Testing the Dual-Component Account of Working Memory with a Serial Recognition Task

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***Abstract*- This study tested the dual-component model of working memory (WM) against its unitary alternative. The former account predicts that WM consists of two functionally distinct mechanisms: a very accessible but capacity-limited primary memory (PM) and a less accessible secondary memory (SM). The latter account assumes only one long-term memory component. We used a novel version of the Sternberg serial recognition paradigm, which selectively impedes access to either early or late items, by asking participants about the location of a probe in relation to either the end or the start of encoded memory set, respectively. When locations matched probes, our manipulation harmed recognition of early items, while it left late items intact, in the case of both latency and accuracy. However, in trials in which locations did not match probes, such an effect regarded only latency but not accuracy. This result suggests that a way of access to WM may depend on the level of conflict among accessed memory items. Finally, confirmatory factor analysis (CFA) revealed two distinct sources of variance in recognition accuracy. In total, our results are consistent with the dual-component view of WM, and they implicate that early items were presumably held in SM, while late items benefited from being held in PM.**

***Keywords*- Working Memory; Primary Memory; Secondary Memory; Serial Recognition**

I. INTRODUCTION

Unitary theories of human memory propose that all effects (e.g., recency/primacy) found in working memory (WM) tasks, namely the tasks that require the active maintenance and transformation of a few chunks of information crucial for a current goal, reflect differences in some parameter value, like activation [1] or the strength of information coding [2], within one and only system of long-term memory (LTM). These theories do not imply any dedicated short-term memory (STM) store.

On the contrary, dual-component accounts of WM postulate that WM tasks involve both STM and LTM, and each memory has distinct functional properties. The former structure is often called [3] *primary memory* (PM), and is responsible for the active maintenance of a number of memory chunks, which due to that maintenance are directly accessible [4, 5, 6]. However, the capacity of PM is strictly limited, probably to as few as three or four memory items on average [7, 8]. The latter component, often called *secondary memory* (SM), reflects items outside of PM, which are passively stored, and which are less accessible because of the need to search SM using contextual cues and indirect retrievals. SM is much more capacious than PM, but it is prone to interference [9, 10] and/or decay [1].

Some studies supported the dual-component account of WM, showing that certain experimental manipulations did harm access to SM items, while access to PM items was left intact. In these studies, PM items were assumed to be a few recent items. SM items were either non-recent items or recent items which were somehow displaced from PM. For example, items supposedly maintained in PM were protected from proactive interference, while items residing in SM were not [11, 12, 13]. Moreover, a few words that were recalled immediately after their encoding were prone to phonological but not to semantic similarity, while the reverse was true for words recalled after several seconds of delay [14]. Also, recall from either PM or SM dissociated recency effects in many ways [8], and recall dynamics of the most recent item substantially differed from recall of earlier items [15]. Finally, latent variable modeling have shown that variables loaded by either PM or SM items from the same recall task shared little common variance [16].

Although the research supporting the dual-component accounts succeeded to dissociate access to PM from SM, interpretation of its results is complicated by the fact that all those experiments involved either recall paradigms, which used a complex output procedure [8, 14, 16], or recognition tests in which experimental conditions presumed to capture SM versus PM differed to great extent [11, 12, 13, 15]. In recall tasks, the need to reproduce many items may make difficult the univocal identification of PM/SM items. For example, during a recall, some not-yet-recalled PM items may need to be transferred to SM. Also, a reproduction of substantial amount of information from SM can make participants use their PM in order to control a recall process, including that people may need to update the actively maintained temporal bindings linking each item to a tag informing whether that item has just been retrieved or it still awaits for retrieval. So, relatively complex formal models [8, 17] are often needed for a description of such an output procedure. On the other hand, so far, recognition tasks aimed at dissociating PM from SM, though required only one simple manual decision (*accept*/*reject*), and thus they seem to escape the problem of understanding what happens during output (also yielding relatively simpler mathematical models [15, 18, 19]), included substantially different conditions of access to SM than to PM. For instance, in Wickens et al.'s study [13], who used the well-known Sternberg task [20], in the SM condition a set of to-be-remembered items and a to-be-recognized probe were separated by a backward counting task lasting for twelve seconds, while in the PM condition the latter was presented almost immediately after the former. Halford et al. [12] used small set sizes to capture PM, while large set sizes involved SM. Conway and Engle [11] differentiated PM from

SM in the Sternberg task by either informing participants in advance (PM condition) or just before a probe (SM) about which pre-learned memory set should be searched for the probe. However, applying each of these manipulations constituted so substantial differences between PM and SM trials that observed dissociations might as well be attributed to other factors than the differences in access to WM (e.g., to the more pronounced involvement of executive control in more difficult conditions).

