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As Time Goes By: Temporal Constraints in Working Memory

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Abstract

Working memory is the system devoted to the simultaneous processing and storage of information needed to perform many cognitive tasks. We present a theory that assumes that time constraints constitute the main limitation of working memory. According to our theory, processing and storage compete for attention, which constitutes a limited resource. As soon as attention is switched away, memory traces suffer from temporal decay, but they can be refreshed by bringing them back into the focus of attention. Because a central bottleneck constrains controlled cognitive activities that require attention so that they must take place one at a time, memory traces decline when the central bottleneck is occupied by processing activities. This results in a sequential functioning of working memory that alternates between processing and maintenance, leading to a trade-off between these two activities. We review empirical evidence of this trade-off and discuss its implications for the increase in working memory capacity over the course of development.

Keywords

working memory, cognitive load, time-based resource sharing, cognitive development

Suppose you are asked to solve 8,867 minus 8,866. Though large numbers are involved, this problem is not so difficult. Because you know the number line, you are immediately aware that the two numbers are successive, with a difference of 1. Now suppose the problem is 8,867 plus 8,866. This is more difficult, but not intractable. Even if no calculator is available, you probably remember the algorithm for solving additions with carries—provided that you have got a pen! But if you were asked to work the problem out in your head, it would be far more difficult. Why is this so, given that the calculation remains basically unchanged? The answer is straightforward: the lack of a pen, which will oblige you to keep intermediary results in mind while performing successive computations.

In other words, what makes the problem tough is that it requires the temporary maintenance of information while performing some computation. Such dual functions of storage and processing characterize working memory functioning. Note that this would not be a problem for you if you could make these computations instantly, or if intermediary results could remain indefinitely in your head. Unfortunately, calculations take time, and as time goes by, you may lose track of intermediary results because they fade away. This phenomenon of forgetting is the main constraint of human cognition and has been characterized by a variety of explanations (e.g., Della Sala, 2010; Lewandowsky, Oberauer, & Brown, 2009). In the past 10 years, we have developed a model of working memory we call the Time-Based Resource-Sharing (TBRS) model to capture and formalize these ideas. In the following sections, we present its main predictions and relevant empirical evidence.

The Time-Based Resource-Sharing Model

To account for the interplay of the two main functions of working memory—the temporary storage and the processing of information—the TBRS model relies on three main assumptions. First, contrary to other theories, such as Baddeley's multicomponent model of working memory (Baddeley, 1986), the TBRS model assumes that both functions are fueled by the same limited resource: attention. The kind of attention we refer to is akin to the executive attention proposed by Engle and Kane (2004)—that is, the controlled, sustained attention needed for maintaining or recovering access to stimulus and goal representations and resolving conflict among activated thoughts or action plans. Indeed, processing requires the elaboration and active maintenance of a goal and associated subgoals, the encoding of relevant incoming information, planning

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strategies and the selection of appropriate procedures, the retrieval of knowledge from long-term memory, the selection of a response, and often some monitoring of the obtained results.

Whereas the idea that these processes require attention is not controversial in cognitive psychology, the involvement of attention in storage and maintenance activities is less commonly endorsed. For example, Baddeley (1986) assumed that maintenance activities rely on specialized mechanisms distinct from the central executive that controls attention-demanding activities, and are fueled by domain-specific resources. Following Cowan's (1999) and Adaptive Character of Thought–Rational (Anderson & Lebière, 1998) models, the TBRS model supposes that the maintenance of memory traces depends on their activation through attentional focusing. The second assumption of the TBRS model is that activation of working memory traces suffers from a temporal decay as soon as the focus of attention is switched away. Third, the TBRS model assumes that a central bottleneck constrains controlled cognitive activities that require attention so that they must take place one at a time, leading to a serial functioning of working memory and the necessary alternation between processing and maintenance activities. As a consequence, working memory traces decline when concurrent processing activities occupy the central bottleneck, but they can be refreshed before being completely lost if they are brought back into the focus of attention. Thus, the dual function of working memory can be achieved through the incessant and rapid switching of attention between processing and maintenance.

