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Is variability in working memory capacity related to differences
in the reactivation of memory traces? A test based on the TBRS model

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Abstract

Working memory performance depends on reactivating memory traces, by rapidly switching between refreshing item representations and performing concurrent cognitive processing (time-based resource sharing account). Prior research has suggested that variation in the effectiveness of this process could be a plausible source of developmental changes in working memory capacity. This could conceivably extend to adults, potentially bridging the barrier between developmental and adult experimental research and providing a possible functional role for attention control and processing speed in working memory tasks. The present work was designed to replicate the finding of developmental differences in reactivation in children, and to test whether the same process could be related to individual differences in adults. Experiment 1 confirmed the finding of more effective reactivation for 14-year-old children than for 8-year-old children. Experiment 2 using the same task in adults manipulated the feasibility of reactivation within an experimental-correlational approach, and failed to find more effective reactivation for individuals with high working memory capacity, contrary to our predictions. Overall, our results support the role of reactivation as defined by the TBRS model as an important process in working memory tasks, and as a possible source of developmental increase in working memory capacity; but they rule out the possibility that adult individual differences in the effectiveness of this process are a major cause of variability in working memory capacity, suggesting that differences between adults are of a different nature.

Keywords

Working memory capacity; Individual differences; Attention control; Processing speed; Time-based resource sharing (TBRS)

Current interest in working memory has been largely driven by its variability: meaningful differences between individuals in their ability to maintain information in working memory. In adults, individual differences in working memory capacity (WMC) are related to performance in complex cognitive tasks (such as language comprehension: Daneman & Merikle, 1996; Linck et al., 2013; and mathematical abilities: Wiley & Jarosz, 2012), and more generally to intelligence (Ackerman et al., 2005), to the point of being the best available predictor of intelligence and reasoning (Oberauer et al., 2005). In children, developmental increases in WMC have been ascribed a central role in cognitive development (Cowan, 2014; Pascual-Leone & Johnson, 2011), and may be causally involved in the emergence of key skills such as executive control (Gonthier et al., 2019). In short, WMC and its variability appear to hold a key position in high-level cognition.

Understanding the origin of variability in WMC – including both developmental changes, and differences between individuals within an age group – is therefore critical to understanding variation in cognitive performance. How do certain individuals come to demonstrate more effective working memory, in the first place? There are clearly multiple mechanisms contributing to variation in WMC (Simmering & Perone, 2013). Some of these mechanisms have relatively clear effects on working memory performance, such as individual differences in strategy use (Bailey et al., 2011), or individual differences in the ability to retrieve information in secondary memory (Unsworth & Engle, 2007a). Things are less clear for other determinants. The focus of the present study is the possibility that working memory largely depends on the dynamic reactivation of memory traces throughout a trial (Barrouillet et al., 2004; Barrouillet et al., 2009; Lépine et al., 2005; Lépine et al., 2005), a hypothesis which has the potential to bring together several fields of working memory literature.

Reactivation of Memory Traces as a Determinant of Working Memory Capacity

The hypothesis that WMC is in part determined by the ability to reactivate memory traces within a trial is best framed in the context of the time-based resource sharing (TBRS) model of working memory functioning (Barrouillet & Camos, 2007, 2012). The TBRS model proposes that memory traces naturally decay with time, so that they need to be reactivated. This reactivation can occur through verbal rehearsal, or through attentional refreshing (Camos et al., 2009, 2011; see also Oberauer & Souza, 2020). According to the TBRS model, attention constitutes a limited resource, particularly taxed in the context of working memory demands, where maintenance in memory is performed concurrently with manipulation of information. In working memory tasks such as complex spans, participants have to alternate between remembering stimuli and performing concurrent operations (Conway et al., 2005; Redick et al., 2012): attention is required both to refresh memory traces and to perform concurrent cognitive processing, and attention control is necessary to rapidly switch the focus of attention back and forth, from processing demands to refreshing memory traces (Barrouillet & Camos, 2007).

The TBRS model hypothesizes that there can be differences in the effectiveness of this reactivation process, and in turn, WMC (e.g. Barrouillet et al., 2009). These differences could be driven, for example, by variation in attention control: adequate attention control would help participants efficiently switch their focus of attention towards memory traces during pauses in the concurrent processing task, yielding a higher reactivation rate (Barrouillet et al., 2004, 2009; Lépine, Barrouillet et al., 2005; Lépine, Bernardin et al., 2005). Since attentional refreshing can be used to reactivate memory traces, better attention control might also facilitate the reactivation itself (Barrouillet et al., 2009). Likewise, processing speed would be necessary to perform concurrent processing as quickly as possible (leaving more free time to refresh

memory traces before they decay; Barrouillet et al., 2009), and/or to perform attentional refreshing as quickly as possible within the available time (Gaillard et al., 2011), with variations of processing speed potentially creating variations in WMC.

In sum, individuals with high WMC would be those who manage to prevent the decay of memory traces in working memory tasks, due to an efficient reactivation process (afforded, for example, by a better ability to control their attention or to proceed quickly through task demands). A major interest of this hypothesis is that it offers a way to bridge the gap between two different fields of literature. On one hand, differences in the ability to reactivate memory traces have been found in cognitive development, although the results are not always clear-cut. On the other hand, adult performance in WMC tasks has been found to decrease when the reactivation of memory traces is prevented, but it has never been tested whether adults differ in their ability to perform this process. We review these two lines of literature in the next two sections.

Reactivation of Memory Traces in Cognitive Development

The possibility that variation in WMC is driven by variation in the effectiveness of reactivation of memory traces as defined by the TBRS model has mostly been tested in the context of developmental studies, and has been claimed as a possible factor contributing to developmental changes of WMC (e.g. Cowan, 2016; see also Bayliss et al., 2005; Plancher et al., 2017). To date, at least two studies have directly tested this hypothesis in children (Barrouillet et al., 2009; Gaillard et al., 2011; see also Camos & Barrouillet, 2011). Both studies investigated the reactivation process by manipulating the demands of a concurrent processing task: when the pace of a concurrent task increases, the feasibility of reactivating memory traces decreases (see Barrouillet et al., 2004; Barrouillet et al., 2011).

The study of Barrouillet and colleagues (2009) with 8- to 14-year-olds showed that younger children were little affected by the pace of concurrent processing demands in a working memory task, and recalled few items under all conditions. Older children had higher working memory spans, but they also grew significantly more sensitive to pace ($\eta^2_p = .11$): their advantage in WMC decreased and mostly disappeared when the concurrent processing task was demanding enough to impede memory trace reactivation (see Figure 1). The authors concluded that the developmental increase in WMC is largely attributable to an increase in the efficiency of the reactivation process, due to increases in both processing speed and attention control.

The study of Gaillard and colleagues (2011) with 9- to 12-year-olds likewise found that older children were more adept at reactivating memory traces, despite a smaller effect size for the interaction between age and pace ($\eta^2_p = .05$). Of secondary interest, this study also found that developmental differences in reactivation disappeared when younger children were allowed more time to reactivate memory traces, suggesting a larger role for processing speed than attention control. This is not however quite incompatible with the possibility that effective attention control influences speed, by helping alternate more quickly between refreshing memory traces and performing concurrent processing (Barrouillet et al., 2004, 2009; Lépine, Barrouillet et al., 2005; Lépine, Bernardin et al., 2005), and/or by helping perform the refreshing itself more quickly (Barrouillet et al., 2009).

Apart from studies in children, the hypothesis that variation in WMC is driven by variation in reactivation of memory traces has also been made for the decline of WMC in older adults (Hoareau et al., 2016; Plancher et al., 2017; see also Loaiza & McCabe, 2012). The corresponding evidence is more ambiguous: the expected interaction between age (younger vs. older adults) and pace does not always appear (Loaiza & Souza, 2018) and seems to only

emerge when a high level of distraction prevents older adults from effectively refreshing memory traces (Loaiza & Souza, 2019; Plancher et al., 2017). This suggests that the decrease of WMC with aging may be caused either by a decline of the reactivation process itself, or by increased vulnerability of this process to other factors.

Together, these studies support the possibility that lifespan differences in the reactivation of memory traces as defined by the TBRS model can elicit differences in working memory performance, especially across children of different ages. This possibility is generally supported by correlational findings regarding the attention control and processing speed abilities thought to be involved in the reactivation process. Attention control develops to a large extent during childhood, and is a plausible contributor to developmental increases in WMC (e.g. Cowan & Alloway, 2009). Processing speed correlates with WMC in children (Demetriou et al., 2014; Fry & Hale, 1996, 2000; Kail, 2007; Kail & Salthouse, 1994), and some authors have hypothesized that changes in processing speed may be the main source of variation of WMC with age, mediating most of the age-related increase in children (Fry & Hale, 1996) and age-related decrease in older adults (Salthouse, 1992; Salthouse & Babcock 1991). Differences of speed may also mediate differences of WMC in certain non-typical groups, such as gifted children (Aubry et al., 2021).

