed recall. *Psychonomic Bulletin & Review*, 22, 1029–1034. <https://doi.org/10.3758/s13423-014-0772-5>
- Case, R., Kurland, M., & Goldberg, J. (1982). Operational efficiency and the growth of short-term memory span. *Journal of Experimental Child Psychology*, 33, 386–404.
- Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information processing system. *Psychological Bulletin*, 104, 163–191. <https://doi.org/10.1037/0033-2909.104.2.163>
- Cowan, N. (1992). Verbal memory span and the timing of spoken recall. *Journal of Memory and Language*, 31, 668–684.
- Cowan, N. (1995). Attention and memory: An integrated framework. New York, NY: Oxford University Press.
- Cowan, N. (1999). An embedded-processes model of working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 62–101). Cambridge, UK: Cambridge University Press.
- Cowan, N. (2005). Working memory capacity. Hove, UK: Psychology Press. <https://doi.org/10.4324/9780203342398>
- Cowan, N., Rouders, J. N., Blume, C. L., & Saults, J. S. (2012). Models of verbal working memory capacity: What does it take to make them work? *Psychological Review*, 119, 480–499. <https://doi.org/10.1037/a0027791>
- Cowan, N., Saults, J. S., & Elliott, E. M. (2002). The search for what is fundamental in the development of working memory. *Advances in Child Development and Behavior*, 29, 1–49. [https://doi.org/10.1016/S0065-2407\(02\)80050-7](https://doi.org/10.1016/S0065-2407(02)80050-7)
- Craik, F. I. M., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, 11, 671–684. [https://doi.org/10.1016/S0022-5371\(72\)80001-X](https://doi.org/10.1016/S0022-5371(72)80001-X)
- Craik, F. I. M., & Watkins, M. J. (1973). The role of rehearsal in short-term memory. *Journal of Verbal Learning and Verbal Behavior*, 12, 599–607. [https://doi.org/10.1016/S0022-5371\(73\)80039-8](https://doi.org/10.1016/S0022-5371(73)80039-8)
- Dagry, I., & Barrouillet, P. (2017). The fate of distractors in working memory: No evidence for their active removal. *Cognition*, 169, 129–138. <https://doi.org/10.1016/j.cognition.2017.08.011>
- Dagry, I., Vergauwe, E., & Barrouillet, P. (2017). Cleaning working memory: The fate of distractors. *Journal of Memory and Language*, 92, 327–342. <https://doi.org/10.1016/j.jml.2016.08.002>
- Darley, C. F., & Glass, A. L. (1975). Effects of rehearsal and serial list position on recall. *Journal of Experimental Psychology: Human Learning and Memory*, 1, 453–458. <https://doi.org/10.1037/0278-7393.1.4.453>
- Dehaene, S. (1992). Varieties of numerical abilities. *Cognition*, 44, 1–42. [https://doi.org/10.1016/0010-0277\(92\)90049-N](https://doi.org/10.1016/0010-0277(92)90049-N)
- Doherty, J. M., Belletier, C., Rhodes, S., Jaroslawska, A., Barrouillet, P., Camos, V., ... Logie, R. H. (2019). Dual-task costs in working memory: An adversarial collaboration. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 45, 1529–1551. <https://doi.org/10.1037/xlm0000668>
- Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General*, 128, 309–331. <https://doi.org/10.1037/0096-3445.128.3.309>
- Estes, W. K. (1972). An associative basis for coding and organization in memory. In A. W. Melton & E. Martin (Eds.), *Coding processes in human memory* (pp. 161–190). Washington, DC: Winston.
- Fanuel, L., Plancher, G., Monsaingeon, N., Tillmann, B., & Portrat, S. (2018a). Temporal dynamics of maintenance in young and old adults. *Annals of the New York Academy of Sciences*, 1424, 137–148. <https://doi.org/10.1111/nyas.13640>
- Fanuel, L., Portrat, S., Tillmann, B., & Plancher, G. (2018b). Temporal regularities allow saving time for maintenance in working memory. *Annals of the New York Academy of Sciences*, 1424, 202–211. <https://doi.org/10.1111/nyas.13611>
- Farrell, S., & Lewandowsky, S. (2002). An endogenous distributed model of ordering in serial recall. *Psychonomic Bulletin & Review*, 9, 59–79. <https://doi.org/10.3758/BF03196257>
- Glenberg, A., Smith, S. M., & Green, C. (1977). Type I rehearsal: Maintenance and more. *Journal of Verbal Learning and Verbal Behavior*, 16, 339–352. [https://doi.org/10.1016/S0022-5371\(77\)80055-8](https://doi.org/10.1016/S0022-5371(77)80055-8)
- Jarjat, G., Hoareau, V., Plancher, G., Hot, P., Lemaire, B., & Portrat, S. (2018). What makes working memory traces stable over time? *Annals of the New York Academy of Sciences*, 1424, 149–160. <https://doi.org/10.1111/nyas.13668>
- Johnson, M. K. (1992). MEM: Mechanisms of recollection. *Journal of Cognitive Neuroscience*, 4, 268–280. <https://doi.org/10.1162/jocn.1992.4.3.268>
- Johnson, M. K., Mitchell, K. J., Raye, C. L., & Greene, E. J. (2004). An age-related deficit in prefrontal cortical function associated with refreshing information. *Psychological Science*, 15, 127–132.
