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The hard fall effect: High working memory capacity leads to a higher, but less robust short-term memory performance

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Abstract

Participants with a high working memory span tend to perform better than low spans in a variety of tasks. However, their performance is paradoxically more impaired when they have to perform two tasks at once, a phenomenon that could be labeled the "hard fall effect". The present study tested whether this effect exists in a short-term memory task, and investigated the proposal that the effect is due to high spans using efficient facilitative strategies under simple task conditions. Ninety-eight participants performed a spatial short-term memory task under simple and dual task conditions; stimuli presentation times either allowed for the use of complex facilitative strategies or not. High spans outperformed low spans only under simple task conditions when presentation times allowed for the use of facilitative strategies. These results indicate that the hard fall effect exists on a short-term memory task and may be caused by individual differences in strategy use.

Keywords : working memory ; individual differences ; dual tasking ; strategy use ; hard fall effect

Working memory (WM) is traditionally defined as the simultaneous storage and processing of information. A central feature of WM is its strong relationship with attentional abilities. Indeed, participants with a high score on a WM task (high spans) consistently demonstrate better attentional abilities than those with a low score (low spans; for a review, see Engle & Kane, 2004).

Additionally, it is known that attentional abilities allow us to perform two tasks at once, a situation often called “dual tasking”. The reason is that performing two tasks simultaneously requires attention to be divided between these two tasks (Baddeley, 1996). One might therefore predict that high spans should be little affected by dual tasking, because of their higher attentional abilities; on the other hand, low spans should be comparatively hurt more by this situation.

Surprisingly, empirical results show the exact opposite: the performance of high spans decreases more from simple to dual task conditions than that of low spans. For example, high spans are less affected by proactive interference than low spans under simple task conditions, but neither group shows a difference in performance under dual task conditions (Kane & Engle, 2000). This suggests that high spans use their attentional abilities to resist interference in the absence of a dual task, and that this resistance is suppressed by the concurrent attentional load under dual task conditions. This study illustrates what could be conveniently labeled the "hard fall effect", defined as a larger decrease of performance from simple to dual task conditions for those participants who are more efficient under simple task conditions. In other words, the higher the WM capacity (WMC), the larger the price to pay under dual task conditions.

The authors who have reported this hard fall effect typically explain it as a difference in the use of facilitative strategies¹ under simple task conditions. This hypothesis has been formulated, for example, in a study observing a hard fall effect in high and low span adult

participants performing a verbal fluency task (Rosen & Engle, 1997; Experiment 2). The authors argued that high spans use their superior attentional abilities to improve their fluency performance under simple task conditions, by sustaining a strategic generation of word exemplars that leads them to be more efficient. This facilitative strategy would no longer be feasible in dual task conditions due to the disruption of attentional abilities, with the consequence of a reduced efficiency for high spans. Low spans, on the contrary, would not use facilitative strategies under simple task conditions because of lower attentional abilities; in turn, dual tasking would have little impact on their performance.

A similar example comes from a developmental study revealing that the hard fall effect exists in children (Ang & Lee, 2010). Indeed, while older children perform better in a visual memory task, their performance decreases more when dual tasking than that of younger children; according to the authors, younger children may be viewed as low spans and older children as high spans. The authors adopted the same line of thought as Rosen and Engle (1997) and suggested that older children, but not younger children, engage their attentional abilities to implement facilitative mnemonic strategies under simple task conditions (e.g., using their fingers to mark spatial positions).

Although all of these authors assumed the hard fall effect to be caused by a differential use of strategies under simple task conditions, a single study has directly assessed this hypothesis within the dual task framework (Schelble, Therriault, & Miller, 2012). A hard fall effect was observed in a verbal fluency task with adult participants. Verbal reports indicated that in simple task conditions, high spans used a more efficient strategy than low spans to retrieve animal exemplars (resorting to their scientific classification); this difference in efficient strategy use disappeared under dual task conditions, with all participants using less efficient strategies. This result suggests that the greater performance decrease for high spans may be directly related to their use of an efficient strategy under simple task conditions.

An additional piece of evidence comes from data on the "choking under pressure" effect. This effect has been defined as performing more poorly than expected given one's skill level (Beilock & DeCaro, 2007), because of some sort of "pressure" (e.g., stressful scenarios like peer pressure or monetary incentives). High-pressure situations disrupt attentional abilities, similar to dual task conditions; results comparable to the hard fall effect are observed within the choking under pressure framework (Beilock & Carr, 2005; Gimmig, Huguet, Caverni, & Cury, 2006; Beilock & DeCaro, 2007). In one experiment, high and low span participants were asked to solve complex math problems either in high-pressure or low-pressure situations (Beilock & DeCaro, 2007). To correctly solve the math problems, the most efficient strategy was to use computationally demanding algorithms. The authors observed that under low-pressure conditions, high spans used these algorithms and showed greater performance. Low spans used simpler shortcuts and showed poorer performance. However, all participants used the shortcuts under high-pressure conditions and showed poorer performance. In other words, the high-pressure situation led high spans to make use of less complex – and less efficient – strategies.