However, these results may not be quite sufficient to draw a definitive conclusion. First, not all authors agree that attentional refreshing of memory traces develops to a significant extent in early childhood (e.g. Tam et al., 2010, found that imposing attentional demands disrupted reactivation to the same extent in 6- and 8-year-olds). Second, both experimental studies of reactivation in children were conducted by the same research group, which leaves open the possibility that the results were due to specific methodological features. One worrying aspect of both studies is the use of all-or-nothing scoring, which counts a trial as correct only

if all stimuli are correctly recalled in the correct serial position. This method is not sensitive to partial recalls and is very demanding (a trial is scored zero unless the recalled sequence is exactly correct), especially for young children. For this reason, all-or-nothing could conceivably create a floor effect in younger children, spuriously leading to the pattern displayed in Figure 1 (see e.g. Jarrold, 2017; and indirectly, Wagenmakers et al., 2012).

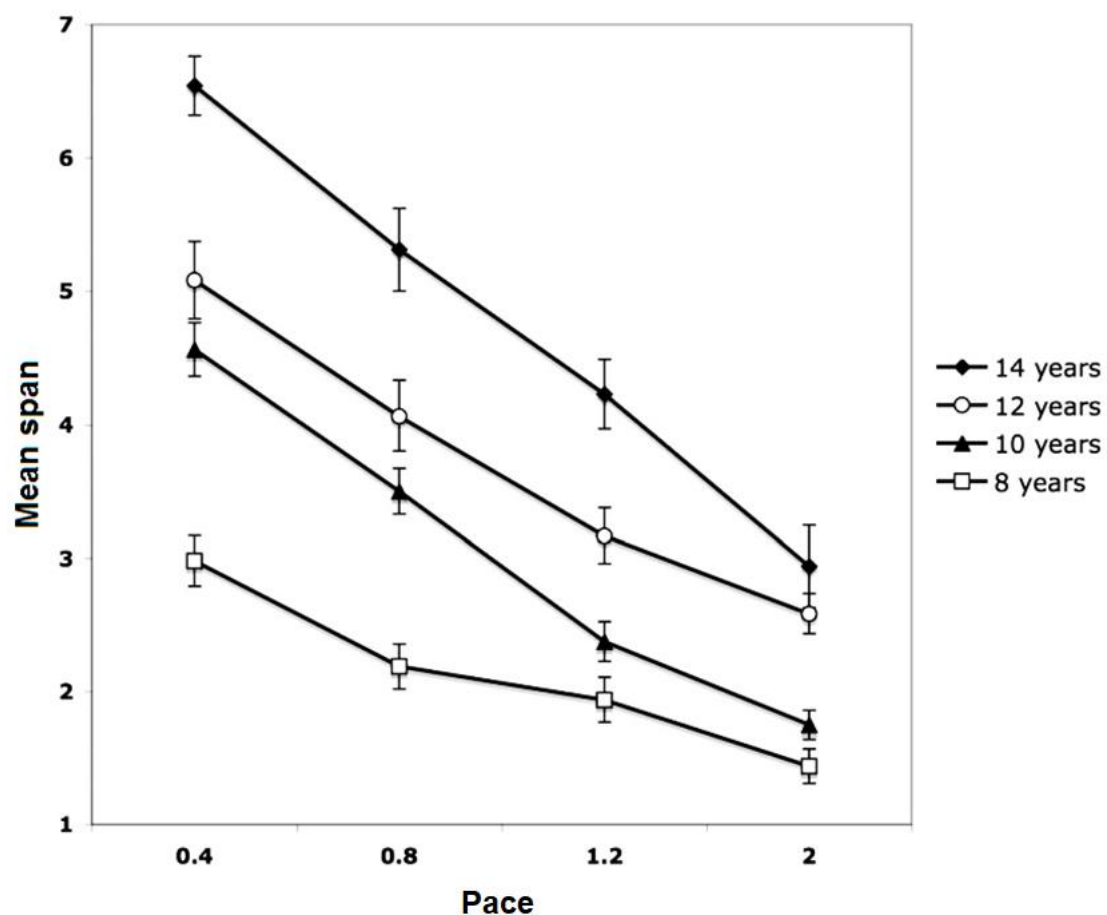


Figure 1. Relationship between age and scores on a reading digit span (RDS) as a function of pace. Adapted from "Working memory span development: A time-based resource-sharing model account" by P. Barrouillet, N. Gavens, E. Vergauwe, V. Gaillard and V. Camos, 2009, *Developmental Psychology*, 45, p. 481. Copyright 2009 by American Psychological Association.

Reactivation of Memory Traces and Adult Individual Differences

Based on the promising results obtained in children – and, to an extent, in older adults – a major question to be solved is whether variation in reactivation of memory traces could also be responsible for adult individual differences in WMC. This hypothesis is not formally part of the TBRS model, but it stems naturally from the literature: the reactivation of memory traces has been largely studied in adults (Barrouillet & Camos, 2007, 2012), confirming that it also plays a role in working memory tasks in adults. Moreover, a pattern very similar to Figure 1 is frequently observed in working memory research on adults: participants with high WMC tend to perform better in complex tasks, but they are also more vulnerable to constraints such as dual tasking, and they tend to experience a larger decrease in performance under such conditions (Beilock & Carr, 2005; Beilock & DeCaro, 2007; Gimmig et al., 2006; Kane & Engle, 2000; Rosen & Engle, 1997; Schelble et al., 2012; Thomassin et al., 2015). This phenomenon, which we have dubbed the "hard fall effect" (see Thomassin et al., 2015), is usually attributed to the fact that a high cognitive load prevents participants with high WMC from using their attentional abilities to bolster their performance, similar to the reactivation hypothesis.

As discussed above, variation in the ability to reactivate memory traces could be driven by variation in attention control and/or processing speed. This makes the reactivation process an especially likely candidate as a source of adult individual differences in WMC. Indeed, the ability to control attention is a keystone of contemporary models of working memory (for a discussion, see Adams et al., 2018; for examples, see Baddeley, 2002; Cowan, 1999; Engle & Kane, 2004), and it has been argued that meaningful variability in WMC is largely driven by individual differences in attention control (Burgoyne et al., 2022; Engle, 2002; Kane et al., 2007; Kovacs & Conway, 2016). A great deal of correlational research has supported this idea

in adults by demonstrating a relation between individual differences in WMC and the ability to control attention (see Engle & Kane, 2004; Kane et al., 2007; Oberauer et al., 2018). To name a few examples, participants with high WMC have proven more adept to resist interference caused by irrelevant words in a Stroop task (Kane et al., 2003) or irrelevant arrows in a flanker task (Redick et al., 2006), to avoid making involuntary eye movements in an antisaccade task (Kane et al., 2001), and to remain focused on a task while avoiding mind-wandering (McVay & Kane, 2009). Likewise, many studies have found relations between WMC and processing speed. Substantial correlations have been observed in adults (Ackerman et al., 2002; Kail & Salthouse, 1994; Kyllonen & Christal, 1990; Salthouse, 1992; Salthouse & Babcock, 1991; including community samples, such as Frischkorn et al., 2019). In young adults, relations between latent variables representing processing speed and WMC are usually in the .30 to .45 range (e.g. Ackerman et al., 2002; Conway et al., 2002; Kyllonen & Christal, 1990).

Differences in reactivation as defined by the TBRS model thus provide a compelling hypothesis to explain the mechanistic role of attention control and processing speed in adults, but these arguments alone are not sufficient. It is unknown whether different adults actually make use of reactivation to different extents, and the phenomenon of hard fall effect has not been studied directly in working memory tasks and has not been directly linked with reactivation. Besides, the similar correlations with attention control and processing speed in adults and children could be driven by different causes at different ages (e.g. Engle & Kane, 2004; see also Kovacs & Conway, 2016). Therefore the possibility of a general role for the effectiveness of the reactivation process as a major causal factor in adult individual differences in WMC remains to be tested.

Rationale for the Present Study

The process of reactivating memory traces, as defined by the TBRS model, has been identified as a possible determinant of variation in working memory performance both in children and in adults. Experimental studies in children provided convincing results, but they are somewhat limited by the lack of replication. Conversely, it is known that the reactivation of memory traces affects performance in adults on average, but there has been no examination of the *variability* of this process in adults: it is unknown to what extent the effectiveness of reactivation actually varies across individuals in a way that can affect WMC.

Confirming that variation in the effectiveness of reactivation of memory traces is broadly related to variation in WMC, in both children and adults, would be a major contribution to reconciling these two lines of research. Variation in performance does not necessarily have the same causes at different ages (e.g. Demetriou et al., 2014; Engle & Kane, 2004), so this is not to be taken for granted. Showing that the reactivation process drives variation in performance in a similar way for children and adults would thus help provide a common framework for developmental and adult experimental and correlational studies.

