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Brief Report

Working memory in children: A time-constrained functioning similar to adults

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ABSTRACT

Within the time-based resource-sharing (TBRS) model, we tested a new conception of the relationships between processing and storage in which the core mechanisms of working memory (WM) are time constrained. However, our previous studies were restricted to adults. The current study aimed at demonstrating that these mechanisms are present and functional before adulthood. For this purpose, we investigated the effect on maintenance of the duration of the attentional capture induced by processing. In two experiments using computer-paced WM span tasks, 10-year-olds were asked to maintain letters while performing spatial location judgments. The duration of this processing was manipulated by varying either the discriminability between target locations or the contrast between targets and background. In both experiments, longer processing times resulted in poorer recall, as we observed previously in adults. These findings suggest that the core mechanisms of WM described by the TBRS model are already settled during childhood.

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Introduction

Working memory (WM) is a capacity-limited cognitive system devoted to the simultaneous maintenance and processing of information that plays a crucial role in complex cognitive activities as well as in many elementary ones (Barrouillet, Lépine, & Camos, 2008; Camos, 2008; Camos & Barrouillet, 2004; Kyllonen & Christal, 1990). It has often been argued that most of the differences in cognition.
between children and adults are due to children’s limitations in WM capacity (Case, 1985; Halford, 1993; Pascual-Leone, 1970). We recently proposed a new model of WM named the time-based resource-sharing (TBRS) model that puts forward a new conception of the relationships between processing and storage in which the core mechanisms are time constrained (Barrouillet, Bernardin, & Camos, 2004; Barrouillet & Camos, 2007). We verified the main assumptions of this model in adults (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Barrouillet et al., 2004), but it remains undetermined whether WM functioning presents the same characteristics and constraints in children. Thus, the current study addressed this question by testing in children the specific predictions of our model concerning the effect of time on WM.

The TBRS model is based on four main proposals. First, the two main functions of WM, which are the processing and maintenance of information, rely on the same limited attentional resource. Second, a bottleneck constrains central processes, allowing only one attention-demanding cognitive step to take place at a time. This sequential functioning of WM means that when attention is occupied by some processing episode, it is not available for the maintenance of memory items. Third, as soon as attention is switched away from maintenance to processing, the activation of the memory items suffers from a time-related decay and their memory traces fade away. Thus, a refreshment of these items is needed before their complete disappearance through reactivation by attentional focusing. Fourth, this sharing of attention is achieved through a rapid and incessant switching of attention from processing to maintenance occurring during short pauses that would be freed while concurrent processing is running. Following these assumptions, when the time allowed to perform the processing component of a WM span task is kept constant, any increase in the duration of the attentional capture this processing involves extends the period during which memory traces fade away, thereby resulting in a greater memory loss. This model leads to a new metric of the cognitive load involved by a given task as the proportion of time during which this task occupies attention.

To test these assumptions, we elaborated a new paradigm of computer-paced WM tasks that permits a careful control of time parameters. In these tasks, participants are presented with items to be recalled, for example, letters. After each letter, they need to perform an intervening task divided into atomic steps, with the duration of this task being controlled. In many experiments, we demonstrated that any increase in the cognitive load induced by this intervening task has a detrimental effect on concurrent maintenance and recall. For example, increasing the number of atomic steps, such as reading digits within a fixed time interval or reducing the time allowed to perform a fixed number of processing steps, resulted in poorer recall (Barrouillet et al., 2004). The most striking test of the TBRS model was to verify that a mere increase in the duration of each atomic processing step results in a memory loss even if the number and nature of processing steps, as well as the total time allowed to perform them, are kept constant. For this purpose, Barrouillet and colleagues (2007) used a task in which each letter was followed by eight stimuli consisting in a black square centered on one of two possible locations in either the upper or lower part of the screen. Adult participants were asked to judge the location of each square as quickly as possible by pressing appropriate keys. According to the TBRS model, longer response selections should be more disruptive on concurrent maintenance of information because they involve a longer occupation of the central bottleneck impeding other attention-demanding processes such as refreshment activities to take place. We manipulated the duration of the response selections by varying the distance between the two possible locations (either 5 or 68 mm apart). As we surmised, the close condition drastically diminished the targets’ discriminability and induced longer responses than did the distant condition (377 and 314 ms, respectively). As the TBRS model predicted, the longer attentional capture induced by the close condition had a detrimental effect on maintenance and resulted in poorer recall performance than did the distant condition (mean spans of 5.51 and 5.81, respectively). This finding lent strong support to the TBRS model by suggesting that longer processing episodes involve longer attentional capture, impeding the switching toward decaying memory traces and their refreshment.