In order to be able to more univocally interpret the selective experimental effects pertaining to SM, it would be optimal that the recognition procedure was the same no matter whether a probe matches PM or SM item. The present study applied such a procedure using a novel version of the Sternberg task, which required deciding whether a presented probe matched an item in a memory set on a particular location, as indicated by a digit co-presented with the probe. The crucial experimental manipulation consisted of asking the participants about the location of a probe in relation to either the start (a positive digit) or the end (a negative digit) of encoded memory set. The main goal of the study was to test if the results supporting the contribution of both PM and SM to the performance in the serial recognition task can also be obtained with the use of such a simpler and presumably better interpretable method, and whether a selective decrement in access to SM in comparison to PM can be observed.

Moreover, in all cited data obtained from recognition tasks, accuracy was at ceiling, and dissociations between SM and PM pertained only to latency of responses. If one assumes that SM is less available than PM, then the respective differences in accuracy of access to WM should also be observed. So, in the present study, both latency and accuracy were tested in an investigation of the differences in access to PM versus SM.

In an analogy to the cited method of SM/PM identification in recall tasks [8, 16], here we also assumed that on most occasions only three recency items would be effectively maintained in PM due to its limited capacity, while the remaining three (prerecency) items would be transferred to SM. This assumption is supported by differences in accuracy between highly correct recognition of recent items and the decreased recognition of the remaining items, often observed in demanding versions of the Sternberg task [4, 15] and in other difficult recognition tests like the *n*-back task [21]. Such a strong recency effect seems to exclude a possibility that participants tend to fix a few early items to PM and then let other stimuli go, because in such a case the strong primacy instead of recency effect should be observed. Of course, such an association of PM to recency items is only probabilistic, and on some trials early items may indeed be kept in PM.

II. GENERAL METHOD

The task used in two reported experiments consisted of the serial presentation of six black letters (*memory set*, MS) shown on a white background, 4 × 6 cm in size, randomly drawn from a set of 18 consonants. A seventh letter was a probe, accompanied either by a digit or by a hash symbol, each around 2 × 3 cm in size and placed above the letter.

The experimental factors regarded a probe position in MS (1 – 6) and a digit sign ("+" or "-"). Moreover, probes could match items in exact positions (*congruent* condition), they could match them in different positions (*incongruent* condition; the digit and the probe position differed by either one or two places), or they could be new items (*digit-new*). Instructions required deciding if the probe was displayed at the serial position indicated by a digit. Also, the standard version of the Sternberg task was tested, which included a hash symbol instead of a digit. Its two conditions, named *no-digit* or *no-digit-new*, for probes included in MS or not, respectively, required participants to accept/reject a probe if it was/wasn't included in MS, no matter what was its real position. The no-digit condition served as a baseline.

The crucial manipulation consisted of making the access to either PM or SM more difficult, by presenting either positive or negative digits, respectively (see Fig.1). The use of positive digits was expected to anchor the memory scanning at the first serial position and so yield more time and/or interference before getting from that reference position to the recent (i.e., PM) than to the early (i.e., SM) positions. Analogously, the use of negative digits should anchor the scanning at the last position ("-1"), and more time and/or interference was expected to be related to getting to the SM positions than to the PM ones. The crucial expectation, drawn from the assumptions of the dual-component models, stated that, because of the more passive and prone nature of SM, access to SM items would be significantly more impacted by the negative digit condition (in comparison to the positive digit one) than access to PM items would be impacted by the positive digit condition (in comparison to the negative digit one). Such a prediction is not expected on grounds of unitary theories of WM.