Another benefit of confirming whether reactivation of memory traces creates individual differences in adults is that it would provide a plausible functional role for attention control and processing speed. In other words, it would help understand by which mechanism effective attention control or high processing speed actually benefit recall in working memory tasks, ultimately leading to higher WMC. Without a detailed mechanistic account, the observed correlations between WMC and attention control or processing speed are not informative enough to help understand variation in WMC: this is especially true given that all these constructs are measured by tasks which involve multiple overlapping processes (see Kovacs & Conway, 2016), potentially creating spurious correlations (for example, some attention control

and processing speed tasks require holding complex instructions in working memory, and most attention control tasks and working memory tasks are speeded).

This issue has been particularly discussed for attention control, which has been described as "a hypothetical entity that sits atop the mountain of working memory and attention like some gigantic Buddha, an inscrutable, immaterial, omnipresent homunculus, at whose busy desk the buck stops every time memory and attention theorists run out of alternatives" (Donald, 1991, p. 327; see Shah & Miyake, 1999). This homuncular problem has plagued models of attention control and working memory since the first works on the topic (see Baddeley, 2002, 2012; Hazy et al., 2007; Logan, 2003; Logie & Cowan, 2015; Shah & Miyake, 1999). The same is true for the role of processing speed (for discussions, see Fry & Hale, 2000; Kail & Salthouse, 1994; Salthouse, 1992), to the point that it is unclear whether processing speed determines WMC or the reverse (Cowan, 1998; Engle & Kane, 2004). It does not help that processing speed is itself a complex construct with multiple dimensions (Danthiir et al., 2005), not all of which seem to have the same relation with WMC (Ackerman et al., 2002). Solving this problem and understanding the functional mechanisms by which attention control and processing speed affect WMC is therefore key to understanding how working memory integrates into the cognitive system as a whole (e.g. Simmering & Perone, 2013).

In sum, the goal of the present study was to test the possibility that variation in the reactivation of memory traces – as defined by the TBRS framework – creates variation in WMC performance in children, and that this generalizes to adults. The TBRS model, as implemented in prior developmental studies (Barrouillet et al., 2009; Gaillard et al., 2011), offers a relatively straightforward way of assessing the effectiveness of the reactivation process: manipulating the pace (operationalized as the amount of free time available to reactive memory traces) of concurrent processing in a working memory task, and measuring the extent to which it affects

recall performance. As represented in Figure 1, individuals with an effective reactivation process are expected to show a large effect of pace, with high performance when a slow pace allows for reactivation and low performance when a fast pace impedes reactivation of memory traces. Individuals with a less effective reactivation process are expected to show a smaller effect of pace.

Experiment 1 was designed as a control experiment to investigate the reactivation process in children by directly replicating prior developmental studies (Barrouillet et al., 2009; Gaillard et al., 2011). This replication attempt was partly motivated by the necessity of testing our implementation of the paradigm before attempting to generalize the results to adults in Experiment 2. It was also partly motivated by the facts that the two prior studies in children were performed by the same research group (raising the possibility that the results were dependent on specific methodological features, especially regarding the use of all-or-nothing scoring) and obtained effect sizes in the small-to-medium range, both factors inviting a new experiment to see if developmental changes in the reactivation process as a possible source of variation in WMC could also be found in an independent replication.

Experiment 2 was designed to test whether the pattern of differences in reactivation found in children could also be obtained in adults. If adult individual differences in WMC are indeed a reflection of differences in the reactivation process, similar results should be observed in adult participants: the advantage of individuals with high WMC in a working memory task should be a function of the feasibility of reactivating memory traces. In other words, participants with high WMC should outperform participants with low WMC, but only to the extent that concurrent processing demands allow them to take advantage of their superior attention control and processing speed to better refresh memory traces.

Experiment 1

Experiment 1 was designed to attempt a direct replication of the results of Barrouillet and colleagues (2009), to test whether we could find an interaction between age and pace in a working memory task. The objectives of this replication were both to confirm the existence of developmental differences in reactivation of memory traces, and to ensure that our implementation of the paradigm worked correctly to detect differences of reactivation before testing the generalization to adult individual differences in the Experiment 2.

For these reasons, we used a Reading Digit Span (RDS) task directly based on Experiment 1 of Barrouillet and colleagues (2009), with a few methodological changes designed to improve the design for the study of individual differences. First, the original study used all-or-nothing scoring, which has been shown to lead to information loss and to be less sensitive to individual differences in WMC than partial-credit scoring (Unsworth & Engle, 2007b; see also Gonthier, 2022). As discussed above, this scoring method could also create a floor effect in children, creating a spurious interaction (Jarrod, 2017). In the current study, performance on the RDS was instead scored using the partial-credit method, i.e. as the total number of stimuli correctly recalled in the correct serial position. This is the currently recommended method for the study of individual differences (Conway et al., 2005; Redick et al., 2012; for an even better alternative, see Gonthier, 2022).

Another methodological change in our implementation of the paradigm is that participants always completed all trials: testing was not terminated when a child failed to recall stimuli perfectly a particular level. This approach ensures that data can be obtained even for trials which do not have perfect recall, and also ensures that participants with higher WMC do not complete more trials (which could raise concerns related to individual differences in resistance to fatigue and buildup of proactive interference; for a discussion, see Gonthier et al.,

2017). Because all children completed all trials, the difficulty level ranged from two to seven letters per trial (instead of one to eight letters in the original study), and children completed two trials per difficulty level (instead of three), so as to limit testing time and avoid confronting children with overly-difficult trials.

Barrouillet and colleagues (2009) compared 8, 10, 12 and 14-year-olds; whereas Gaillard and colleagues (2011) compared 9 and 12-year-olds and found a smaller effect size, perhaps due to the more limited age range. In an effort to maximize effect size (Preacher et al., 2005) and increase the probability of replicating the effect found in the original studies, we collected only two groups of children corresponding to the extreme age groups of the first study: one group of 8-year-old children and one group of 14-year-old children.

Method

Statistical Power and Sample Size

Data collection was planned for the same sample size as the original study of Barrouillet and colleagues (2009): 16 children per pace condition per age group, or 96 children in total. A post-hoc power analysis using G*Power (Faul et al., 2007) indicated that achieved power for the reported effect size of $\eta^2_p = .11$ was .92 with this sample size. Two classes of 30 children per age group were invited to participate, and all children for whom consent was obtained were included in the study.

Participants

A sample of 105 children completed the experiment (achieved power = .94). They were recruited in two school grades: $n = 53$ children in 3rd grade (French *CE2*; 26 girls and 27 boys; mean age = 8.47 years, $SD = 0.30$), and $n = 52$ children in 9th grade (French *troisième*; 28 girls and 24 boys; mean age = 14.27 years, $SD = 0.35$). All participants were native French speakers. Written informed consent was obtained from all parents and oral consent from all children prior

to the experiment. Children were recruited in four different schools (two schools for each age group), all of average socioeconomic status.

Materials

Reading Digit Span Task. The reactivation of memory traces was assessed using the RDS (Barrouillet et al., 2004, 2009). The version used here was adapted from the study of Barrouillet and colleagues (2009; Experiment 1). In each trial, a series of letters were displayed sequentially on the screen. Participants were instructed to memorize and recall all letters in the same order. A series of irrelevant numbers was presented between each letter to divert attention from memory trace reactivation. To ensure processing of the numbers, participants were instructed to read aloud all stimuli displayed on the screen. All letters were monosyllabic consonants chosen for their phonologic distinctivity in French (F, G, H, J, K, L, N, Q, R, S, X, and Z). Numbers ranged between 1 and 12. The letters and numbers presented within a trial were determined randomly, but they never repeated within the same sequence.

Trials started with a fixation cross displayed for 1000 ms, followed after a delay of 500 ms by the first letter in the sequence. Letters were always displayed for 1500 ms. The presentation pace for numbers varied as a function of experimental condition: after each letter, participants had to read either 4 numbers in 10 seconds (or 0.4 number per second; slow pace condition), 10 numbers in 8 seconds (1.25 number per second; medium pace condition), or 12 numbers in 6 seconds (2 numbers per second; fast pace condition)¹. As in the original study (Barrouillet et al., 2009), the presentation time of each number was divided in 75% of display

¹ These three specific conditions were chosen so that a higher pace was also associated with more distractors. This avoided the possibility of distractors counteracting the role of reactivation, as could happen if a lower pace was associated with more distractors. Indeed, resistance to the interference caused by distractors could also play a role in this type of task (Oberauer et al. 2016), although presumably a lesser role than reactivation (see e.g. Barrouillet et al., 2017).

and 25% of inter-stimulus interval (e.g., in the fast pace condition, each number was presented for 375 ms and followed by a 125 ms delay). At the end of a trial, the recall prompt appeared after a 1000 ms delay. Participants had unlimited time for recall.

Difficulty levels ranged from two to seven letters to memorize. As in prior studies, trials were presented in ascending order of difficulty. Children completed two trials per difficulty level, for a total of 12 trials. Performance was scored using partial-credit scoring (Conway et al., 2005; Redick et al., 2012): as described above, the number of letters correctly recalled in the correct serial position was summed across all trials, yielding a total score between 0 and 54. Internal consistency was good (.88 overall, and respectively .85, .82 and .75 for the low, medium and fast pace conditions).