These proposals constitute a renewed conception of working memory in which temporal factors are preponderant. Traditional views considered working memory as mainly being required by complex and difficult mental activities, such as reasoning, problem solving, and comprehension. This conception of working memory is reflected in the construction of the complex span tasks used to measure its capacity, such as the reading span and operation span tasks, in which participants maintain words or letters for later recall while reading sentences for comprehension or solving complex arithmetic equations (Daneman & Carpenter, 1980; Turner & Engle, 1989). The rationale underpinning the format of these tasks is that a proper measure of working memory capacity, as opposed to short-term memory, requires the concurrent performance of a secondary task that is sufficiently complex and demanding to hamper the maintenance of memory items.

The TBRS conception departs from this view by assuming that complexity is not needed to tap working memory. Whatever its complexity, any activity that occupies attention for protracted and frequent periods of time should prevent the refreshing of decaying memory traces and have a highly detrimental effect on their concurrent maintenance. By contrast, those activities that frequently leave attention free for maintenance activities should have little impact. Thus, recall performance on complex working memory span tasks that require both storage and processing should depend on a balance between periods during which memory traces decay because attention is occupied by processing, and periods during which attention is available for the refreshing of memory traces. Accordingly, within the TBRS framework, the cognitive load of a given activity—that is, its effect on the performance of concurrent activities—corresponds to the proportion of time during which this activity occupies attention (Fig. 1). In complex span tasks, recall performance should be a function of the cognitive load of the processing component of the task, with higher cognitive load resulting in lower levels of performance.

The Processing/Storage Function

We tested this hypothesis in several studies. In our first inquiry, we explored the effect of various levels of cognitive load on concurrent maintenance by having participants maintain series of letters of increasing length for later recall while reading digits that were presented successively after each letter (Barrouillet, Bernardin, & Camos, 2004). We manipulated the cognitive load of this intervening activity by varying the number of digits to be read (4, 8, or 12 digits) and the duration of the interletter intervals (i.e., the total time participants had to read them; 6, 8, or 10 seconds); this design resulted in nine different *number of digits:time* ratios, with higher values of this ratio corresponding to higher cognitive load (see Fig. 1). The results revealed that working memory spans (as indexed by the maximum number of letters participants were able to recall in correct order) linearly decreased as cognitive load increased (Fig. 2a).

It is worth noting that the TBRS model assumes that cognitive load depends on the duration of attentional capture, independently of the nature of the distracting activity. We recently verified this point by comparing the effect 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 of prepotent responses), and we used the ratio of processing times to the total time allowed to perform these tasks as a proxy of cognitive load (Barrouillet, Portrat, & Camos, 2011). Whatever the nature of the intervening task, mean spans still proved to be a linear function of cognitive load (Fig. 2b).

This perfect trade-off between processing and storage is what the hypothesis of time-based resource sharing between the two functions predicts. Increasing the rate of the concurrent task progressively decreases the time during which attention is available for restoring decayed memory traces after each processing episode, resulting in memory loss.

Indeed, the TBRS model assumes that working memory functioning is serial in nature, such that memory traces are refreshed in a cumulative fashion, starting from the first list item and proceeding successively to the last (McCabe, 2008). Thus, the level of cognitive load (i.e., the balance between the duration of attentional capture caused by the processing of each memory item and the consecutive free time during which memory traces can be refreshed before the next processing