However, Towse and Hitch (2006) cogently noted that the findings supporting the TBRS model are restricted to adults and that it is not clear that our interpretation would necessarily apply to children. We must admit that this remark is quite sound. Although we have studied children’s WM, we never specifically tested in children the central assumption of the TBRS model concerning time-related effects. Barrouillet and Camos (2001) observed in 9- and 11-year-olds that increasing the difficulty of
the processing component while keeping constant the time allowed to perform it resulted in lower WM span, but they did not address the precise mechanism underlying this trade-off. Gavens and Barr-ouillet (2004) extended these results by demonstrating that increasing the attentional demand of the processing resulted in lower span in 8- and 10-year-olds, but their work did not explore the specific effect of time on storage.

Even if the TBRS does not claim that children and adults must be alike, the model assumes that the core mechanisms of WM should be functional before adulthood. It is known that refreshing mechanisms such as articulatory rehearsal are not used before 7 years of age (Henry & Millar, 1993), and it is probably the same for the attentional refreshment hypothesized by the TBRS model. For example, simple span tasks constitute a reliable measure of WM in young children, suggesting that they do not use any strategy or refreshing mechanism to maintain information highly activated (Cowan et al., 2005). We recently obtained evidence that WM spans in children under 7 years of age are not affected by variations of the cognitive load involved by concurrent processing, indicating that the attentional refreshing mechanism is not yet efficient (Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, in press). However, at least from 7 years onward, we assume that the core mechanisms of WM should be functional and that the same factors should constrain adults’ and children’s WM. This conception is at odds with Towse and Hitch’s (Towse & Hitch, 1995; see also Hitch, Towse, & Hutton, 2001) model of WM in children. These authors assume that, in complex WM span tasks, there is no attempt to actively maintain the memory traces during processing and no attentional refreshing mechanism. Thus, recall performance does not depend on the cognitive load of the intervening task; rather, it merely depends on the delay of retention during which memory traces suffer from a time-related decay.

In the following experiments, we tested in 10-year-olds the pivotal prediction that any increase in the duration of the attentional capture involved by each step of the processing component of a WM span task results in a decrease in recall performance, although the total delay of retention during which memory decay could occur was kept constant. Experiment 1 aimed at replicating in children Barrouillet and colleagues’ (2007) finding reported above. Experiment 2 extended this result by introducing a new manipulation of the duration of the processing component of the task.

**Experiment 1**

This experiment aimed at replicating Barrouillet and colleagues’ (2007) Experiment 2 in which adults were asked to remember letters while performing series of response selections by judging the location of squares presented on either the upper or lower part of the screen. The duration of each response selection was manipulated by varying the discriminability of the two possible locations on which the squares appeared. In the current experiment, 10-year-olds were presented with the same task. The TBRS model predicts that longer response selections should result in poorer recall performance.

**Method**

**Participants**

Twenty-four French fifth graders (15 girls and 9 boys, mean age = 10 years 5 months, \(SD = 4\) months) from primary schools in Dijon, France, participated as volunteers.

**Material and procedure**

The material, the procedure, and the temporal characteristics of the tasks were the same as in Barr-ouillet and colleagues’ (2007) Experiment 2 except for the lengths of the to-be-remembered series of letters that were reduced to be adapted to children’s capacities. Children were seated approximately 60 cm from the laptop screen and were presented with series of one to five consonants. Each consonant was followed by a series of eight stimuli successively displayed on the screen. These stimuli consisted in a black square (side = 18 mm subtending 2° in visual angle) centered on one of two possible locations in either the upper or lower part of the screen. In the **distant** condition the two locations were 68 mm apart (6.5° in visual angle), whereas in the **close** condition this distance...
was reduced to 5 mm (0.5° in visual angle), thereby creating a 13-mm overlap between the two targets. For each length, 3 series of consonants were associated with each condition of discriminability of the location judgment task, resulting in a total of 30 series of consonants to be remembered that were presented to each participant according to two fixed random orders of presentation.