Procedure

Children performed the experiment individually in a quiet room at their school. As in the original study, each child completed only one of the three conditions of the RDS (either low, medium or fast pace) so as to limit testing time. Each child was assigned an experimental condition at random. Participants first completed three training trials for the RDS demonstrating their assigned pace condition, before proceeding to the main task. The experimental session lasted approximately 20 minutes per child.

Results and Discussion

The data file for this study can be accessed via the Open Science Framework at <https://osf.io/nhakg/>. The data were first screened for outliers using Cook's distance; no participants were excluded. Descriptive statistics are displayed in Table 1. All measures approximately followed a normal distribution, with no marked floor or ceiling effects.

Table 1

Descriptive statistics for Experiment 1

Age group	Pace	<i>n</i>	<i>M</i>	<i>SD</i>	Range	Skewness	Kurtosis
3 rd grade	Low	16	19.13	5.56	12 to 30	0.52	-0.35
	Medium	19	10.11	4.15	1 to 21	0.55	2.44
	High	18	9.56	4.50	3 to 19	0.58	-0.38
9 th grade	Low	17	37.35	7.87	19 to 47	-0.82	0.02
	Medium	18	22.17	7.43	9 to 35	0.04	-0.58
	High	17	15.71	6.43	7 to 29	0.69	-0.10

Note. Possible scores range from 0 to 54.

The main analysis was conducted using the general linear model, with a 3 (pace, between-subjects) x 2 (age group, between-subjects) design. This analysis revealed the expected main effect of pace, $F(2, 99) = 60.48$, $MSE = 37.45$, $p < .001$, $\eta^2_p = .55$, with higher paces again eliciting lower recall in the RDS (see Table 1). The expected main effect of age was also significant, $F(1, 99) = 103.09$, $MSE = 37.45$, $p < .001$, $\eta^2_p = .51$, confirming that older children had higher recall scores on the RDS. Lastly, the two-way interaction between age and pace was significant, $F(2, 99) = 8.26$, $MSE = 37.45$, $p < .001$, $\eta^2_p = .14$. This interaction reflected a greater effect of pace for 14-year-olds than for 8-year-olds, compatible with an increase in the effectiveness of the reactivation process with age. These results are depicted in Figure 2.

This analysis was then replicated under a Bayesian framework, using the *BayesFactor* package (Morey & Rouder, 2015) for the R statistical environment (R Core Team, 2022); analysis performed with default prior scales and with 100000 samples). The results showed that the model with main effects and an interaction between age and pace was preferred over the model with only main effects by a Bayes Factor of $BF_{10} = 53.82$, providing very strong evidence (Kass & Raftery, 1995) in favor of the interaction. The interaction was also significant

when comparing only the slow pace condition to the medium pace condition, $F(1, 66) = 4.05$, $MSE = 40.94$, $p = .048$, $\eta^2_p = .06$; and when comparing only the medium pace condition to the fast pace condition, $F(1, 68) = 4.74$, $MSE = 33.15$, $p = .033$, $\eta^2_p = .07$, with both restricted comparisons showing comparable effect sizes. Thus, the interaction appeared stable overall.

Experiment 1 provided a replication of prior studies (Barrouillet et al., 2009; Gaillard et al., 2011), with an effect size for the interaction between age and pace very close to that reported by Barrouillet et al. (2009). These results confirmed both that there are indeed developmental differences in the ability of taking advantage of a slow pace to reactivate memory traces, and that our version of the paradigm – with less trials and partial-credit scoring – adequately picked up on variation in the effectiveness of the reactivation process.

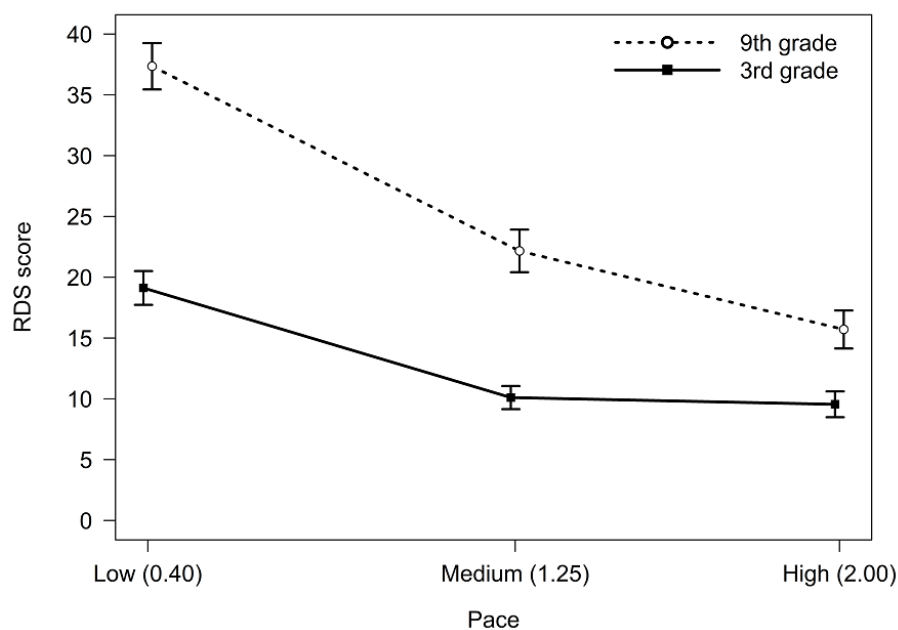


Figure 2. Average score on the reading digit span task (RDS) as a function of pace and age group. Possible scores range from 0 to 54.

Experiment 2

Experiment 2 was designed to test whether adult individual differences in WMC were related to the effectiveness of the reactivation of memory traces, by porting the methodology of Experiment 1 and prior developmental studies (Barrouillet et al., 2009; Gaillard et al., 2011) to an adult sample.

This experiment required a measure of individual differences in WMC, but WMC could not be assessed based on performance in the RDS task: this would have biased the analysis by conflating the effect of pace with performance (because performance decreases with pace, a high performance in the RDS task is necessarily driven by higher performance in the slow pace condition, which means subjects with high performance necessarily show a larger effect of pace; see also Thomassin et al., 2015). Individual differences in WMC were thus assessed independently with a battery of complex span tasks. Complex spans are a consensual choice of task in the individual differences literature (see Conway et al., 2005; Redick et al., 2012), are available in French (Gonthier et al., 2016), correlate well with the RDS task (Lucidi et al., 2014), and have the same basic structure (differing only by the complexity of concurrent processing demands), making it more likely to find a relation between the two.

As in Experiment 1, the effectiveness of the reactivation process was assessed by manipulating pace in the RDS task (Barrouillet et al., 2004, 2009). Contrary to Experiment 1 and other developmental studies, this manipulation of pace was performed within-subjects: all participants performed the working memory task under conditions of low, medium or fast pace, allowing for a more decisive test of the interaction between WMC and the effect of pace in a given subject.

The key advantage of this experimental-correlational design (Cronbach, 1957), combining a measure of individual differences in WMC with an experimental manipulation, is

to allow for a test of the causal effect of reactivation. If individual differences in WMC are determined by differences in reactivation, then experimentally decreasing the feasibility of reactivating memory traces by increasing pace should necessarily decrease the correlation between WMC and performance in the RDS task. Conversely, observing the correlation between WMC and performance even when removing the possibility of reactivating memory traces would indicate that differences in WMC are not due to reactivation. In other words, the expected interaction between WMC and pace would suggest that reactivation is causally involved in the emergence of WMC differences (for other examples of this approach in the context of working memory research, see Gonthier & Thomassin, 2015; Rosales et al., 2022). This pattern of interaction, similar to Experiment 1, is what we expected to find in this study.

Method

Relevant materials for this study can be accessed via Open Science Framework at <https://osf.io/nhakg/>. This repository contains the task script, and R code to replicate the power analyses.

Statistical Power and Sample Size

A statistical power analysis was conducted using Monte Carlo simulation (Muthén & Muthén, 2002; made necessary by the unusual design with an interaction between a continuous variable and a within-subjects three-modality categorical variable) to determine the most appropriate sample size for the present study. Gaillard and colleagues (2011) reported an effect size of $\eta^2_p = .05$ for the two-way interaction between age and pace; Barrouillet and colleagues (2009) found an effect size of $\eta^2_p = .11$, and our own Experiment 1 found an effect size of $\eta^2_p = .14$. A power analysis based on the median effect size of $\eta^2_p = .11$ indicated that a sample size of $N = 45$ was sufficient to detect an effect of this size with .80 power under the present design, and that a sample size of $N = 70$ was necessary to achieve .95 power. Data collection

was planned for 80 participants, enough to detect effect sizes as small as $\eta^2_p = .07$ with .80 power.

Participants

A sample of 83 undergraduate students participated for course credit (16 males and 67 females; mean age = 20.37 years, $SD = 1.87$). All participants were native French speakers, and none of them had completed the reading digit span task before. All participants provided written informed consent prior to the experiment.