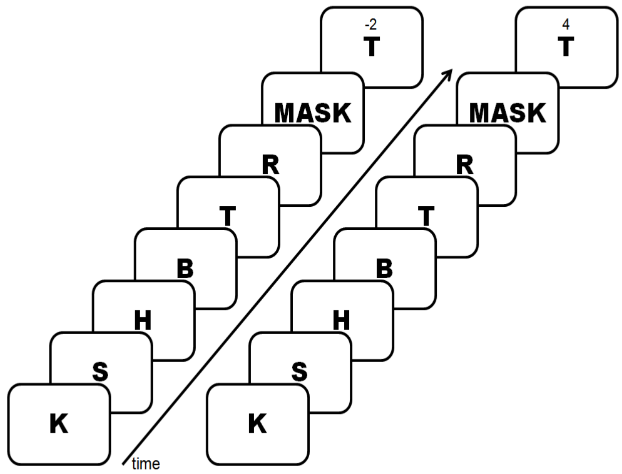

Fig. 1 Two sample trials of the modified Sternberg task

Each sequence of events in a trial consisted of a presentation of six letters followed by a mask, and then a display of a target letter accompanied by a digit. On the left, the negative digit, congruent condition is shown. On the right, the positive digit, incongruent condition is shown. In the no-digit conditions, the digit was replaced by the hash symbol (#).

In fact, the adopted method seemed not to pertain to any specific nature of SM limitations. As argued, checking positions in relation to the end of a sequence (in comparison to its start) should be disruptive for retrievals from SM no matter if SM is limited by decay (as more time would be needed to access items located at larger distance from the reference position), interference (as probably there would be more processing steps to move further from the reference position), or discrepancy between context at study and at recognition (as the context would change more when moving further from the reference position). In the present paper, we make no particular commitments to the exact cause of SM's lesser accessibility, which is a disputed issue in literature [1], [5], [8], [9], [10].

The digit-new and no-digit-new conditions were necessary only in order to balance participants' biasing of accepting versus rejecting decisions. As our hypotheses did not pertain to these trials (positions did not apply), we only note that these conditions yielded close-to-ceiling effects (*M*s > .90 and *M*s > .86, in Experiments 1 and 2, respectively), which indicate that participants had little problem with detecting the fact that items had not been presented to them.

III. EXPERIMENT 1

A. Participants

A total of 86 students of the Jagiellonian University in Krakow participated. There were 55 women, the mean age was 21.8 years (*SD* = 3.05). Each participant was tested for one hour and received a course credit.

B. Procedure

Each trial consisted of a fixation point shown for 500 ms, followed by a sequence of six stimuli presented for 800 ms apiece, each masked for 200 ms. Then, another mask was shown for 500 ms, and followed by a probe along with either a digit or a hash sign. The participants were instructed to respond to the probe with the mouse by pressing its left button for an *accept* decision in case of targets, while using its right button for a *reject* decision in case of lures. The time allowed for response was 3 s. There were a total of 270 fully randomized trials: 60 congruent, 60 incongruent, 60 digit-new, 60 no-digit, and 30 no-digit-new trials. There were 47 subjects (the positive-digit group) to whom positive digits were presented in digit trials, and 39 (the negative-digit group) who saw negative digits. The test was preceded by detailed instructions and twelve training trials including at least two trials from each condition.

C. Data Screening and Analysis

The mean response accuracy (i.e., the proportion of either correctly accepted targets or correctly rejected lures) and the mean latency of correct responses were dependent variables. Responses emitted in less than 250 ms were counted as errors. Response times larger than individual's mean in a position × condition cell plus three median absolute deviations were trimmed to this criterion value (less than 2% of results).

D. Results and Discussion

First, we ran a 2 (digit sign) × 6 (item position) ANOVA in accuracy, in the congruent condition. The two-way interaction, presented in Fig. 2 (top panel), was significant, $F(5, 420) = 4.09$, $p < .001$, $\eta^2 = .06$, and it indicated that the difference between the groups was significantly larger in the case of three early item positions then in the case of three late item positions, as shown by the respective contrast, $F(1, 84) = 12.59$, $p < .001$, $\eta^2 = .13$. Accuracy at the former positions was significantly lower in the negative-digit group, $F(1, 84) = 13.93$, $p < .001$, while a respective difference regarding the latter positions was not significant, $F = 0.17$. Unfortunately, an analogous interaction was not significant in the incongruent condition (bottom panel in Fig. 2), $F(5, 420) = 1.13$, $p = .334$. Difference between the groups was insignificant in all serial positions (all *p*s > .15).