- Johnson, M. R., & Johnson, M. K. (2009). Top-down enhancement and suppression of activity in category-selective extrastriate cortex from an act of reflective attention. *Journal of Cognitive Neuroscience*, 21, 2320–2327.
- Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review*, 99, 122–149. <https://doi.org/10.1037/0033-295X.99.1.122>
- Lee, C. L., & Estes, W. K. (1977). Order and position in primary memory for letter strings. *Journal of Verbal Learning and Verbal Behavior*, 16, 395–418.
- Lee, C. L., & Estes, W. K. (1981). Item and order information in short-term memory: Evidence for multilevel perturbation processes.

- Journal of Experimental Psychology: Human Learning and Memory*, 7, 149–169. <https://doi.org/10.1037/0278-7393.7.3.149>
- Lehman, M., & Malmberg, K. J. (2009). A global theory of remembering and forgetting from multiple lists. *Journal of Experimental Psychology: Learning Memory and Cognition*, 35, 970–988. <https://doi.org/10.1037/a0015728>
- Lehman, M., & Malmberg, K. J. (2011). Overcoming the effects of intentional forgetting. *Memory and Cognition*, 39, 335–347. <https://doi.org/10.3758/s13421-010-0025-4>
- Lehman, M., & Malmberg, K. J. (2013). A buffer model of memory encoding and temporal correlations in retrieval. *Psychological Review*, 120, 155–189. <https://doi.org/10.1037/a0030851>
- 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. <https://doi.org/10.3758/s13423-017-1282-z>
- 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. <https://doi.org/10.1037/a0019764>
- Lewandowsky, S., Geiger, S. M., & Oberauer, K. (2008). Interference-based forgetting in verbal short-term memory. *Journal of Memory and Language*, 59, 200–222. <https://doi.org/10.1016/j.jml.2008.04.004>
- Lewandowsky, S., & Oberauer, K. (2015). Rehearsal in serial recall: An unworkable solution to the nonexistent problem of decay. *Psychological Review*, 122, 674–699. <https://doi.org/10.1037/a0039684>
- Lewandowsky, S., Oberauer, K., & Brown, G. D. A. (2009). No temporal decay in verbal short-term memory. *Trends in Cognitive Sciences*, 13, 120–126. <https://doi.org/10.1016/j.tics.2008.12.003>
- Loaiza, V. M., & McCabe, D. P. (2012). Temporal-contextual processing in working memory: Evidence from delayed cued recall and delayed free recall tests. *Memory & Cognition*, 40, 191–203. <https://doi.org/10.3758/s13421-011-0148-2>
- Lovett, M. C., Reder, L. M., & Lebière, C. (1999). Modeling working memory in a unified architecture: An ACT-R perspective. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 135–182). Cambridge, UK: Cambridge University Press.
- Ma, W. J., Husain, M., & Bays, P. M. (2014). Changing concepts of working memory. *Nature Neuroscience*, 17, 347–356. <https://doi.org/10.1038/nn.3655>
- 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. <https://doi.org/10.1016/j.jml.2007.04.004>
- Mora, G., & Camos, V. (2013). Two systems of maintenance in verbal working memory: Evidence from the word length effect. *PLoS ONE*, 8, e70026. <https://doi.org/10.1371/journal.pone.0070026>
- Nairne, J. S. (1990). A feature model of immediate memory. *Memory & Cognition*, 18, 251–269. <https://doi.org/10.3758/BF03213879>
- Nelson, T. O. (1977). Repetition and depth of processing. *Journal of Verbal Learning and Verbal Behavior*, 16, 151–171. [https://doi.org/10.1016/S0022-5371\(77\)80044-3](https://doi.org/10.1016/S0022-5371(77)80044-3)
- Norris, D. (2017). Short-term memory and long-term memory are still different. *Psychological Bulletin*, 143, 992–1009. <https://doi.org/10.1037/bul0000108>
- Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 28, 411–421. <https://doi.org/10.1037/0278-7393.28.3.411>
- Oberauer, K., Farrell, S., Jarrold, C., & Lewandowsky, S. (2016). What limits working memory capacity? *Psychological Bulletin*, 142, 758–799. <https://doi.org/10.1037/bul0000046>
- Oberauer, K., & Kliegl, R. (2006). A formal model of capacity limits in working memory. *Journal of Memory and Language*, 55, 601–626. <https://doi.org/10.1016/j.jml.2006.08.009>
- Oberauer, K., & Lewandowsky, S. (2013). Evidence against decay in verbal working memory. *Journal of Experimental Psychology: General*, 142, 380–411. <https://doi.org/10.1037/a0029588>
- Oberauer, K., & Lewandowsky, S. (2014). Further evidence against decay in working memory. *Journal of Memory and Language*, 73, 15–30.