Materials

Working Memory Capacity. Individual differences in WMC were assessed with the Composite Complex Span (CCS; for details, see Gonthier et al., 2016). The CCS is composed of shortened versions of three classic complex span tasks: the reading span, the symmetry span and the operation span (Redick et al., 2012). In each complex span subtest, participants are required to memorize simple stimuli (digits for the reading span, spatial locations for the symmetry span, consonants for the operation span) while solving judgment tasks (deciding whether sentences are correct, whether pictures are symmetrical, and whether math operations are correct, respectively). The score on each subtest is computed as the total number of stimuli correctly recalled across all trials. The three scores are then standardized and averaged to yield a single composite WMC score. The CCS has demonstrated excellent reliability (internal consistency = .86 in a sample of students) and validity, and population norms have been computed on a sample of more than 1000 participants (Gonthier et al., 2016).

Reading Digit Span Task. The reactivation of memory traces was assessed using the same version of the RDS task used for Experiment 1, with the following differences. Because pilot testing with two students suggested that the set sizes used with children may be too easy for some adult participants, difficulty levels were made to range from three to eight letters to

memorize. In order to limit testing time (given that pace was manipulated within-subjects in this experiment, and the experimental session also included the CCS), participants completed one trial per difficulty level, in ascending order, for each condition of pace, for a total of 18 trials. As a result, total scores ranged from 0 to 33 in each condition; reliability was good at the task level ($\alpha = .84$), but lower for each experimental condition considered separately ($\alpha = .64$, $.70$, and $.68$ for the low, medium and fast pace conditions).

Procedure

Participants performed the experiment individually in a university testing room. The first task of the experimental session was the CCS. After a short break, participants completed three training trials for the RDS demonstrating the low, medium and fast pace conditions. They then performed the three conditions of the RDS in random order². The experimental session lasted approximately 60 minutes.

Results and Discussion

The data were first screened for outliers using Cook's distance; two participants with critically low performance in the slow pace condition (less than two stimuli recalled per trial) were excluded from the sample, yielding a final sample size of $N = 81$. All analyses yielded equivalent results when keeping these participants. Descriptive statistics are displayed in Table 2. All measures approximately followed a normal distribution, with no marked floor or ceiling effects. A Kolmogorov-Smirnov test indicated that the distribution of scores on the CCS did not significantly differ from the parent population used to norm the task (Gonthier et al.,

² The order of experimental conditions had a significant main effect on performance, $p = .021$, with subjects performing somewhat higher when the slow pace condition was performed first and lower when the fast pace condition was performed first. However, there were no interactions of interest: Order*Pace, $p = .259$, Order*WMC, $p = .281$, or Order*Pace*WMC, $p = .746$.

2016; $D = .09$, $p = .562$), suggesting that the sample recruited for the present study was representative in terms of WMC.

The main analysis was conducted using the general linear model, with a 3 (pace, within-subjects) x continuous (WMC, between-subjects) design. This analysis revealed the expected main effect of pace, $F(2, 158) = 200.63$, $MSE = 14.25$, $p < .001$, $\eta^2_p = .17$, with higher paces eliciting lower recall in the RDS (see Table 2) in line with the predictions of the TBRS framework. The main effect of WMC was also significant, $F(1, 79) = 16.15$, $MSE = 58.07$, $p < .001$, $\eta^2_p = .17$, confirming that individual differences in WMC were predictive of recall scores on the RDS.

Contrary to our predictions, however, the two-way interaction between WMC and pace was not significant, $F(2, 158) = 0.57$, $MSE = 14.25$, $p = .569$, $\eta^2_p = .01$, indicating that the relationship between WMC and performance on the RDS did not vary across paces. (For reference, the slope for the relation between WMC and recall performance varied very little from the lowest pace [slope = 2.50, standard error = 0.60, $p < .001$] to the highest pace condition [slope = 2.52, standard error = 0.69, $p < .001$]). In other words, participants with high WMC were not more impaired when reactivation of memory traces was impeded³. These results are depicted in Figure 3. To better visualize the effect of pace on the absolute value of performance and to facilitate comparison with Figure 1, an alternative representation of the two-way interaction between WMC and pace is also provided in Figure 4 with WMC treated as a categorical variable.

³ An alternative way to analyze these results would be to treat pace as a continuous variable and compute, for each subject, the slope for the decrease of their recall performance as a function of pace. The average slope was -7.34 (standard deviation = 3.28), confirming that increased pace impeded the reactivation of memory traces. However, individual slopes for the effect of pace were completely uncorrelated with WMC, $r = .00$.

Table 2

Descriptive statistics for all measures in Experiment 2

Measure	<i>M</i>	<i>SD</i>	Range	Skewness	Kurtosis
CCS: Composite WMC	-0.02	0.86	-1.89 to 1.60	-0.17	-0.74
RDS: Slow pace	23.49	5.08	14 to 33	0.15	-0.92
RDS: Medium pace	15.75	6.28	3 to 30	0.35	-0.60
RDS: Fast pace	11.81	5.68	1 to 30	1.09	1.83

Note. CCS = Composite Complex Span; RDS = Reading Digit Span. Because the composite WMC score is expressed as an average of standardized scores, the value 0 corresponds to the mean of the normative sample (and because the component standardized scores are correlated, its standard deviation is less than 1). Possible values for RDS scores range from 0 to 33.

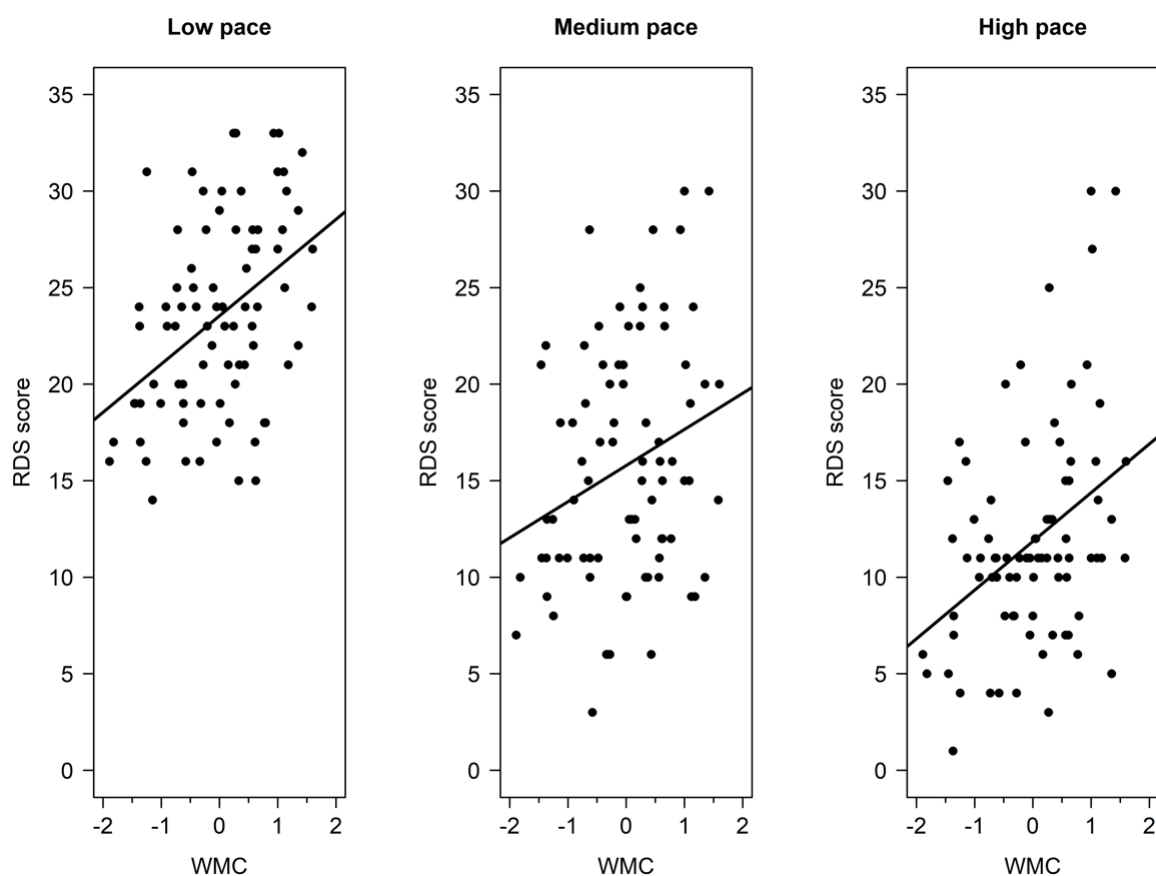


Figure 3. Relationship between working memory capacity (WMC) and scores on the reading digit span (RDS) as a function of pace. Possible scores range from 0 to 33.