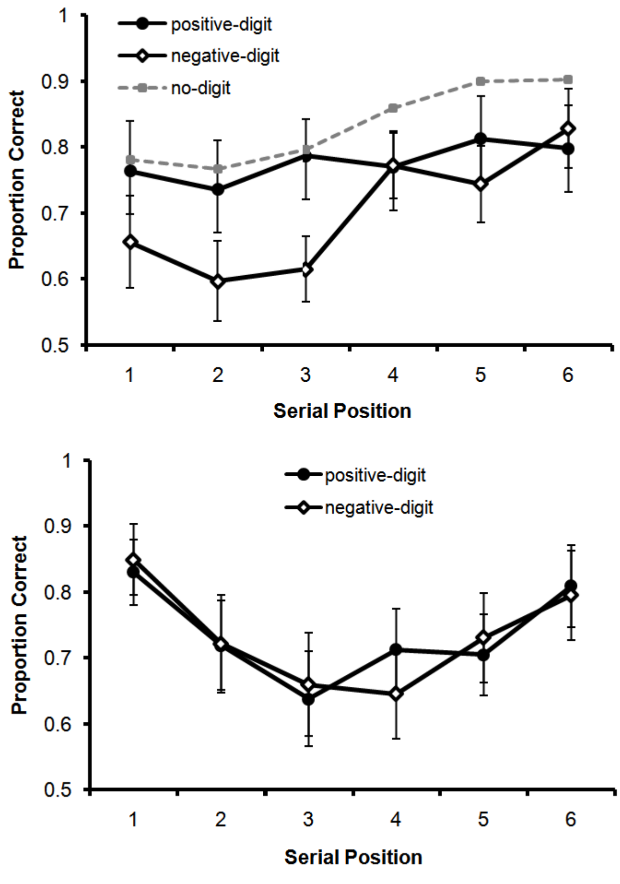

Fig. 2 Mean response accuracy in the congruent-digit (top panel) and incongruent-digit (bottom panel) conditions of Experiment 1, for the positive- and negative-digit groups

However, the effect was presented in the mean latency of correct responses (see Fig. 3), $F(5, 420) = 5.18$, $p < .001$, $\eta^2 = .06$, and it indicated that in the case of three early items the difference in mean RT between the negative- and positive-digit conditions, $F(1, 84) = 31.41$, $p < .001$, $\eta^2 = .27$, was higher than the respective difference for three late items, $F(1, 84) = 3.86$, $p = .023$, $\eta^2 = .04$. In the congruent condition such an interaction was also found, $F(5, 420) = 12.61$, $p < .001$, $\eta^2 = .13$, showing higher RT difference between the negative- and positive-digit conditions in the case of three early items, $F(1, 84) = 18.98$, $p < .001$, $\eta^2 = .18$, than was the respective difference for three late items, which was not significant, $F(1, 84) = 0.06$.