In summary, experimental studies consistently report the counter-intuitive observation that high spans, despite their better attentional abilities, are more affected by dual tasking than low spans². This effect is attributed to individual differences in strategy use, with high spans using more efficient strategies only under simple task conditions.

The present study had two goals. Our first goal was to test whether the hard fall effect exists in an adult sample when a short-term memory task is involved. The hard fall effect has only been investigated in a handful of situations: six studies were conducted with adult samples and involved verbal fluency tasks (Rosen & Engle, 1997; Schelble et al., 2012), a proactive interference task (Kane & Engle, 2000), a fluid intelligence task (Gimmig et al., 2006) and numeric cognition tasks (Beilock & Carr, 2005 ; Beilock & DeCaro, 2007); a single

study was conducted with memory tasks and involved a child sample (Ang & Lee, 2010). In other words, the hard fall effect has never been observed in an adult sample with a memory task.

While it has never been tested, it is likely that a hard fall effect will emerge on a short-term memory task. Firstly, it is well-known that the use of efficient strategies, such as semantic elaboration, grouping or imagery, is related to performance on both short-term memory tasks (e.g., DeMarie & Ferron, 2003) and working memory tasks (Bailey, Dunlosky, & Kane, 2008; Dunlosky & Kane, 2007; McNamara & Scott, 2001; Turley-Ames & Whitfield, 2003). Secondly, individual differences in WM are related to individual differences in strategy use on various memory tasks: high spans tend to use effective strategies more often than low spans on both short-term memory tasks (McNamara & Scott, 2001) and working memory tasks (Study 2, Bailey, Dunlosky, & Kane, 2011; Study 2, Kaakinen & Hyönä, 2007). In other words, it seems that using efficient strategies leads to a better performance on memory tasks, and that high spans process to-be-remembered information more strategically. If this is the case, then these strategies should be disrupted by dual tasking and the hard fall effect should appear in a short-term memory task, similar to a high-level cognitive task.

Our second goal was to experimentally investigate the hypothesis that the hard fall effect reflects individual differences in strategy use, by directly manipulating the feasibility of implementing strategies. Indeed, all the studies we have reviewed investigated strategy use either indirectly by drawing inferences from participants' response patterns, or more directly with verbal report – asking participants what they did during the task. While both these approaches are perfectly valid, we believe they would benefit from more experimental evidence.

A method consistently used in the literature to experimentally study strategic behavior relies on time constraints. It can be hypothesized that implementing facilitative strategies

requires time; semantic elaboration, for example, would require some processing time to convert a phonological representation into a semantic representation. Consequently, several studies have tried to disrupt strategy use by limiting the time allowed for information processing (e.g., Lépine, Barrouillet, & Camos, 2005; Friedman & Miyake, 2004; St Clair-Thompson, 2007). The authors observed that placing such a time constraint on a working memory task tends to decrease span scores, which suggests that implementing facilitative strategies does require time. It is therefore possible to study the role of strategies by manipulating processing times on a memory task.

In the present study, a sample of adult participants completed a spatial short-term memory task as well as a working memory task. In order to test our first hypothesis, the existence of a hard fall effect in a short-term memory task, the participants performed the task under both simple and dual task conditions. We expected to observe a classical hard fall effect, with a higher WMC being associated with a larger decrease in performance from simple task to dual task. Our second hypothesis, the idea that the hard fall effect is caused by strategy use, was tested by manipulating presentation times on the short-term memory task so as to create a time constraint. The hard fall effect was expected not to emerge when presentation times were constrained; indeed, if the hard fall effect does depend on efficient strategy use by high spans under simple task conditions, then the effect should appear only if processing times do allow for the implementation of facilitative strategies.

Method

Participants

Ninety-eight undergraduates from the University of Savoie participated for course credit (Mean age = 21.1 years , $SD = 5.2$ months; 81 females and 17 males). All participants had normal or corrected-to-normal vision and none of them had a color perception deficiency. They all gave informed consent prior to completing the experiment.

Materials

WMC was assessed with a French version of the Automated Operation Span (AOSpan; adapted from Unsworth, Heitz, Schrock, & Engle, 2005). The primary task was a Spatial Colors Location Task (SCLT). Random Number Generation (RNG) was used as a secondary task, in line with a large number of dual task studies (Hegarty, Shah, & Miyake, 2000).

Automated Operation Span. The AOSpan, a type of complex span task, was used to measure WMC. The task was translated and adapted from Unsworth et al. (2005), and implemented under the software E-prime (Schneider, Eschman, & Zuccolotto 2002). Participants were to remember series of letters while solving mathematical operations. Each trial started with a display presenting an equation (e.g., " $3 + 9 = 12$ "); the participants were to decide whether this equation was correct or not. The next display presented a letter that had to be memorized for later recall. This operation-letter sequence repeated a variable number of times. At the end of the trial, the participant had to recall all letters in the correct order. The task began with a short training sequence: participants completed three trials without the operations (length 3), solved 15 operations without remembering letters, and completed three more trials with both letters and operations (length 3). The task presented up to 15 trials of increasing difficulty – from three to seven letters in a trial, with three trials per difficulty level. The task was interrupted when participants failed either two or all three trials in a level (contrary to Unsworth et al., 2005). Participants' scores were computed as the sum of the average number of correctly recalled letters per difficulty level (equivalent to a partial-credit load scoring; Conway, 2005). Participants who correctly answered less than 85% of operations on the AOSpan were excluded from data analysis (Unsworth et al., 2005).