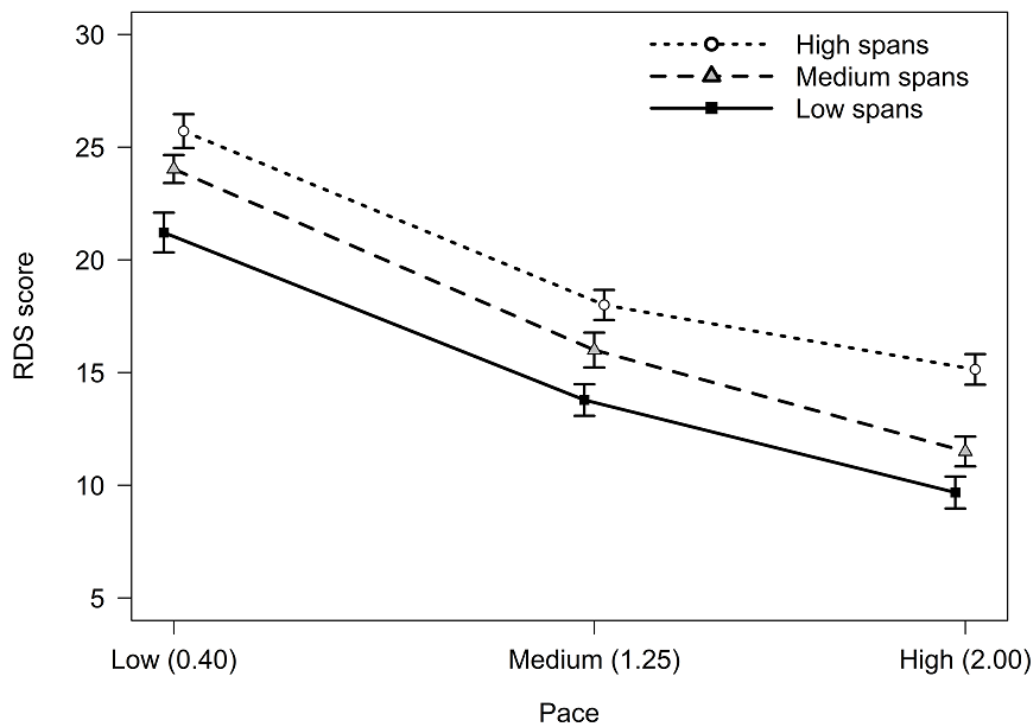


Figure 4. Average score on the reading digit span task (RDS) as a function of pace and working memory group. The low span and high span groups are composed of participants from the first and fourth quartile of WMC scores respectively. Possible scores range from 0 to 33. Error bars represent within-subjects standard errors of the mean (Morey, 2008).

In order to obtain a clearer picture of evidence in favor of the null hypothesis, the analysis was replicated under a Bayesian framework. The results revealed that the model without an interaction between WMC and pace was preferred over the interaction model by a Bayes Factor of $BF_{01} = 23.48$. In other words, the data indicated that the null hypothesis was more than 23 times more likely, providing strong evidence (Kass & Raftery, 1995) against the hypothesis that the relationship between individual differences in WMC and working memory performance depends on pace. Thus, adult individual differences in WMC appeared unrelated to efficiency of the reactivation process.

In sum, the results showed that there was no meaningful variability of the reactivation process in adults: individuals with low or high working memory capacity did not differ in their tendency to reactivate memory traces, and all took advantage of pauses to refresh to-be-remembered items to the same extent. These results are broadly compatible with the TBRS account in showing a major impact of reactivation on performance (all participants had much higher performance under slow pace than fast pace), but rule out the possibility that individual differences in reactivation are a major source of individual differences in WMC, contrary to our predictions.

Could methodological issues be the cause of this null finding? The experiment was adequately powered and Bayesian evidence was unambiguously in favor of the null hypothesis. The paradigm was similar to Experiment 1, which found a significant interaction. One difference was the use of a single trial per set size per pace condition in the RDS, which was necessary to keep a reasonable testing time, but yielded limited reliability; however, this is unlikely to be the cause of the non-significant interaction given that this did not prevent performance in the RDS to substantially correlate with WMC in each pace condition (see Figure 3). The correlation between WMC and average scores on the RDS was $r = .41$, approximately in the same range as in prior studies using similar tasks (e.g. Lépine et al., 2005; Lucidi et al., 2014).

Apart from this, the methods mostly replicated the design of Experiment 1 and the original study of Barrouillet and colleagues (2009). The other major difference was the use of partial-credit scoring instead of all-or-nothing scoring: as discussed above, the use of all-or-nothing scoring could create floor effects in participant with low WMC, leading to spurious interactions. In fact, this pattern could be created in our data just by switching to all-or-nothing scoring: the results then appeared very similar to Figure 1, with a significant interaction

between WMC and pace ($p = .002$, $\eta^2_p = .14$), entirely driven by a floor effect in participants with low WMC who performed very low in all conditions of pace. However, there was no such floor effect in the data when using partial-credit scoring, and performance demonstrated a satisfying range and distributions close to normal in each condition and for all levels of ability (see Table 2 and Figure 3), suggesting that the lack of an interaction here was actually due to a lack of adult individual differences in the reactivation process.

Comparison Between Child and Adult data

The combination of Experiments 1 and 2 suggested that differences in the effectiveness of the reactivation process was a source of developmental variation in WMC, but not a source of adult individual differences. A possible interpretation of these results is that the effectiveness of the reactivation process progressively increases during childhood, but no longer differs to a significant extent across individuals once it is firmly in place. Although this was not a major objective when we designed the present study, these results raised the question of how reactivation in younger and older children compared to reactivation in adults. The use of a largely identical task for the two experiments made it possible to compare the datasets of Experiment 1 and Experiment 2 directly, for exploratory purposes.

For this analysis, total scores on the RDS were recomputed after excluding trials that were not performed by all subjects (i.e. excluding trials of set sizes 2 in children and set sizes 8 in adults). This transformation does not make the tasks exactly identical (children performed two trials per set size with pace manipulated between-subjects, whereas adults performed one trial per set size with pace manipulated within-subjects), but makes it possible to perform a

meaningful comparison of the effect of pace⁴. The analysis itself was performed using mixed models, implemented with package *lme4* (Bates et al., 2015) in *R* (R Core Team, 2022), equivalent to the general linear models used for Experiments 1 and 2 but with the addition of a random intercept per subject for adults⁵; this approach made it possible to test the effect of pace while taking into account the within-subjects design for adult data. Adults were treated as a single group for this analysis (i.e. without including WMC as a predictor).

The results of this analysis are displayed in Figure 5. The interaction between age group and pace was significant, $\chi^2(4) = 11.55, p = .021$. Pairwise comparisons between age groups indicated that the interaction was only significant when comparing Adults and children in 3rd grade, $\chi^2(2) = 8.76, p = .013$, or when comparing children in 9th grade and children in 3rd grade, as already tested in Experiment 1: $\chi^2(2) = 16.29, p < .001$ with this analysis. The interaction was non-significant when comparing Adults and children in 9th grade, $\chi^2(2) = 1.40, p = .496$. As is visible in Figure 5, this reflected the fact that despite higher performance on average for adults, the groups of adults and 14-year-olds showed very similar effects of pace, apparently taking advantage of free time to reactivate memory traces to similar extents; whereas 8-year-olds had a significantly lower slope than either group.

⁴ Another solution to meaningfully compare the child and adult groups would be to recode performance in terms of percentage of targets correctly recalled, taking into account all trials. This alternative analysis led to the same conclusions (p -values were .016 for the interaction between age group and pace, .006 for the pairwise comparison between adults and 8-year-olds, and .649 for the pairwise comparison between adults and 14-year-olds).

⁵ More specifically, the tested model was Performance ~ AgeGroup * Pace + (1|SubjectID). For pairwise comparisons, this model was re-run by removing one age group.