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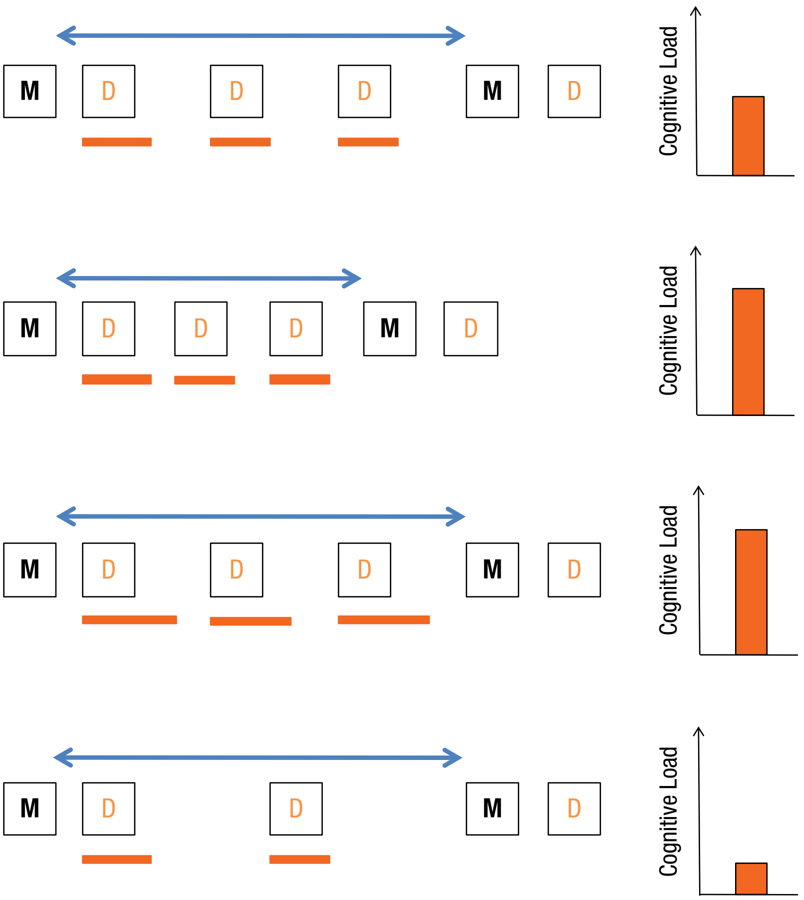

In the interval between the presentation of 2 memory items, 3 distractors have to be processed. Let us assume this corresponds to a medium cognitive load.

Reducing the time to process the same number of distractors increases cognitive load.

Increasing the duration of attentional capture with a more difficult task also increases cognitive load.

On the contrary, reducing the number of distractors to be processed in the same interval leads to a reduced cognitive load.

Fig. 1. Schematic illustration of different ways to vary the cognitive load of the processing component of a complex span task in which to-be-processed distractors (boxes marked "D") are interleaved between memory items (boxes marked "M"). The horizontal orange bars represent hypothetical durations of attentional capture caused by the processing of each distractor, and the blue arrows represent the duration of the intervals between memory items. The bar graphs represent resulting variations in cognitive load.

episode) determines the number of items in memory that can be sufficiently reactivated during free time and thereby survive temporal decay and be retrieved after the next processing episode.

This means that increased processing time and increased free time have opposite effects on maintenance. Increasing the duration of attentional capture caused by processing results in greater decay. More time is needed to restore these degraded memory traces and, consequently, fewer memory items can be reactivated within a given period of free time at the level needed to make them retrievable in the future. Conversely, increasing free time allows more memory items to be refreshed. Note that this model leads to the counterintuitive prediction that, as long as cognitive load remains constant (i.e., the pace at which intervening distractors are processed remains unchanged), increasing the number of distractors should not affect recall performance. Once the equilibrium between decay and refreshing has been reached (i.e., once working memory holds the maximum number of items that can be refreshed during free time to survive processing episodes), this equilibrium is not modified by the repetition of periods of decay and refreshing of unchanged duration.

These predictions received ample empirical support. When the time available for maintenance activities was increased—for example, when the pace of the intervening activities was relaxed—recall performance increased (e.g., Barrouillet et al., 2004). Conversely, when processing time was increased but the duration of free time remained unchanged, recall performance decreased. This was recently shown by Barrouillet, De Paepe, and Langerock (2012), who compared the effect of the verification of multiplications on the concurrent maintenance of series of five letters, the presentation of each letter being followed by three successive multiplications. Processing time was varied by presenting these multiplication problems either with digits (4 × 3 = 15?) or with words (four × three = fifteen?); processing time in the latter condition was about 400 ms longer, whereas free time was kept constant across conditions. After solving each arithmetic problem, participants gave their response ("correct" or "false") by pressing one of two keys, with each key press triggering a constant 800 ms delay before the presentation of the next operation or letter. As the TBRS model predicts, the longer processing times elicited by multiplication problems expressed with words resulted in poorer recall performance. Interestingly, this effect could