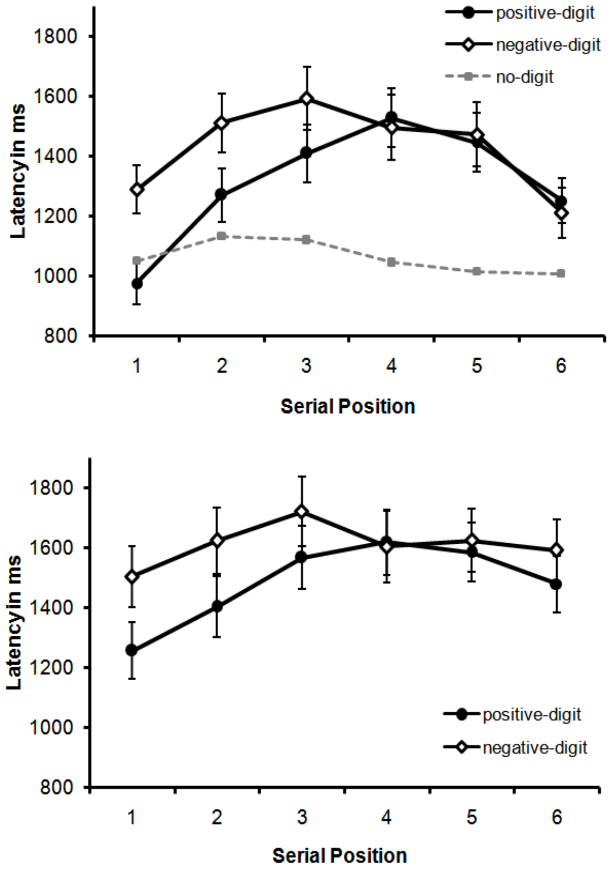

Fig. 3 Mean response latency in ms in the congruent-digit (top panel) and incongruent-digit (bottom panel) conditions of Experiment 1, for the positive- and negative-digit groups

Both the latency and accuracy data in the congruent condition confirmed our hypothesis assuming that the manipulation with a digit sign would harm only access to three early items (associated with SM), while it would leave recent items (associated with PM) intact. However, the same manipulation was not effective in the incongruent condition, because it only influenced time to respond to SM items, but not the accuracy of responding.

Using a between-subjects design yielded in fact two slightly different experimental procedures for both groups. So, a within-subjects design was used in the next experiment in order to verify data obtained so far with a more homogenous procedure and with more observations in each condition. Additionally, with such a design, we were able to correlate the PM and SM indices from the WM task, which was this time the same for all participants.

IV. EXPERIMENT 2

A. *Participants*

A total of 97 students of various colleges in Krakow participated. There were 61 women, the mean age was 22.6 years old (*SD* = 4.72). Each participant was tested for three hours and received an equivalent of four EUR.

B. *Procedure*

The general procedure was the same as in Experiment 1, with only two changes in the experimental design, which regarded within-subjects manipulation with positive and negative digits, and the pattern of trials. There were 384 trials in total: 48 congruent-positive, 48 congruent-negative, 48 incongruent-positive, 48 incongruent-negative, 24 positive-digit-new, 24 negative-digit-new, 96 no-digit, and 48 no-digit-new trials. Subjects practiced three conditions (i.e., positive, negative, and no-digit ones) separately (in random order), and then trained all of them together.

C. *Data Screening and Analysis*

We tested an analogous two-way interaction of factors as in Experiment 1. Data screening was also identical to that in Experiment 1. Additionally, we excluded data from the no-digit condition of four participants who scored less than 25% in that condition (they probably failed to learn what the hash symbol indicated).

For confirmatory factor analysis (CFA) of the accuracy of memory recognition, we used the decision-bias-corrected indices of performance, that is, differences between hit rates in the congruent-digit condition and false alarm rates in the incongruent condition [22]. We did not model latency data, because of the huge individual differences in mental and motor speed observed among participants (i.e., such a model would mostly reflect speed factor beyond the WM domain). The two alternative, unitary versus dual-component, models were calculated with Statistica software (ver. 9) using the maximum-likelihood estimation. We evaluated the goodness of fit of those models with standard indices: chi-square value divided by the number of degrees of freedom (χ^2/df), Bentler's comparative fit index (CFI), and the root mean square of approximation (RMSEA).

D. *Results*

In case of accuracy data in the congruent condition, presented in Fig. 4 (top panel), the examined interaction was significant, $F(5, 480) = 9.64$, $p < .001$, $\eta^2 = .09$. As in Experiment 1, it reflected the fact that a difference between the positive and negative conditions was significantly larger in the case of three early item positions then in the case of three late item positions, as shown by the respective contrast, $F(1, 96) = 39.74$, $p < .001$, $\eta^2 = .29$. This time, not only accuracy for three early items significantly differed between positive- and negative-digit trials, $F(1, 96) = 162.00$, $p < .001$, but also did accuracy for three late positions, $F(1, 96) = 18.98$, $p < .001$.