- 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. <https://doi.org/10.3758/s13423-012-0272-4>
- Page, M. P. A., & Norris, D. (1998). The primacy model: A new model of immediate serial recall. *Psychological Review*, 105, 761–781. <https://doi.org/10.1037/0033-295X.105.4.761-781>
- Pashler, H. (1998). *The psychology of attention*. Cambridge, MA: MIT Press.
- Peterson, L., & Peterson, M. J. (1959). Short-term retention of individual verbal items. *Journal of Experimental Psychology*, 58, 193–198. <https://doi.org/10.1037/h0049234>
- Plancher, G., & Barrouillet, P. (2013). Forgetting from working memory: Does novelty encoding matter? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 39, 110–125. <https://doi.org/10.1037/a0028475>
- Plancher, G., Boyer, H., Lemaire, B., & Portrat, S. (2017). Under which conditions can older participants maintain information in working memory? *Experimental Aging Research*, 43, 409–429. <https://doi.org/10.1080/0361073X.2017.1369730>
- Plancher, G., Lévêque, Y., Fanuel, L., Piquandet, G., & Tillmann, B. (2018). Boosting maintenance in working memory with temporal regularities. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 44, 812–818. <https://doi.org/10.1037/xlm0000481>
- Portrat, S., Barrouillet, P., & Camos, V. (2008). Time-related decay or interference-based forgetting in working memory? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 34, 1561–1564. <https://doi.org/10.1037/a0013356>
- 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. [https://doi.org/10.1016/S0010-9452\(08\)70451-9](https://doi.org/10.1016/S0010-9452(08)70451-9)
- Rey, A., Versace, R., & Plancher, G. (2018). When a reactivated visual mask disrupts serial recall: Evidence that refreshing relies on memory traces reactivation in working memory. *Experimental Psychology*, 65, 263–271. <https://doi.org/10.1027/1618-3169/a000414>
- Ricker, T. J., & Cowan, N. (2010). Loss of visual working memory within s: The combined use of refreshable and non-refreshable features. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 36, 1355–1368. <https://doi.org/10.1037/a0020356>
- Ricker, T. J., Vergauwe, E., & Cowan, N. (2014). Decay theory of immediate memory: From Brown (1958) to today (2014). *Quarterly Journal of Experimental Psychology*, 69, 1969–1995. <https://doi.org/10.1080/17470218.2014.914546>
- Saito, S., & Miyake, A. (2004). On the nature of forgetting and the processing-storage relationship in reading span performance. *Journal of Memory and Language*, 50, 425–443.
- Shallice, T., & Warrington, E. K. (1970). Independent functioning of verbal memory stores: A neuropsychological study. *Quarterly Journal of Experimental Psychology*, 22, 261–273.
- Shiffrin, R. M. (1975). Short-term store: The basis for a memory system. In F. Restle, R. M. Shiffrin, N. J. Castellan, H. Lindman, & D. B. Pisoni (Eds.), *Cognitive theory* (Vol. 1, pp. 193–218). Hillsdale, NJ: Erlbaum.
- Souza, A. S., & Oberauer, K. (2017). Time to process information in working memory improves episodic memory. *Journal of Memory*

- and Language, 96, 155–167. <https://doi.org/10.1016/j.jml.2017.07.002>
- 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. <https://doi.org/10.1111/nyas.12603>
- Sternberg, S. (1966). High-speed scanning in human memory. *Science*, 153, 652–654.
- Sternberg, S. (2016). In defence of high-speed memory scanning. *Quarterly Journal of Experimental Psychology*, 69, 2020–2075. <https://doi.org/10.1080/17470218.2016.1198820>
- Towse, J. N., & Hitch, G. J. (1995). Is there a relationship between task demand and storage space in tests of working memory capacity? *Quarterly Journal of Experimental Psychology*, 48A, 108–124. <https://doi.org/10.1080/14640749508401379>
- Unsworth, N., & Engle, R. W. (2007). The nature of individual differences in working memory capacity: Active maintenance in primary memory and controlled search from secondary memory. *Psychological Review*, 114, 104–132. <https://doi.org/10.1037/0033-295X.114.1.104>
- 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. <https://doi.org/10.1037/a0015859>
- Vergauwe, E., Barrouillet, P., & Camos, V. (2010). Do mental processes share a domain-general resource? *Psychological Science*, 21, 384–390. <https://doi.org/10.1177/0956797610361340>
- 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. <https://doi.org/10.1037/a0035779>
- Vergauwe, E., & Cowan, N. (2014). A common short-term memory retrieval rate may describe many cognitive procedures. *Frontiers in Human Neuroscience*, 8, 126. <https://doi.org/10.3389/fnhum.2014.00126>
- Vergauwe, E., & Cowan, N. (2015). Attending to items in working memory: Evidence that refreshing and memory search are closely related. *Psychonomic Bulletin & Review*, 22, 1001–1006. <https://doi.org/10.3758/s13423-014-0755-6>
- Warrington, E. K., & Shallice, T. (1969). The selective impairment of auditory verbal short-term memory. *Brain*, 92, 885–896.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.