Spatial colors location task. The SCLT was the primary task of interest, from which the performance variations between simple and dual task conditions were calculated.

Participants were asked to recall patterns of colored squares presented within a 5x5 matrix. Colored squares were used instead of simpler stimuli because the hard fall effect is typically observed only when the task is sufficiently difficult (Beilock & Carr, 2005; Beilock & DeCaro, 2007). Presentation times were either 500 ms or 3000 ms. The colors of all squares in a pattern were derived from a single color palette (randomly assigned to each trial), and each square's color was randomly selected among 6 shades of this initial color. At the end of each pattern presentation, the participants were asked to put back colored squares (aligned at the bottom of the screen) in their correct locations (see Figure 1 for an overview of the procedure). Participants were given feedback on their performance at the end of each trial. There were three sequential difficulty levels. The difficulty level increased progressively from three to five colored squares to remember at the same time, with six trials per difficulty level. Each participant completed all trials. Participants' scores were computed as the mean proportion of colored squares correctly replaced across all trials. This scoring method was chosen because it provided the largest range of scores and the distribution closest to normal.

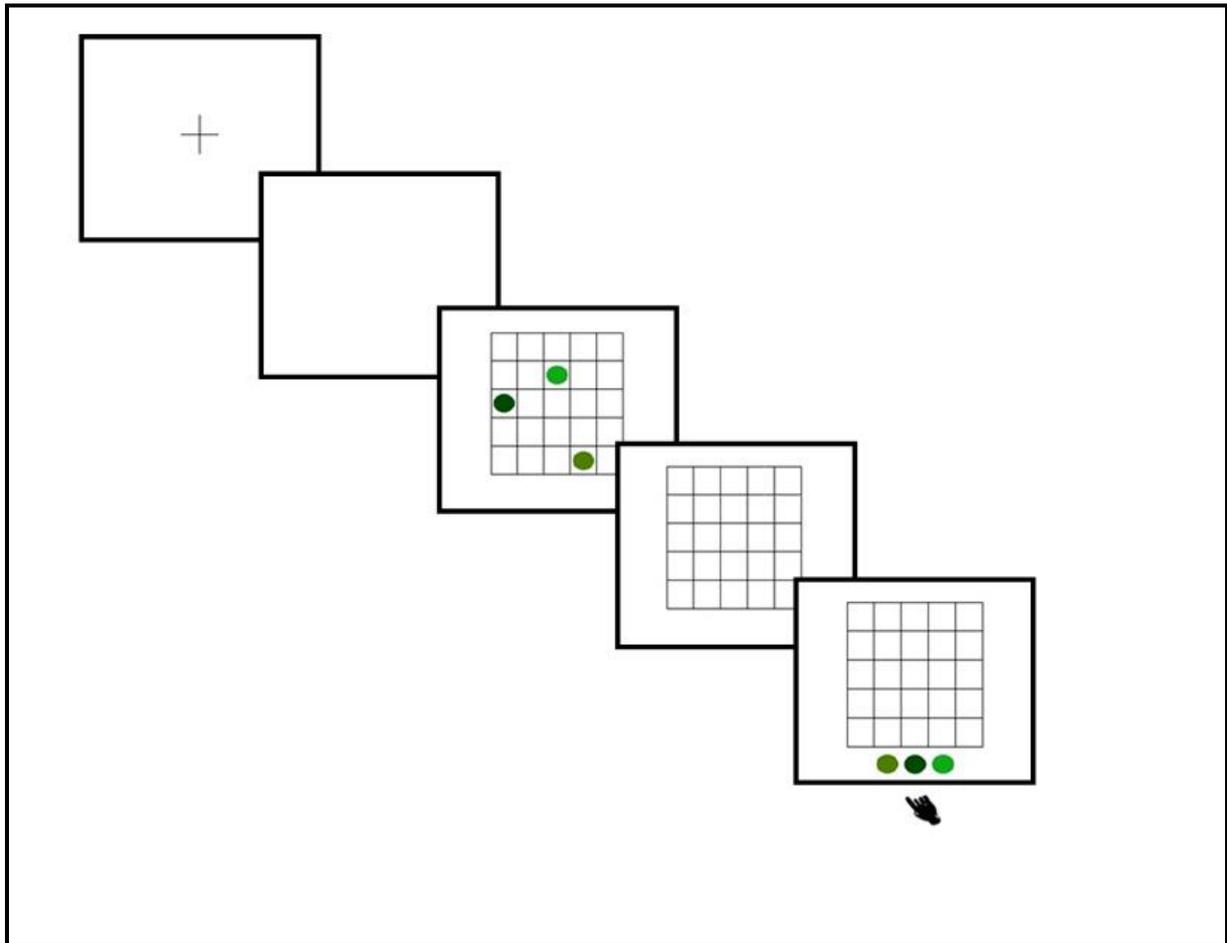


Figure 1. Time course for a level three trial in the Spatial Colors Location Task.