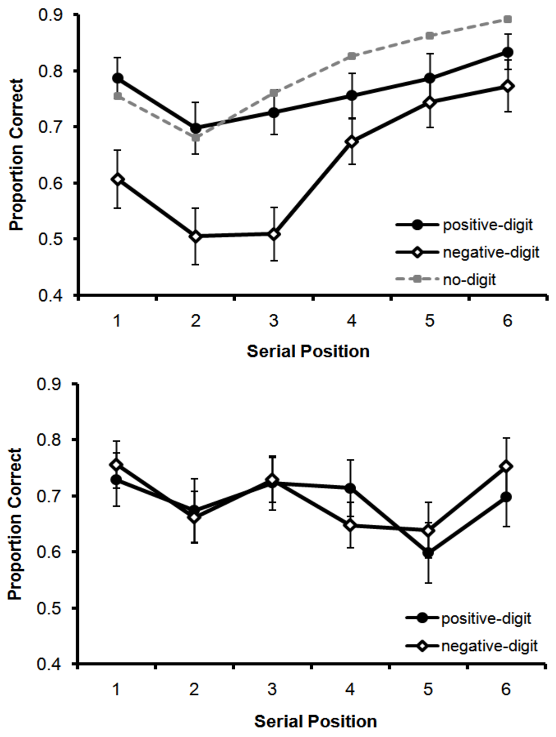

Fig. 4 Mean response accuracy in the congruent-digit (top panel) and incongruent-digit (bottom panel) conditions of Experiment 2, for the positive- and negative-digit conditions

Although in the incongruent condition (accuracy data are presented in bottom panel of Fig. 4) the two-way interaction was significant, $F(5, 480) = 3.71$, $p = .003$, $\eta^2 = .04$, it yielded an insignificant contrast between the positive and negative conditions regarding the three early versus three late positions, $F = 0.01$, and it indicated no respective difference for the later nor for the former, both Fs < 0.38.

As in Experiment 1, the effect in the incongruent condition was present in the mean RT (see Fig. 5), $F(5, 440) = 6.34$, $p < .001$, $\eta^2 = .07$. It indicated that responses to four early items were slower in the negative than in the positive condition, $F(1, 93) = 41.78$, $p < .001$, while no such difference occurred in the case of two late items, $F(1, 93) = 1.98$, $p = .163$. A similar effect on RT was found between three early and three late items in the congruent condition, $F(5, 440) = 14.54$, $p < .001$, $\eta^2 = .15$, showing the higher RT difference between the negative- and positive-digit conditions in the case of three early items, $F(1, 93) = 238.53$, $p < .001$, $\eta^2 = .73$, than was the respective difference for three late items, $F(1, 93) = 87.55$, $p < .001$, $\eta^2 = .49$.

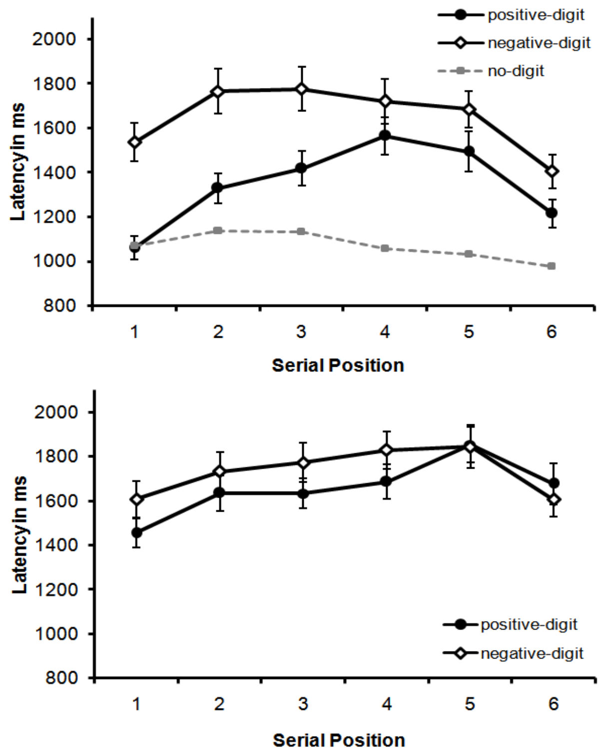

Fig. 5 Mean response latency in ms in the congruent-digit (top panel) and incongruent-digit (bottom panel) conditions of Experiment 2, for the positive- and negative-digit conditions

Finally, we tested the CFA dual-component model by estimating the correlation between the latent variables representing SM and PM, the former loaded by the bias-corrected indices for Positions 1 – 4, and the latter loaded by the corresponding indices for Positions 3 – 6. The overlap between variables in the Positions 3 and 4 reflected commonly observed individual differences in PM capacity.