Each series began by a first screen indicating the condition and the number of letters to be remembered (e.g., “close squares / 3 letters”). After a 500-ms white screen, a ready signal (an asterisk) centered on the screen for 750 ms was followed by a 500-ms delay. Next, the first letter succeeded for 1500 ms. After a postletter delay of 500 ms, each of the eight squares of the location judgment task appeared for 667 ms and was followed by a 333-ms delay, resulting in a total of 1 s per stimulus. The subsequent consonant then appeared for 1500 ms, followed by the eight ensuing squares, and so on. At the end of each series, the word “rappel” (recall) was displayed on the screen. In each condition and each series, squares were randomly displayed in the upper and lower locations with the same frequency. Children were asked to read aloud each letter when it appeared, to judge the location of each square as quickly as possible without sacrificing accuracy by pressing either a left- or right-handed key for the lower and upper locations, respectively, and then to write down the remembered letters in correct order by filling out frames containing the appropriate number of boxes. Recall performance was computed as WM span scores in which each correctly recalled series counted as one third. The total number of thirds was added up to provide a span score (Barrouillet et al., 2004). For example, the correct recall of all the series of one and two letters and of one series of three letters resulted in a span of \((3 + 3 + 1) / 3 = 2.33\). Response time and accuracy during the location judgment task were also recorded.

A training phase familiarized participants with the location judgment task, with 104 stimuli in each experimental condition. Children heard a beep if they made a mistake or took too long to respond (i.e., more than 1 s). If children did not reach 80% of correct responses, they were asked to perform the same series of squares again with a maximum of three training phases. Before the experimental session itself, they performed the WM task with three series of letters and stimuli to be processed: “close squares / 1 letter,” “distant squares / 3 letters,” and “close squares / 2 letters.”

Results and discussion

All of the children reached the 80% criterion during the training phase and took part in the experimental session. As we anticipated, the close condition elicited longer response times than did the distant condition (488 ms, SD = 36, and 431 ms, SD = 51, respectively), \(t(23) = 7.83, d = 1.27, p < .001\), and also fewer correct responses (66%, SD = 9, and 89%, SD = 10, respectively), \(t(23) = 12.47, d = 2.57, p < .001\). As we predicted, these longer processing times had a disruptive effect on recall. The close condition resulted in poorer WM span than did the distant condition (2.86, SD = 0.65, and 3.39, SD = 0.75, respectively), \(t(23) = 3.88, d = 0.75, p < .001\).

Thus, this experiment extended to children the findings observed previously in adults. As in adults, decreasing target discriminability induced longer response times and resulted in lower recall performance. As predicted by the TBRS model, the increase in the duration of the attentional capture involved by the close condition had a detrimental effect on concurrent maintenance of verbal information. The fact that this close condition also elicited a higher rate of errors does not question this conclusion. More errors in the close condition could only reflect less attention paid to the intervening task and, thus, more attention available to maintain memory items, a trade-off that would run counter to our hypothesis.

Experiment 2

To strengthen the results of the previous experiment, we tested the same hypothesis of a time-related effect on maintenance using another experimental manipulation inspired from Liefooghe, Barrouillet, Vandierendonck, and Camos (2008). In that study, adults were asked to perform either parity or magnitude judgment on series of digits presented sequentially during each interletter interval. In one condition, the duration of these judgments was increased by a stimulus degradation.
through the addition of a visual noise to the digits displayed on the screen. In line with studies suggesting that stimulus degradation puts special demands on attention (e.g., Heitz & Engle, 2007; Lu & Dosher, 1998), this stimulus degradation should lengthen the capture of attention involved in recognizing and processing each digit and, thus, should have a damaging effect on concurrent maintenance. As we predicted, the longer response times induced by this degradation yielded lower recall performance.

Similarly, in the current experiment, the response times of the location judgment task used in Experiment 1 were increased by presenting visually degraded squares. For this purpose, the distant condition was presented with either normal or degraded stimuli. As in Experiment 1, we predicted that the condition inducing longer processing times should result in lower spans.

Method

Participants

A total of 28 French fifth graders (17 girls and 11 boys, mean age = 10 years 8 months, SD = 3 months) from primary schools in Dijon participated as volunteers. None of them participated in the previous experiment.

Material and procedure

The material and procedure were the same as in the previous experiment except for the stimuli to be processed in the concurrent task. Children needed to maintain series of one to five letters while performing a location judgment task in which the two possible locations of squares were always 68 mm apart, as in the distant condition of the previous experiment. Squares appeared on a gray background prepared with Microsoft PowerPoint 2004 software (luminosity level of 50%). In the normal condition squares appeared in black (luminosity level of 0%), whereas in the degraded condition they were gray with 1% of luminosity added to the gray background (luminosity level of 51%). Span scores, response time, and accuracy in the location judgment task were recorded as in the previous experiment.