Random number generation (RNG). The RNG task required participants to verbally produce series of random digits. The production was to follow the pace of a metronome (40 bpm). The score on this task was an estimation of the degree of randomness of responses (see Appendix 1 for further information on the scoring method).

Procedure

The experiment lasted approximately 45 minutes. Participants completed the tasks individually. The first task was the AOSpan, followed by two minutes of RNG which provided a baseline RNG score. Participants were then randomly assigned to either the short (500 ms) or the long (3000 ms) presentation time condition of the SCLT. They first completed the SCLT under dual task conditions, while simultaneously performing the RNG task – the RNG started with the first SCLT trial and ended after the last trial was completed. After a

short break, participants completed the SCLT under simple task conditions. All participants completed the dual task before the simple task, with the idea that completing the simple task first would have allowed strategies to develop and transfer to the dual task. Given that it should be difficult for participants to develop facilitative strategies under dual task conditions, the fixed order should limit this problem.

Design

The design was a 2 (presentation time) x 2 (task conditions) x 3 (difficulty level) mixed-model, with presentation time (500 ms, 3000 ms) as a between-subjects variable, and task conditions (simple task, dual task) and difficulty level (three squares, four squares, five squares) as within-subjects variables. WMC was treated as a continuous variable.

Results

Seven participants were excluded from the data analysis because they did not meet the accuracy criterion on the AOspan. The final sample included 91 participants ($N = 46$ for the short presentation time condition, and $N = 45$ for the long presentation time condition). All statistical tests presented here used the linear general model; this type of analysis is mathematically equivalent to a regression or an ANOVA, except that it allows to simultaneously model the effects and interactions of categorical and continuous variables. In all following analyses, presentation time, task conditions and difficulty level were treated as categorical variables, and WMC was treated as a continuous variable. Descriptive statistics are available for short presentation times (see Table 1) and for long presentation times (see Table 2).

Table 1. Descriptive statistics for all variables in the short presentation time condition.

Variable	Mean	SD	Range	Skewness	Kurtosis
Working memory score	56.57	11.60	29–75	-0.63	-0.32
SCLT Simple task – LV3	0.62	0.14	0.33–0.94	0.17	-0.43
SCLT Simple task – LV4	0.45	0.13	0.04–0.71	-0.23	0.94
SCLT Simple task – LV5	0.28	0.10	0.07–0.57	0.20	0.38
SCLT Dual task – LV3	0.34	0.16	0.06–0.83	0.27	0.62
SCLT Dual task – LV4	0.23	0.11	0.00–0.46	0.33	-0.19
SCLT Dual task – LV5	0.15	0.07	0.00–0.37	0.33	0.67

Note. LV3 = lower level of difficulty (length 3); LV4 = intermediate level of difficulty (length 4); LV5 = higher level of difficulty (length 5). $N = 46$.

Table 2. Descriptive statistics for all variables in the long presentation time condition.

Variable	Mean	SD	Range	Skewness	Kurtosis
Working memory score	55.40	12.66	27–75	-0.59	-0.70
SCLT Simple task – LV3	0.81	0.15	0.44–1.00	-0.89	0.23
SCLT Simple task – LV4	0.64	0.14	0.38–0.92	0.16	-1.03
SCLT Simple task – LV5	0.42	0.15	0.17–0.73	0.43	-0.48
SCLT Dual task – LV3	0.43	0.21	0.06–0.94	0.33	-0.19
SCLT Dual task – LV4	0.31	0.14	0.00–0.67	0.42	0.51
SCLT Dual task – LV5	0.17	0.10	0.03–0.47	0.95	0.92

Note. LV3 = lower level of difficulty (length 3); LV4 = intermediate level of difficulty (length 4); LV5 = higher level of difficulty (length 5). $N = 45$.

Preliminary Analyses

The first set of preliminary analyses focused on sequentially testing the main effect of each variable of interest on SCLT performance, by collapsing the data over the other conditions. Overall, there was a main effect of presentation time; long presentation times elicited a higher performance than short presentation times on the SCLT, $F(1, 85) = 53.01$, $MSE = 28152.4$, $p < .001$, $\eta_p^2 = .38$. There was also a main effect of difficulty level, with performance decreasing as difficulty increased, $F(2, 170) = 298.72$, $MSE = 21891.3$, $p < .001$, $\eta_p^2 = .78$. The classic negative impact of dual tasking on performance compared with simple task was reflected as a main effect of task conditions, $F(1, 85) = 454.12$, $MSE = 17502.2$, $p < .001$, $\eta_p^2 = .84$. Lastly, performance on the SCLT increased with WMC, $F(1, 85) = 16.42$, $MSE = 28152.4$, $p < .001$, $\eta_p^2 = .16$.

Any effects of interest on the SCLT could be caused by differences in WMC or RNG performance between the experimental conditions. Consequently, the second set of preliminary analyses aimed to test the effect of experimental conditions on these variables. First, the distribution of WMC scores in the short presentation time condition ($M = 56.57$, $SD = 11.60$) was similar to the distribution of WMC scores in the long presentation time condition ($M = 55.40$, $SD = 12.66$), $t < 1$, *ns*. In other words, there were no sample differences across presentation time conditions that could have subtended an effect of presentation time. Second, there were no interactions between experimental conditions and WMC for performance on the RNG task (see Appendix 1). Therefore, the results observed on the SCLT are unlikely to be caused by a differential impact of dual tasking or presentation times on the RNG task for low span and high span participants.