Descriptive statistics and reliabilities of manifest variables used in CFA, as well as the matrix of correlations between them, are presented in Table 1. The data show that all variables nicely approximated the normal distribution and had acceptable reliability.

TABLE I STATISTICS AND CORRELATION MATRIX FOR BIAS-CORRECTED INDICES OF WORKING MEMORY USED IN CFA (N = 97)

Variable	1.	2.	3.	4.	5.	6.
1. Position 1	–					
2. Position 2	.74	–				
3. Position 3	.58	.61	–			
4. Position 4	.64	.56	.64	–		
5. Position 5	.48	.50	.65	.68	–	
6. Position 6	.41	.33	.51	.49	.68	–
Mean	.46	.29	.37	.47	.41	.55
SD	.32	.31	.27	.28	.33	.30
Range	-.25 – 1.0	-.31 – 1.0	-.31 – .81	-.25 – .94	-.31 – 1.0	-.19 – 1.0
Skew	-.32	.13	-.38	-.21	-.20	-.78
Kurtosis	-.71	-.61	-.70	.66	-.64	-.12
Reliability	.80	.62	.60	.72	.75	.80

All correlations were significant on at least $p = .004$ level. Reliabilities are split-half correlations adjusted with the Spearman-Brown formula.

The initial model had an excellent fit, df = 6, χ^2/df = 1.18, RMSEA = .019, CFI = .997, but the correlation between the SM and PM variables was significant (r = .65; p < .001), though it also significantly differed from unity, t(95) = 4.43, p < .001, which is the r value predicted by the unitary model. An alternative CFA model, including all six positions loading onto one latent WM variable, was not acceptable, df = 9, χ^2/df = 5.19, RMSEA = .211, CFI = .890. The significant correlation between SM and PM might result from using incongruent condition data (reflected in the bias-corrected index). When accuracy from the sole congruent condition was used in the final dual-component model, df = 6, χ^2/df = 0.92, RMSEA = .0, CFI = 1.0, such a correlation was much weaker, r = .26, and only marginally significant, t(95) = 1.87, p = .061 (see the model in Fig. 6), matching the result obtained by Unsworth et al. (2010).

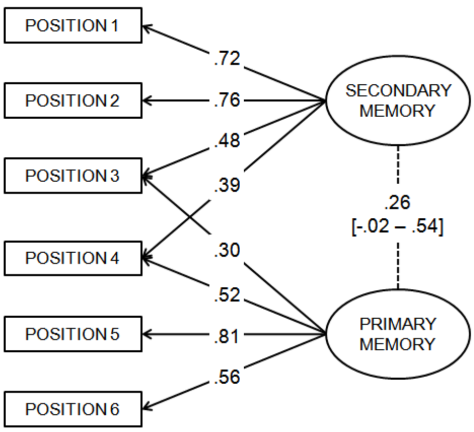

Fig. 6 The CFA model relating the primary memory and secondary memory latent variables

Boxes represent manifest variables, “Position 1” to “Position 6” represent bias-corrected indices of accuracy in serial positions of Experiment 2. Large ovals represent latent variables. Values between ovals and boxes represent relevant standardized factor loadings (all ps < .001). The value between ovals represents a path coefficient among latent variables (p < .001), while the values in brackets indicate its 95% confidence intervals.

V. GENERAL DISCUSSION

An expected dissociation between non-recency and recency items in the congruent condition of our task was found in both experiments, in case of both latency and accuracy data. Changing a digit’s sign into the negative one presumably made access to non-recent items more difficult, and it substantially decreased accuracy of their recognition, while no such effect was present for the most recent items.