Results and discussion

All of the children reached the 80% criterion during the training phase and took part in the experimental session. Our manipulation was successful, and response times were longer for degraded stimuli than for normal stimuli (502 ms, SD = 52, and 431 ms, SD = 45, respectively), t(27) = 9.55, d = 1.47, p < .001. Even if the degraded condition was slightly more difficult than the normal condition, children achieved a good rate of correct responses in both conditions (87%, SD = 7, and 91%, SD = 5, respectively), t(27) = 3.58, d = 0.62, p < .01. As we predicted, the condition that elicited the longer processing times resulted in significantly lower spans (3.30, SD = 0.83, and 3.58, SD = 0.72, for the degraded and normal conditions, respectively), t(27) = 2.19, d = 0.37, p < .05. As predicted by the TBRS model, the longer attentional capture induced by the visual search of degraded stimuli disrupted concurrent maintenance. Thus, as we observed in Experiment 1, the manipulations that affect adults’ WM performance had similar effects in children, and increasing the processing time resulted in a significant memory loss.

General discussion

In two experiments, we showed that factors that affect WM functioning in adults have a similar impact in children. As we observed in adults, even small increases in the duration of response selections had a disruptive effect on concurrent maintenance and resulted in poorer recall performance. These facts suggest that, at least from 10 years of age onward, WM has the same time-constrained functioning in children as in adults (Barrouillet et al., 2007). Processing and maintenance share a common supply in a time-based competition. When attention is occupied by processing episodes, it is no longer available to refresh memory traces that inescapably decay through time. Their maintenance requires switching attention from processing to storage.
Moreover, the size of the effect observed in Experiment 1 suggests that children suffer from a stronger temporal decay than do adults. The 57 ms of additional processing time per stimulus resulted in a reduction of 16% ($d = 0.75$) in recall performance compared with 5% ($d = 0.29$) in adults (Barrouillet et al., 2007, Experiment 2) for approximately the same extra processing time (63 ms). This difference could also be due, at least in part, to less efficient refreshing mechanisms when attention is available or to a lower capacity to adaptively switch attention from processing to storage. Overall, our results suggest that the developmental changes from childhood to adulthood affect the efficiency of the mechanisms implicated in processing, storage, and their coordination rather than the structure and the core functioning of WM that remain unchanged.

It is worth noting that most of the current models of WM have difficulties in accounting for the current results. The detrimental effect of visuospatial processing on verbal maintenance is incompatible with a multicomponent view of WM that assumes separate resources for verbal and visuospatial domains (e.g., Baddeley, 1986). Furthermore, our findings are at odds with models such as Oberauer and Kliegl (2006), assuming that the interference phenomenon is the unique source of forgetting in WM. It is actually quite difficult to conceive that representation-based interference could be responsible for the effects we observed. Indeed, it cannot be assumed that representations of locations of squares share common features that could overlap with phonological representations of letters. It seems definitely improbable that mere reduction in luminance contrast, as in Experiment 2, would increase the level of interference between these representations. Similarly, we cannot imagine what kind of process-based interference could occur between judging spatial locations and maintaining letters and could lead to the observed memory loss. The simplest way to account for these phenomena is to assume that processing visuospatial information and maintaining phonological material rely on the same general resource, as the TBRS model assumes. Moreover, discarding any interference account leads to assuming that there is a time-related decay of memory traces responsible for forgetting in WM in adults as well as in children.

This time-related forgetting, which is particularly pronounced in children, echoes frequent proposals about the role of WM in children’s performance and cognitive development. It has often been assumed that the limitation in children’s cognitive performance is due to their relative incapacity to maintain a large amount of relevant information while performing concurrent activities. The use of slow algorithmic strategies in arithmetic problem solving increases the probability of forgetting the operands involved and jeopardizes the learning of operand–answer associations in long-term memory (Barrouillet, Mignon, & Thevenot, 2008; Geary, 1993). Releasing the constraint related to a fast decay of memory traces is probably one of the main factors of WM, as well as cognitive development, by either a greater efficiency of refreshment mechanisms, a higher ability to control attention allocations between processing and storage, or an endogenous diminution in the speed of decay. Future studies should enlighten the respective roles of these different factors.

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