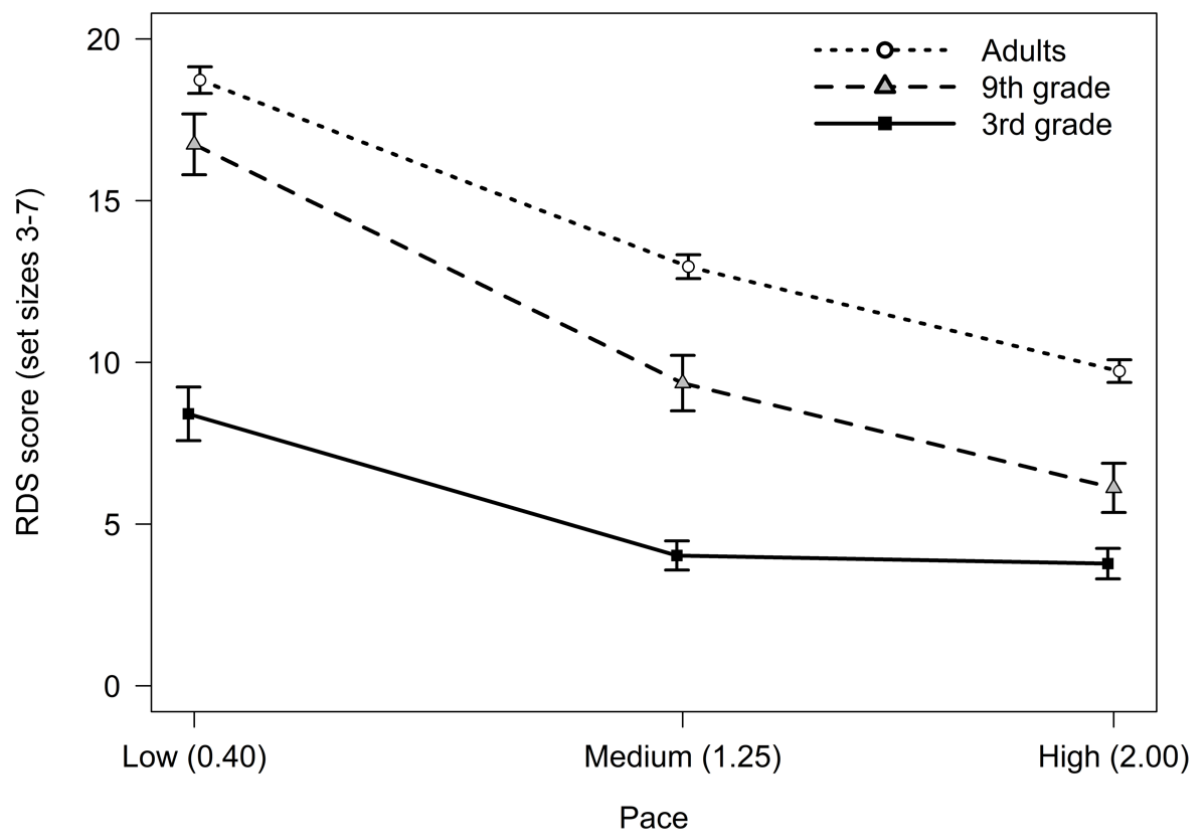


Figure 5. Performance on the reading digit span task (RDS) as a function of pace and age group, for adults and children (restricted to set sizes completed by all subjects). Error bars represent between-subjects standard errors of the mean for children and within-subjects standard errors of the mean (Morey, 2008) for adults.

General Discussion

We set out to demonstrate that variability in the process of reactivating memory traces before they decay is a primary determinant of variation in working memory performance, including both developmental variation and individual differences between adults; and therefore constitutes a plausible mechanism to explain the correlation between attention control and processing speed, and WMC. The two experiments provided partial support for this

hypothesis: Experiment 1 replicated the finding of developmental differences in reactivation, but Experiment 2 using the same task failed to find a relationship between reactivation and adult individual differences in WMC. Thus, variations in the effectiveness of reactivation as defined by the TBRS model are a possible candidate for developmental differences, but do not appear to drive adult individual differences.

Our results were fully compatible with the main tenets of the TBRS model: on average, performance substantially decreased as a function of pace, as expected, and the results appeared descriptively comparable to those of prior studies using the same task (Barrouillet et al., 2004, 2009). This confirms that reactivation of memory traces did play a critical role in the task and directly influenced performance: working memory spans significantly suffered when reactivation was impeded. This was true in all age groups, indicating that participants of all the ages considered here made use of this reactivation process.

The fact that older children made more effective use of reactivation when allowed by the task pace, in line with the literature, confirms that there can be variation in the use of reactivation. However, the fact that there was no longer any difference between adults with different WMC in terms of reactivation, contrary to our hypothesis, suggests that this variation is mostly to be found in the course of cognitive development and perhaps aging. This highlights the fact that variation in performance does not necessarily have the same cause at different ages (for other examples in the development of high-level cognition, see Demetriou et al., 2014; and the discrepancy between Gonthier et al., 2019, and Rosales et al., 2022).

Young adults with low and high WMC apparently engaged in similar reactivation of memory traces, and benefited to the same extent. This finding precludes the natural extension of the TBRS model to explain individual differences in WMC, which we had hoped to establish here. However, our findings do not actually contradict the TBRS model, which only makes

predictions about the dependence of working memory performance on reactivation availability in general, not about the specific possibility that individual differences in WMC depend on the individual ability to reactivate memory traces. The fact that there seems to be no meaningful variation between individuals in terms of reactivation runs counter to our hypothesis, but it is not a challenge to TBRS theory: many mechanisms have a large effect in the context of experimental manipulations, but are not associated with major individual differences.

The case of vision is a simple analogy. Vision is critical to success in a visual memory task, and experimentally decreasing the availability of vision (e.g. by closing one's eyes) will dramatically decrease performance in the task; on the other hand, in a typical sample of young adults, the correlation between individual differences in visual acuity and performance in a visual memory task is close to zero. Likewise, reactivation of memory traces demonstrates a major effect on performance when experimentally manipulated through the task pace, but appears to be similarly available to all young adults. This amounts to saying that like visual acuity, the level of memory trace reactivation does not sufficiently differ between typical young adults to elicit a difference of memory performance between them.

Development of Reactivation of Memory Traces

These and prior results (Barrouillet al., 2009; Camos & Barrouillet, 2011; Gaillard et al., 2011) are sufficient to draw a rough outline of the development of the reactivation process as defined by the TBRS model. Dynamic reactivation of memory traces seems to emerge around 6-7 years old (Camos & Barrouillet, 2011, found evidence of reactivation for 7- but not 6-year-olds; but see Tam et al., 2010), develop throughout childhood (Barrouillet et al., 2009, descriptively reported in Figure 1 a difference between the highest and lowest paces of approximately 1.57 points for 8-year-olds, 2.83 points for 10-year-olds, 2.53 points for 12-year-olds and 3.62 points for 14-year-olds), then stabilize somewhere around 14 years of age.

The comparison of Experiments 1 and 2 makes it clear that there is no longer a major difference in reactivation between 14-year-olds and adults (who show a similar effect of pace despite adults performing substantially higher), and the results of Experiment 2 suggest that once this process has stabilized, it is no longer conducive to meaningful differences of WMC between individuals.

These results confirm that progressive increases in the effectiveness of the reactivation process constitute a possible source of developmental differences in WMC, and a possible functional consequence of developmental increases in attention control and processing speed. This is an important step in reconciling correlational studies with studies interested in mechanisms of working memory performance. The other missing piece of the hypothesized causal chain is to test whether effectiveness of the reactivation process is actually related with individual differences in processing speed and attention control. This constitutes an important possibility for future studies. Besides, it is also worth recalling here that our results do not suggest that increases in reactivation of memory traces are the *only* source of developmental variation in WMC. On the contrary, it seems very likely that other processes contribute to this developmental variation (Simmering & Perone, 2013).

The results of Experiment 1 (and the comparison between Experiments 1 and 2) are partly reminiscent of the pattern observed for the development of subvocal rehearsal, one of the two mechanisms allowing for reactivation of memory traces along with attentional refreshing (Camos et al., 2009, 2011). Rehearsal of to-be-remembered stimuli also seems to progressively emerge during childhood, with some authors claiming that children younger than 7 years of age do not rehearse stimuli at all (e.g. Gathercole, 1998; Gathercole et al., 1994). This may be partly related to the lower effectiveness of the reactivation process, in that both patterns reflect difficulty on the part of younger children in actively maintaining memory

traces. However, the findings for subvocal rehearsal are more nuanced: the lack of rehearsal in young children is observed only when stimuli are presented visually, requiring verbal recoding (see Gathercole, 1998); and part of the null results for rehearsal in young children may be due primarily to methodological difficulties (Jarrold, 2017). Moreover, there is substantial evidence that variability in the articulation rate – reflecting the effectiveness of rehearsal – is related to individual differences in WMC in adults (Baddeley et al., 1975; Cowan et al., 1998; Gathercole et al., 1994; Standing & Curtis, 1989), which does not seem to be the case for variability of the reactivation process given the results of our Experiment 2.

Of secondary interest, the present results illustrate the importance of considering scoring carefully: in Experiment 2, the expected pattern of lower sensitivity to pace could be spuriously created by using an all-or-nothing method of scoring, as is often done in developmental studies. Our successful replication of the expected developmental differences fortunately confirmed that this was not the source of prior results (Barrouillet et al., 2009; Gaillard et al., 2011), but the results still confirm that this scoring method should be avoided, including in developmental studies. Partial-credit scoring is the recommended method because it is more sensitive, allowing for a greater diversity of scores and for more fine-grained distinctions between individuals (Conway et al., 2005; Redick et al., 2012; Gonthier, 2022), and because it typically leads to better relations with other constructs (Friedman & Miyake, 2005; Unsworth & Engle, 2007). The newer method of edit-distance scoring (Gonthier, 2022) is also a good alternative. Here we show that an additional reason to avoid all-or-nothing scoring is that it may lead to a floor effect in low-performing individuals, who may have difficulty correctly recalling *all* stimuli in a trial while still retaining a significant amount of information. The possible role of floor effects in creating spurious developmental interactions (Jarrold et al., 2017) is reason enough to avoid this method in developmental studies.