First hypothesis: the hard fall effect exists in a short-term memory task

We hypothesized that a hard fall effect would appear on the SCLT, with performance decreasing more from simple task to dual task conditions for participants with a higher WMC.

In other words, we expected an interaction between WMC and task conditions. This first hypothesis was tested with a 2 (task conditions) x WMC design; given that no hard fall effect should emerge with a short presentation time, the analysis was restricted to the long presentation time condition. The hard fall effect has been shown to exist only when the task is difficult enough (Beilock & Carr, 2005; Beilock & DeCaro, 2007); consequently, the analysis was further broken down by level of difficulty.

For the highest level of difficulty, we observed the expected interaction between WMC and task conditions, $F(1, 42) = 7.93$, $MSE = 4976.62$, $p = .01$, $\eta_p^2 = .16$. The same interaction was not significant for either the intermediate level of difficulty, $F < 1$, *ns*, or the lowest level of difficulty, $F < 1$, *ns*. In other words, a hard fall effect appeared with a long presentation time, but only on the highest level of difficulty. A performance decrease from simple task to dual task was calculated as the difference between both scores; for the highest difficulty level, this performance decrease was larger with a higher WMC, $r(44) = .39$, $p = .007$, congruent with our hypothesis. Performance on the SCLT was related to WMC under simple task conditions, $r(44) = .46$, $p = .001$ (see Figure 2), but not under dual task conditions, $r(44) = .03$, $p = .86$ (see Figure 3).

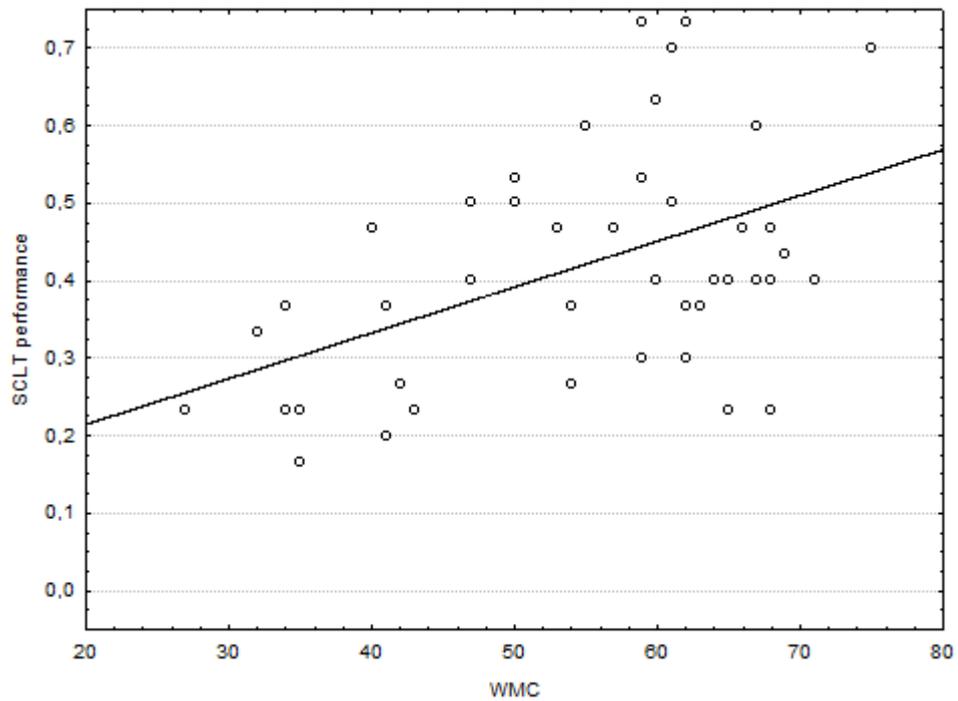


Figure 2. Percentage of colors correctly replaced as a function of WMC under a long presentation time and simple task conditions. The analysis is restricted to the highest difficulty level. $N = 44$.