However, in the incongruent condition, only latency was affected by our manipulation, while accuracy was not. This result is surprising, as the way of encoding the memory traces had to be the same in both congruency conditions (i.e., participants did not know in advance whether the current trial was either congruent or incongruent). Assuming that the effect of a digit’s sign did uncover the dual-component nature of WM, as suggested by the differences in latency in both conditions as well as by the accuracy difference in the congruent condition, we considered two explanations of the fact that the accuracy effect did not show up in the incongruent condition. Firstly, participants could respond with a very conservative bias – in uncertain cases they were choosing to reject the probes than to accept them. As the early positions in the negative-digit trials imposed larger difficulty on participants than in the positive-digit trials, and thus there could be a larger number of guesses in the former trials, only the congruent condition was harmed, because in the incongruent condition the right answers (i.e., reject) were often guessed. However, this hypothesis seems unlikely, as the mean index of bias (i.e., the proportion of incorrect accept decisions to all errors) was moderate (e.g., β = .54 in Exp. 2), suggesting that both *accept* and *reject* answers were guessed with comparable probability.

A more plausible explanation pertains to differences related to access to WM. Participants, in order to search WM, could use in parallel both the probe and the serial position indicated by a digit, and might simultaneously check a position of that probe and an item occupying that position [23]. The access might depend on how many memory traces getting activated during such a check. Specifically, in the congruent condition, both ways led to activation of the same trace, so no conflict was incurred. The more available was that trace (in terms of differences between SM and PM), the better it was accessed. So, the differences in availability of items were reflected in the differences in accuracy between SM and PM. Such a straightforward nature of WM access in congruent trials is suggested by accuracy in those trials comparable to the baseline condition, M = .77 and M = .79, respectively.

However, in incongruent trials, the access to WM might not rely on a one-step process. The conflict between initially activated versus perceived probes/positions might not yield immediate reject decisions, but might yield an additional process of careful recollection of complete memory traces for both the probe and the indicated position (i.e., so-called *recall-to-reject* process [18, 24]). If the respective traces had been encoded in SM, then this additional process could successfully retrieve them in both the positive and negative digit conditions, so no differences in accuracy for SM items might be observed. However, the effective retrieval of less accessible SM traces in the negative condition would take longer. So, the way of access to WM would depend on the amount of conflict among memory items. A greater need for using the recall-to-reject process in the positive-incongruent condition can be deduced from the substantially lower overall accuracy in that condition (M = .69) than in the baseline condition (M = .79). Its occurrence is also suggested by approx. 180 ms longer overall latency of correct rejections in comparison to correct accept decisions.

Could the unitary account explain the observed data? For instance, our manipulation might affect only weak memory traces of non-recent items, while strong traces of recent items could be more robust to changes in the position estimation procedure. Also, responses to weak traces could be influenced by decisional biases to greater extent than responses to strong traces. However, such explanations seem less plausible than the dual-component explanation.

Firstly, any supposedly weaker memory traces of non-recent items should have resulted in significantly worse performance for these items, regardless of a task condition. On the contrary, in the congruent condition, the accuracy for non-recent and recent items was comparable. Secondly, any unitary explanation, assuming that a single mechanism was responsible for scores on all item positions, is problematic when facing two distinct sources of variance revealed by our CFA model. Latent variable analysis indicated that variance in the bias-corrected indices of discriminability, calculated for recent and non-recent items, were shared only to moderate extent (i.e., 42.3% of variance was shared; 6.7% when only hit rates were taken into account).

Summing up, the experimental effects showing the selective sensitivity of accuracy (in congruent trials) and latency (in both congruent and incongruent trials) of WM access, together with the CFA results, seem to be very consistent with the dual-component account of WM, while they are problematic for the unitary alternative. The present study has demonstrated that even the simple manipulation done to the recognition task, which involved minimal changes between experimental conditions, can lead to selective impediment of access to items associated with SM, but not – with PM. The main contribution of this research is related to the fact that it helps to reject an interpretation, which was not univocally eliminated by the previous studies, saying that dissociations between SM and PM performance might have arisen due to factors other than SM/PM differences, for instance factors related to the complexity of recall or substantial differences in the recognition procedure. On the contrary, our novel version of the Sternberg task showed that these dissociations can easily be found also in a relatively simpler recognition paradigm, and as such, they further support the dual-component theory of WM.

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