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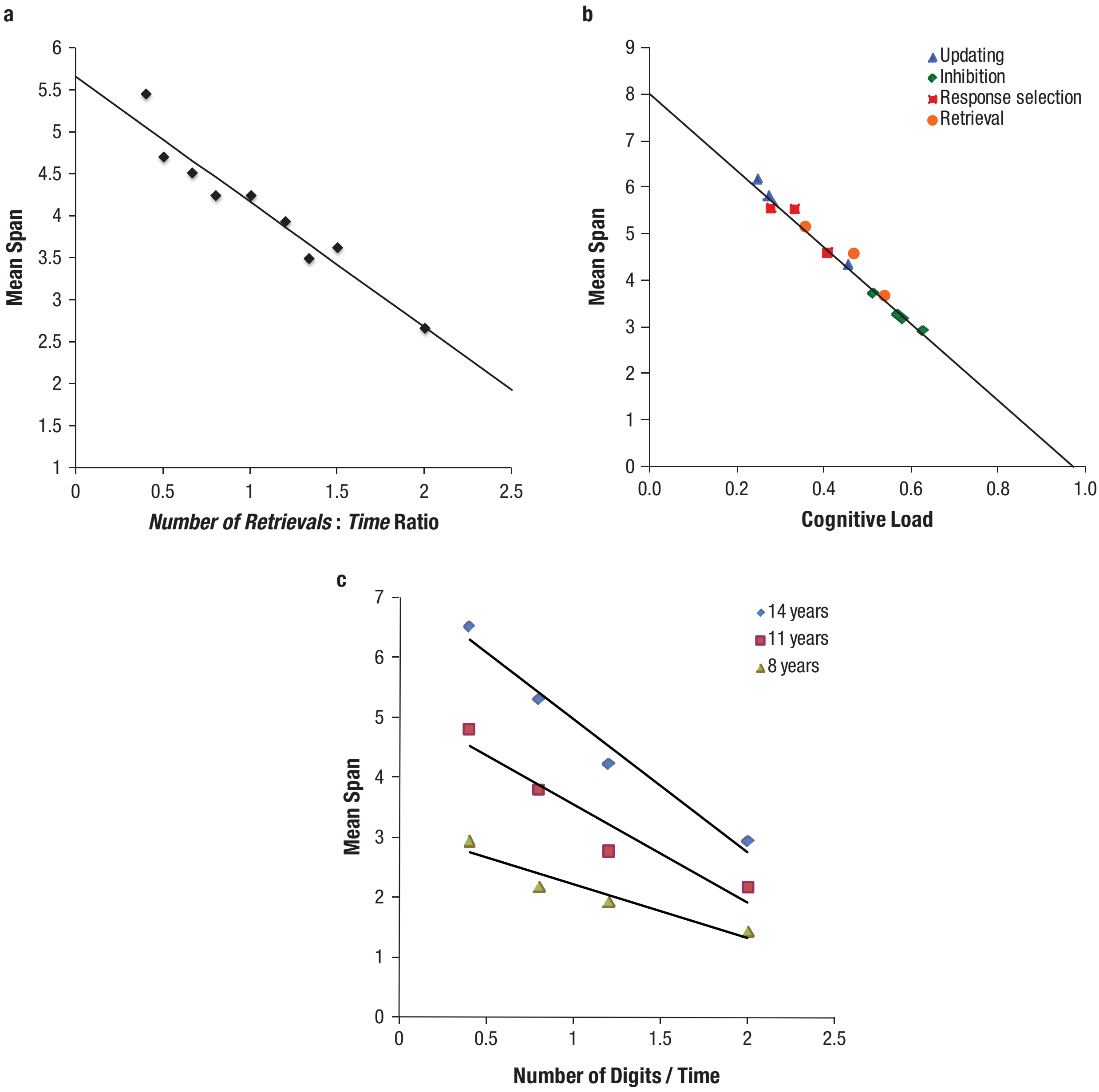

Fig. 2. Illustrations of the relation between processing and storage in working memory. Panel (a) shows mean span as a function of the number of digits to be read per second between memory items. Panel (b) shows mean span as a function of the cognitive load induced by different tasks involving executive functions. Panel (c) shows mean span as a function of the number of digits to be read per second between memory items in different age groups.