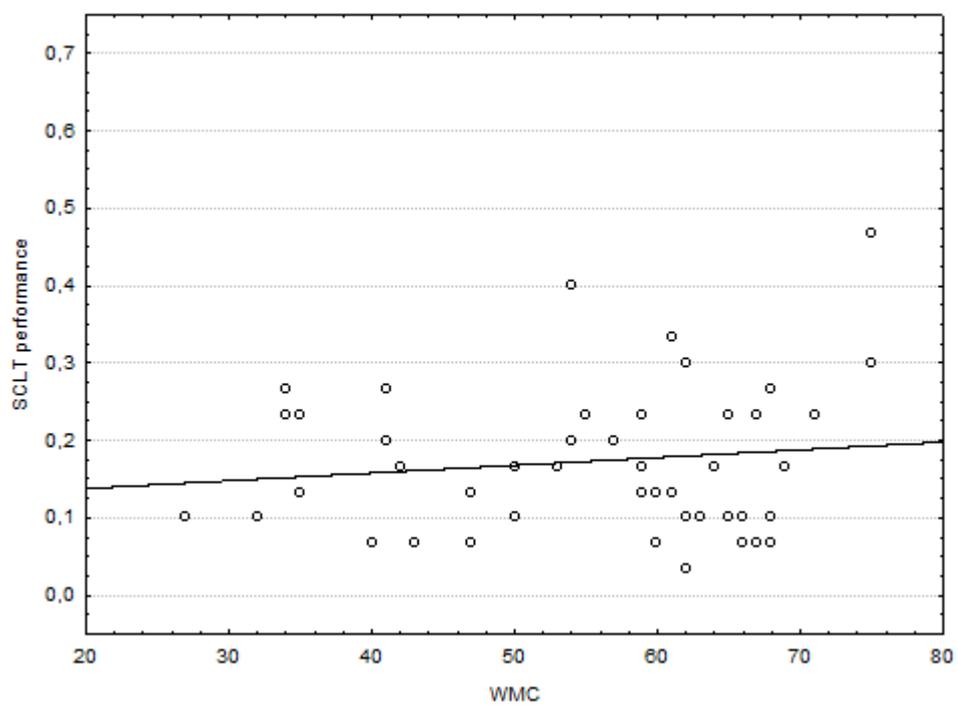


Figure 3. Percentage of colors correctly replaced as a function of WMC under a long presentation time and dual task conditions. The analysis is restricted to the highest difficulty level. $N = 44$.

Second hypothesis: the hard fall effect depends on the feasibility of strategies

We expected that the hard fall effect would only emerge when presentation time allowed for the implementation of facilitative strategies. The analysis for this second hypothesis used a 2 (presentation time) x 2 (task conditions) x WMC design. Given that no hard fall effect appeared on the two lower levels of difficulty, the analysis was restricted to the highest level.

We observed a significant three-way interaction between WMC, task conditions and presentation time, $F(1, 85) = 3.83$, $MSE = 7931.2$, $p = .05$, $\eta_p^2 = .04$; in other words, the hard fall effect did depend on presentation time. Although a hard fall effect appeared for long presentation times, the interaction between WMC and task conditions was not significant for short presentation times, $F < 1$, *ns*. Congruent with our hypothesis, a higher WMC was not associated with a larger performance decrease from simple task to dual task with a short presentation time, $r(43) = .02$, $p = .87$. Performance on the SCLT was not related to WMC, either under simple task conditions, $r(43) = .09$, $p = .56$ (see Figure 4), or under dual task conditions, $r(43) = .11$, $p = .46$ (see Figure 5).

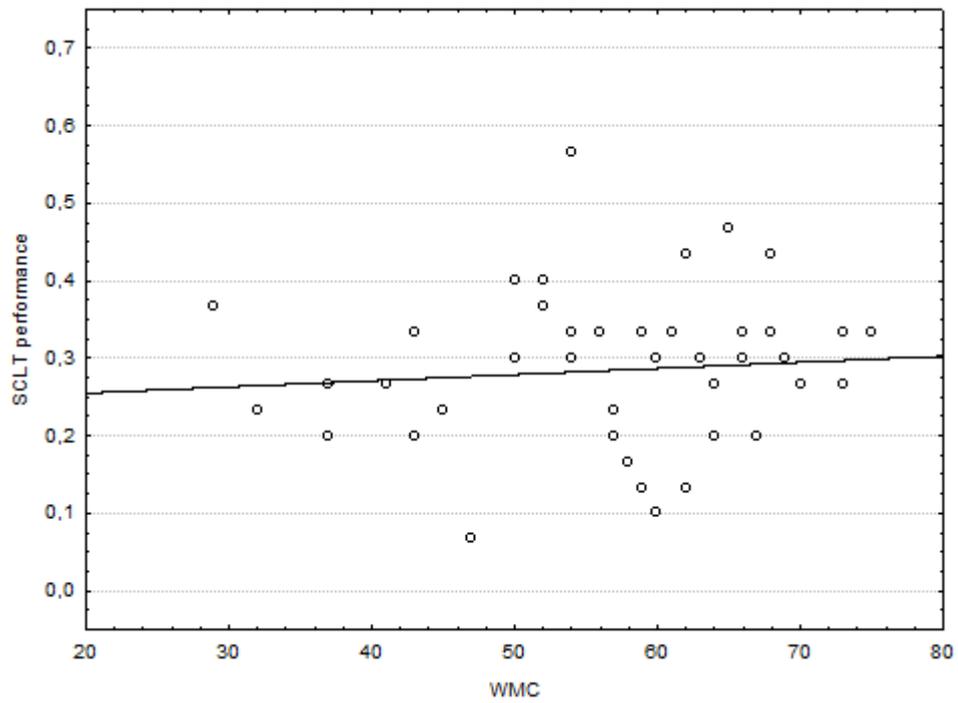


Figure 4. Percentage of colors correctly replaced as a function of WMC under a short presentation time and simple task conditions. The analysis is restricted to the highest difficulty level. $N = 43$.