Sources of Adult Individual Differences in Working Memory Performance

Experiment 2 showed that individual differences in WMC, as measured with a reliable battery of complex spans, did not interact with the effect of pace. There were robust individual differences in WMC, and there was an effect of pace on average, indicating that adults reactivated memory traces, but the two were not related. A major advantage of Experiment 2 was its experimental-correlational design (Gonthier & Thomassin, 2015; Rosales et al., 2022): the correlation between individual differences in WMC and performance in the RDS task was assessed in different conditions experimentally manipulating the feasibility of reactivating memory traces. The key interest of this design is that it allows for causal conclusions: finding no difference in the correlation between WMC and performance between conditions with different feasibility of reactivation, means that reactivation – at least as defined by the TBRS model – does not play a major causal role for individual differences in WMC.

We have confidence in this null finding, given that the experiment was adequately powered, the bayesian evidence was firmly in favor of the null, the sample was representative of the larger norming sample in terms of individual differences in WMC, and the RDS task had a correlation with WMC similar to the literature. It is always possible that an experiment with a larger sample could manage to find a significant interaction, but given the current results, this interaction would be expected to be of a very small size ($\eta^2_p = .01$ in this experiment). This stands in stark contrast with the large observed range of individual differences in working memory performance (see Figure 3). In other words, even if a very slight variation in the reactivation process did exist, it would be unlikely to be a major contributor to differences between individuals. Likewise, the difference of design between Experiment 1 and Experiment 2 is unlikely to explain the null finding of Experiment 2: the RDS task had the same structure in both cases, and the complementary analysis showed that there was no major

difference in reactivation between adults and 14-year-olds when restricting the analysis to trials with the same set size. The only major difference was the within-subjects design in Experiment 2, but given that condition order did not interact with pace, this is unlikely to cancel an effect of reactivation, and if the role of reactivation was fragile enough to be canceled by a within-subjects design, it would be unlikely to be of major interest.

Of course, our results do not rule out the possibility that attention control and processing speed have a causal effect on working memory performance, just the possibility that their functional role translates into differences in reactivation of memory traces in the RDS task. If the large individual differences in performance in Experiment 2 were not created by differences in the reactivation of memory traces, then by what mechanisms do attention control and processing speed produce individual differences of performance in working memory tasks? Many possible candidates have been put forward in the literature.

Effective attention control might help participants attend to target items (Engle & Kane, 2004), inhibit irrelevant distractors (Engle & Kane, 2004) or competing sets of items (Rosen & Engle, 1998), confer a higher level of activation to memory traces at encoding (Barrouillet et al., 2009), implement effective mnemonic strategies (Ang & Lee, 2010; this is unlikely here given that strategies take time to implement and would hardly be feasible in the fast pace condition: Thomassin et al., 2015), resist the buildup of proactive interference throughout the task (Kane & Engle, 2000), perform elementary information processing with greater speed (Barrouillet et al., 2008), actively maintain memory traces (Unsworth & Engle, 2007a) or reactivate them before they decay (Barrouillet et al., 2004), avoid transitory attentional lapses during the task (Adam et al., 2015), or generate and use cues to retrieve information in secondary memory (Unsworth & Engle, 2007a).

Possible contributions of processing speed in a working memory tasks include faster rehearsal of to-be-remembered items (related to the finding that working memory performance is correlated with speech rate: Hulme et al., 1984), faster mental scanning of serial positions (though Smyth & Scholey, 1996, find no support for this hypothesis), faster computation of those concurrent operations that may be required by the working memory task (Salthouse, 1992; this is unlikely in the present case, as a benefit in reading digits should have scaled with pace), slower decay of information in memory (Salthouse, 1992, studied this possibility but did not find support for it), faster search for items in short-term memory (Puckett & Kausler, 1998), and shorter duration of pauses between stimuli at recall, which might be associated with differences in retrieval rate (Cowan et al., 1998; although this appears unlikely, see Cowan et al., 2006).

These possibilities are mostly open for future research. Some remain to be explored (such as the proposed relationship between attention control and resistance to proactive interference buildup in working memory tasks), whereas others would prove a challenge to test experimentally (such as the idea that effective attention control elicits a higher level of activation of memory traces at encoding). Critically, these various mechanisms are not exclusive, and it is plausible that attention control performs several functions in a working memory task. On the other hand, it seems unlikely that all the functions that have been assigned to attention control actually rely on isomorphic processes (in other words, that all these functions are performed by the same psychological entity that could be named "attention control"; for an example, see Friedman & Miyake, 2004). It also seems unlikely that they all impact working memory performance to the same extent.

Alternative Explanations based on Delay and Interference

The RDS task manipulates pace by changing the number of distractors and/or the delay between to-be-remembered stimuli. For this reason, performance can be affected by reactivation of memory traces (pace), resistance to interference caused by distractors (number of distractors), and/or simple decay of memory traces over time (delay). The TBRS model places more emphasis on pace, due to studies showing that performance scales with the ratio between time and number of distractors, i.e. pace, more than with each factor separately (see Barrouillet et al., 2011). However, it also acknowledges resistance to interference and forgetting over time as possible sources of variation (e.g. Barrouillet & Camos, 2009).

In the present study, pace was inversely related to delay, so that a faster pace came with a shorter delay between stimuli: it would be difficult to claim that delay length played a substantial role in the results given the very large decrease of performance over faster paces (i.e. shorter delays). By contrast, pace varied in the same direction as number of distractors, so that a faster pace also came with more distractors. This was a deliberate design choice: having a slower pace come with more distractors could have spuriously created the expected interaction (the slower pace condition would have given an advantage both to subjects more skilled at reactivating memory traces, and to subjects more skilled at resisting distractor interference), especially given that both cognitive development and high WMC are supposed to be associated with better resistance to distraction (e.g. Engle & Kane, 2004). This situation was avoided by the design, and thus the results of Experiment 1 can hardly be driven by resistance to interference, which should have made older children perform relatively better than younger children in the fast pace condition (which had more distractors).

Conversely, in the case of Experiment 2, one could imagine a way to draw on resistance to interference to reconcile our null results with the possibility of individual differences in

reactivation of memory traces as defined by the TBRS model: it would be necessary to hypothesize that both reactivation and resistance to interference caused by distractors played a role; that participants with high WMC benefited from effective reactivation in the slow pace condition, and from effective resistance to interference in the fast pace condition, eliciting better performance in both cases; and that these two phenomena almost exactly balanced each other, creating a general advantage but no interaction with pace. Testing this possibility would require manipulating pace independently of number of distractors (e.g. in Barrouillet et al., 2009, two conditions presented 12 stimuli in 6000ms or 10000ms), which constitutes a possible extension of the present work. However, this contrived hypothesis seems unlikely given that resistance to interference generally shows a lesser role in the RDS task than pace (Barrouillet et al., 2013, 2018).

Task Specificity of Mechanisms of Working Memory

An important point of discussion is that it is possible that some of functions of attention control or processing speed contribute to variability in WMC in some tasks, but not in others. There are indeed substantial differences in the mechanisms at play between different types of tasks. For example, the complex span tasks usually used to measure WMC (Conway et al., 2005; Redick et al., 2012) require subjects to maintain memory traces in the face of very complex demands, such as checking math operations or interpreting complicated sentences. By contrast, tasks like the RDS used here (Lucidi et al., 2014) require subjects to perform a very simple concurrent task – reading digits out loud. It may be the case that processing speed does affect the effectiveness of reactivation in complex span tasks where complex cognitive processing is required, but not reactivation in tasks like the RDS where reading digits may be performed at similar speeds by all subjects. Therefore a possible extension of the present work would be to use a more diverse set of tasks – for example estimating WMC with something

other than complex spans. Given that complex spans were chosen for their high correlation and similar structure to the RDS (Lucidi et al., 2014), we are not necessarily optimistic that a larger relation with reactivation would be found with different measures, but this remains a possibility.

In the same logic, in tasks like the RDS, reactivation of memory traces also appears to play a relatively larger or smaller role, when compared to resistance to distractors, depending on the precise features of the task (Barrouillet et al., 2013, 2018). It is also noteworthy that the literature has repeatedly shown correlations between processing speed and WMC as measured with complex span tasks, but the relation between tasks like the RDS and processing speed has not been investigated. In other words, predictors of individual differences may be different in these types of tasks, so that attention control and processing speed do not contribute to performance in the same way.

The use of different experimental tasks by different research groups is another barrier that will need to be bridged. For all these reasons, we argue that fully understanding the workings of working memory and its place in cognition will require dedicated efforts to fractionate attention control and processing speed into component processes (Danthiir et al., 2005; Kovacs & Conway, 2016) and to precisely specify how these processes come into play into different types of working memory tasks. The present work, showing that variability in WMC is not critically related to variability in attention-based reactivation of memory traces, constitutes a step in that direction.

Open Practices Statement

The data and materials for Experiments 1 and 2 are available at <https://osf.io/nhakg/>

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