Panel (a) is adapted from "Time Constraints and Resource Sharing in Adults' Working Memory Spans," by P. Barrouillet, S. Bernardin, and V. Camos, 2004, *Journal of Experimental Psychology: General, 133*, p. 94. Copyright 2004 by the American Psychological Association. Adapted with permission. Panel (b) is adapted from "On the Law Relating Processing to Storage in Working Memory," by P. Barrouillet, S. Portrat, and V. Camos, 2011, *Psychological Review, 118*, p. 182. Copyright 2011 by the American Psychological Association. Adapted with permission. Panel (c) is adapted from "Working Memory Span Development: A Time-Based Resource-Sharing Model Account," by P. Barrouillet, N. Gavens, E. Vergauwe, V. Gaillard, and V. Camos, 2009, *Developmental Psychology, 45*, p. 481. Copyright 2009 by the American Psychological Association. Adapted with permission.

not be attributed to representation-based interference because it was replicated when the memoranda were not verbal but visuospatial, in a task in which participants were asked to maintain series of three spatial locations. Finally, the counter-intuitive prediction that increasing the number of distractors should have no effect on recall performance as long as the

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pace of their presentation and cognitive load remain constant was verified in several experiments (Barrouillet et al., 2004; Barrouillet, Portrat, Vergauwe, Diependaele, & Camos, 2011; Plancher & Barrouillet, in press).

Developmental Differences

One of the strengths of the TBRS model is that it accounts for working memory functioning not only in adulthood but also over the course of development. Interestingly, we and our colleagues (Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009) observed that the linear relationship between cognitive load and working memory spans generalized to children and adolescents, with steeper slopes among older participants (Fig. 2c). According to the TBRS model, three factors account for these developmental changes: processing speed, rate of temporal decay, and efficiency of refreshing processes. Developmental psychologists conceive of processing speed as one of the main bases of individual and developmental differences in higher-order cognition, including memory (Kail & Salthouse, 1994). Because of their slower processing speed, younger children take longer to perform the same tasks as older children, which indicates that they face higher cognitive loads. Moreover, an equivalent cognitive load could have a more detrimental effect on performance for young children than older children, because young children's memories could suffer from faster temporal decay during processing episodes and be refreshed less efficiently during free time. Developmental changes in rate of temporal decay have already been documented by Cowan (Cowan, Nugent, Elliott, & Saults, 2000; Saults & Cowan, 1996), who demonstrated that the persistence of memory increases with age.

In a recent study, we explored the roles of processing speed and efficiency of refreshing in working memory development in a sample of 8- and 11-year-old children (Gaillard, Barrouillet, Jarrold, & Camos, 2011). We used for this purpose a working memory span task in which the children were presented with series of letters of increasing length for later recall. The presentation of each letter was followed by the successive presentation of three digits at a fixed and constant pace. In an initial baseline condition, children in both age groups had to complete the same task of adding 1 to each digit. Unsurprisingly, older children largely outperformed younger children in recall performance. However, this difference may have been due in part to the fact that older children were faster at performing additions. We controlled for this source of difference by asking the older children to add 2 to each digit instead of 1 (we had previously established that 11-year-old children take approximately as long to add 2 to numbers as younger children take to add 1). When processing times were equated across age in this way, the difference between the two groups in working memory spans was reduced, but still significant. This result, which corroborated previous observations (Gavens & Barrouillet, 2004), contradicted the findings of Case, Kurland, and Goldberg (1982), who reported that developmental differences in working memory span were eliminated when processing efficiency was equated across age.