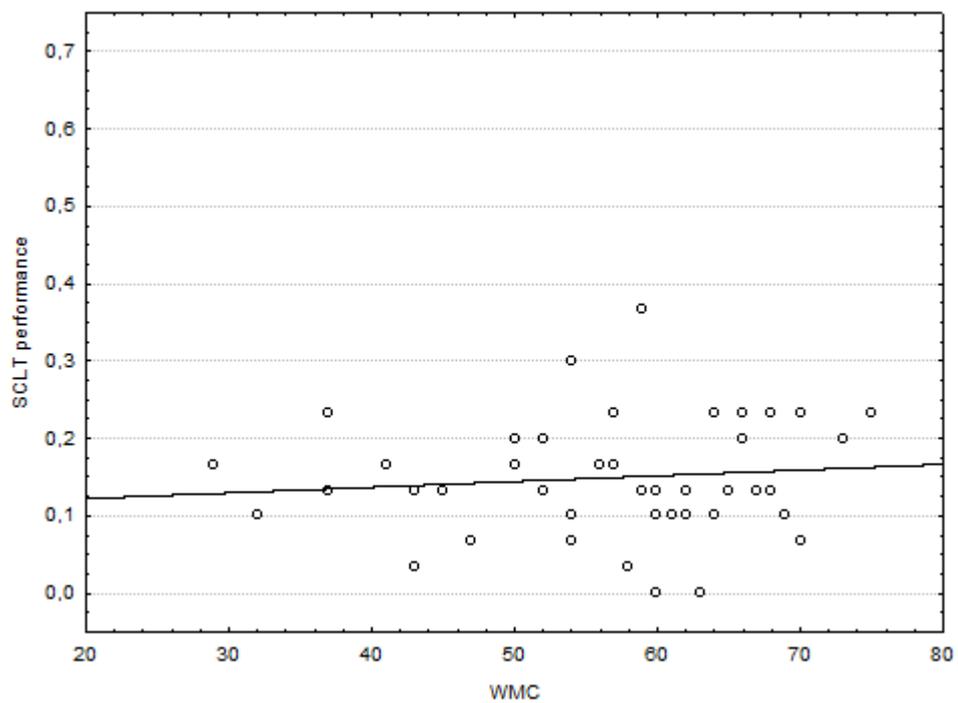


Figure 5. Percentage of colors correctly replaced as a function of WMC under a short presentation time and dual task conditions. The analysis is restricted to the highest difficulty level. $N = 43$.

Discussion

This study aimed to investigate whether the hard fall effect exists in a short-term memory task for adult participants, and whether the hard fall effect is attributable to individual differences in strategy use. On the highest difficulty level of a spatial short-term memory task, the performance of high spans decreased more from simple task to dual task conditions than the performance of low spans, indicating the presence of a hard fall effect. This effect only existed when presentation times allowed for the implementation of facilitative strategies, suggesting that the hard fall effect is indeed subtended by strategy use. In summary, our results provide evidence that high spans, but not low spans, tend to engage in facilitative strategies on a memory task. These results are a step towards understanding the differences in behavior as a function of WMC. Importantly, they suggest that quantitative differences (high spans have higher attentional abilities) are associated with qualitative differences in processing (high spans use different strategies).

Understanding the nature of these qualitative differences in processing in the context of our experiment is quite challenging. It is known that the more efficient strategies used by high span participants in verbal memory tasks are semantic in nature (McNamara & Scott, 2000; Study 2, Bailey, Dunlosky, & Kane, 2011; Study 2, Kaakinen & Hyönä, 2007); this includes sentence generation, mental imagery, or relating the items to events of personal significance. However, these strategies seem hardly applicable to the non-significant spatial items in the SCLT. Likewise, the use of overt verbal strategies such as verbal coding seems unlikely, because the SCLT used items presenting shades of the same color, making it difficult to rely on verbal codes. Little is known about the nature and specificities of

facilitative strategies in spatial memory tasks, making it difficult to propose other alternatives. One well-known spatial encoding strategy is chunking, the process of dividing spatial sequences into smaller blocks to facilitate encoding and improve performance (St Clair-Thompson, 2007). Since this strategy is recognized to be efficient for spatial memory tasks, it is possible that a higher WMC is associated with more efficient chunking strategies.

Why should higher attentional abilities lead to the use of more efficient strategies? It is often proposed that one of the central features of attention control is the ability to actively maintain a task goal (Kane & Engle, 2003). This goal maintenance ability may play a central role in strategy use: because facilitative strategies require time and effort to be implemented, it is possible that maintaining the task goal in a state of high activation over the course of the experimental session allows high spans to implement more complex strategies to reach this goal, and to carry out these strategies consistently. Conversely, failing to maintain the task goal would lead low spans to carry out simpler strategies that require less constant attention.

The fact that the hard fall effect only existed for the highest difficulty level in our experiment is congruent with data from the choking under pressure framework, which evidences that the hard fall effect only emerges when the task is sufficiently difficult (Beilock & Carr, 2005; Beilock & DeCaro, 2007). Several reasons could explain why the hard fall effect does not emerge in the easier conditions: it is possible that the lower difficulty allows the low spans to perform well even without using facilitative strategies; a more likely possibility is that under easier conditions, low spans are actually able to implement facilitative strategies because these require lesser attentional abilities. Indeed, low spans seem to be able to implement facilitative strategies, although they tend to do so less efficiently than high spans (e.g., McNamara & Scott, 2001; Turley-Ames & Whitfield, 2003).

Altogether, our results indicate that the hard fall effect exists in memory tasks, in addition to a wide range of high-level cognitive tasks. This implies that the relationship

between WM and strategy use may be a very general phenomenon, with high spans using facilitative strategies to enhance their performance on very different high-level cognitive tasks (including verbal fluency, Schelble et al., 2012; numeric cognition, Beilock & DeCaro, 2007; short-term memory, McNamara & Scott, 2001). This observation fits well with the view that WM relies on domain-general attentional abilities (Engle & Kane, 2004). It also raises the interesting possibility that the strong predictive utility of WM for many high-level cognitive tasks (Engle & Kane, 2004) is, in fact, related to strategy use: high span participants would be more efficient on a variety of complex tasks because they tend to implement more efficient strategies on these tasks.

This possibility may seem incompatible with several results indicating that strategy use does not mediate the relationship between WM capacity and high-level cognitive tasks (Dunlosky & Kane, 2007; Bailey, Dunlosky & Kane, 2011), and that controlling for strategy use even increases this relationship (Turley-Ames & Whitfield, 2003). However, these experiments have only studied facilitative strategies on the WM tasks used to classify participants – not on the high-level cognitive tasks themselves. In other words, these results do suggest that the relationship between WM capacity and complex tasks is not subtended by strategy use in WM tasks, but they tell us nothing about the role of strategy use in high-level cognitive tasks. It is therefore possible that the predictive utility of WM is related to strategy use in complex cognitive tasks, but not to strategy use in the WM task itself. This possibility is in line with the fact that strategy use does not seem to be transferable from one task to another (Bailey et al., 2008), which could explain why there is little connection between strategies on WM tasks and high-level cognitive tasks. Additionally, recent results show that the correlation between WM and performance on a verbal fluency task is significantly reduced when controlling for strategy use (Schelble et al., 2012). It might be interesting for

future studies to extend these results and test whether strategy use on other complex tasks underlies at least part of their correlation with WM.

In summary, we have provided evidence that the hard fall effect observed for high spans in various tasks can be observed in short-term memory tasks, and that this effect may rely on individual differences in strategy use. High spans seem to use facilitative strategies to enhance their performance, but dual tasking as well as time constraints impair this performance-increasing process. Thus, a greater performance decrement under dual task conditions does not necessary mean attentional difficulty, but may rather reflect higher attentional abilities.

Footnotes

¹ Little attempt has been made to assess the precise nature of facilitative strategies in the context of high-level cognitive tasks; it is likely that these strategies vary from task to task.

² Under dual task conditions, high spans no longer performed better than low spans in all reviewed studies but one (Ang & Lee, 2010).

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Appendix 1 : RNG analysis

RNG scoring method. Ten conventional randomness ratings for the RNG task were used. Eight were adapted from Sagaspe, Charles, Taillard, Bioulac, and Philip (2003) : *errors* (percentage of incorrect responses), *runs* (variability of the length of the ascending sequences), *coupon* (mean number of responses produced before all possible responses are given), *RNG* (index of randomization), *RNG2* (distribution of interleaved pairs), *adjacency combined score* (percentage of ascending or descending pairs or adjacent ciphers), *turning point index* (number of responses that mark a change between ascending and descending sequences), and *repetition gap* (measure of repetition performance). Two were adapted from Towse and Neil (1998): *PD* (measure of diagrams repetition) and *PS* (measure of stereotyped diagrams).

Each of the 10 random ratings was calculated on each participant's baseline RNG data. We conducted a Principal-Components Analysis (PCA) based on these ratings in order to (a) reduce their number and (b) check their validity. Three factors explaining 76,6% of variance were found. Taking into account only loads strictly superior to .70, *adjacency combined score*, *turning point index*, *runs* and *PS* loaded on the first factor called *Prepotent Associates*; *errors*, *coupon* and *repetition gap* loaded on the second factor called *Equality of Response Usage*; *RNG*, *RNG2* and *PD* loaded on the third factor called *Randomization*. This factorial structure is consistent with previous studies (Friedman & Miyake, 2004; Towse & Neil, 1998). A factorial score was calculated for all three factors for each participant, and these scores were used throughout the rest of the analysis.

RNG preliminary analysis. Using these three indicators, RNG data was analyzed to ensure that there were no unexpected interactions that may have subtended differences in the SCLT. The analysis was a 2 (presentation time) x 2 (task conditions) x WMC design; it was conducted for all three indicators. No interaction was observed between WMC and

presentation time, no interaction was observed between WMC and task, and no significant three-way interaction was observed (for *Prepotent Associates*, all $F_s < 1$ except the three-way interaction, $F(1, 82) = 1.19$, $MSE = 0.41$, *ns*; for *Equality of Response Usage*, all $F_s < 1$; for *Randomization*, all $F_s < 1$ except the interaction between WMC and presentation time, $F(1, 84) = 2.03$, $MSE = 1.20$, *ns*). In other words, the effects of task conditions and presentation time on RNG performance were comparable for low spans and high spans.

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