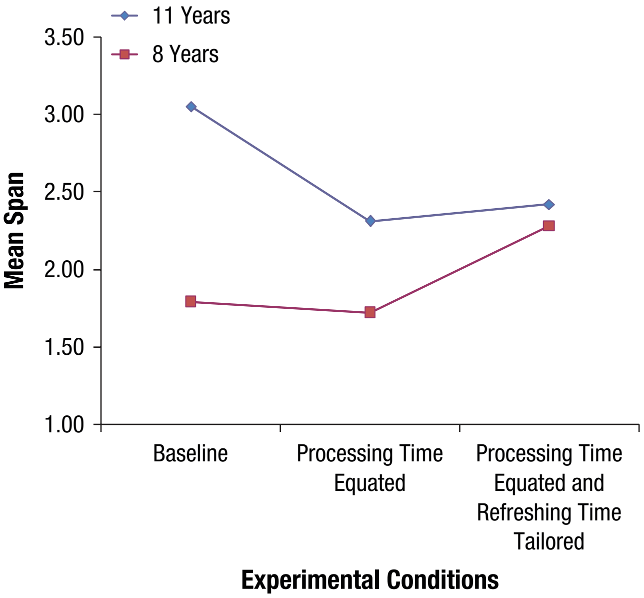

Fig. 3. Developmental differences in mean span as a function of the manipulations of processing time and refreshing time introduced by Gaillard, Barrouillet, Jarrold, and Camos (2011). In the baseline condition, both groups performed the same working memory span task. In the second experiment, processing time was equated across age, and in the third, processing time was equated and refreshing time was tailored to children's capacities to allow younger children to benefit from longer refreshing times.

However, where did the residual developmental difference come from? One possibility is that older children were better able to refresh decayed memory traces during the free time available after each addition, thus achieving better recall performance. Such a developmental increase in the rate of reactivation of memory traces has been documented by Cowan et al. (1998). We verified this hypothesis by tailoring the duration of free time given to each age group. We reasoned that the advantage of better refreshing in older children could be abolished if the younger children were given the time they needed to achieve the same amount of refreshing work as their older peers. Accordingly, in our final experiment, we still equated processing time between the two age groups by having older children add 2 to digits instead of 1, but younger children were given longer free times after each addition (the amount of extra time was extrapolated from a comparison of the two age groups in a series of speeded tasks). In these conditions, age no longer influenced performance (Fig. 3). In line with the TBRS model, these findings suggest that temporal factors play a major role in developmental changes in working memory.

Conclusions

Our first aim in proposing the TBRS model was to shed light on the relationship between the two functions of working

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memory—processing and storage—but the model went further by providing us with a metric for this relationship. Working memory capacity is a direct function of the cognitive load of processing, which corresponds to the proportion of time during which this processing occupies attention. Moreover, this metric resolves the issue of the relationship between short-term and working memory by integrating the two concepts in a common and coherent framework. As illustrated in Figure 2b, when cognitive load tends toward 0, working memory capacity tends toward Miller's magic number of 7 ± 2. Thus, short-term memory is equivalent to working memory when it does not "work," or when it works for maintenance purpose only. Likewise, a maximum cognitive load of 1 would result in a complete loss of memory traces (i.e., a span of 0). As we have seen, the same theoretical framework accounts for developmental differences in working memory, providing evidence that time is the major constraint of working memory functioning.

Though the TBRS model has proved successful in accounting for a range of working memory–related phenomena, there remain several unresolved issues that correspond to key questions in cognitive psychology. Are individual and developmental differences determined by the same factors (e.g., processing speed, rate of temporal decay, and efficiency of refreshing processes)? Our first investigation of this question led to promising results. When processing times are equated between low- and high-span individual and refreshing times tailored to individual capacities, differences in span tend to vanish (Barrouillet & Lucidi, 2011). Might these three factors reflect a single, general speed of processing (Fry & Hale, 1996; Salthouse, 1996), or do they reflect distinct rates of processing, as suggested by Cowan et al. (1998)? Finally, though the TBRS model focuses on temporal constraints, is working memory also limited in the number of chunks of information it can hold simultaneously (see Cowan, 2005)? These questions point toward a future research agenda.

Recommended Reading

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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