Modeling Individual Differences in Working Memory Search Task

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Abstract

The paper presents proposal of a new ACT-R model of working memory (WM) search process, explaining both 'serial-like' and 'parallel-like' modes of processing observed in this task. The model implements an idea of WM focus of attention: due to updating process a few items may be actively kept and easily accessed in ACT-R goal buffer. Search process consist of two phases. In the first one, goal buffer is scanned serially. If the result of scanning is negative, the second phase – standard parallel chunk retrieval from ACT-R declarative memory – occurs with certain probability. The model aptly simulates steep decrease in accuracy as well as steep increase in latency for responses to five most recent stimuli, and shorter latencies of accurate negative responses than latencies of positive responses to less recent stimuli. These two predictions are impossible to obtain for existing ACT-R one-phase parallel model of recognition memory. Moreover, our model predicts 94.8% of variance for two groups of Ss that differ in latency pattern of search process.

Introduction

Despite intensive research on different cognitive strategies exploited by humans in complex tasks like reasoning, problem solving, and decision making, individual differences in elementary cognitive processes are rarely modeled. Such simple processes are treated as fixed part of human cognitive architecture, and its parameters are believed to be invariant. However, empirical results from a memory search tasks (refered to as MST in the rest of this paper) suggest that people differ substantially in a way they perform such kind of tasks.

In the paper, we present a new two-phase model of recognition memory that simulates different chronometric patterns of a search process (i.e. 'parallel-like' vs. 'serial-like' ones) observed in MST, with the change in only one parameter: the scope of simulated WM focus of attention.

Is WM Search Serial or Parallel?

In his seminal paper, Saul Sternberg (1966) examined whether people search short-term memory (STM) in a serial or parallel way. Ss were shown 1 up to 6 digits (memory set, MS), and then another digit, that could belong (positive condition) or not (negative condition) to MS. Sternberg found steep linear RT curve rising with increased MS size. He concluded that STM had been searched serially and approximately 38 ms was needed to scan one MS element.

Sternberg result, steep linear MS size curve, was replicated in countless studies. However, some studies show that when MS size exceeds six elements, RT curve slope becomes moderate and it looks rather curvilinear (Theios, 1975) or log-like (Jou, 2000). It may indicate that items which cannot be held in STM are retrieved from long-term memory in parallel-like search process (Theios, 1975).

Moreover, Townsend's study (1974) showed that even in case of MSs not exceeding six elements, Sternberg's results can also be predicted by parallel models that are capacity-limited. Thus, one cannot discriminate between these two models on the basis of linearity of MS size curve. The focus of research switched to the issue of whether memory search is self-terminating or exhaustive (i.e. it cannot stop until all items are scanned), with more evidence for the former idea (Van Zandt & Townsend, 1993).

In most of the experiments within Sternberg paradigm verbal stimuli and relatively long presentation times (about 1 sec. per element) were used. Exploitation of non-verbal stimuli and/or shorter presentation times brings even more confusion to the issue of modeling STM search. In such experimental conditions MS size curves become almost perfectly flat (Nęcka & Orzechowski, in preparation; Balas, Stettner, & Piotrowski, 2005).

Another problem in evaluating model of STM search appears when individual differences in MST are examined. Even with relatively slow presentation time of 700 ms, two different ways of processing can be identified (Chuderski & Orzechowski, 2005). People who respond faster obtain flat MS curves, while people responding slower show steep curves. Accuracy of both groups do not differ significantly, so the differences in MS curve slopes cannot be explained in terms of speed-accuracy trade-offs.

It seems that people are capable of both serial-like and parallel-like memory search, and there exist significant individual differences in this process among them.

Examining Individual Differences in MST

In order to evaluate the proper model of WM search, but facing confusions cited above, we decided to gather and model data rather on position curves (i.e. relationship between a position of an item in MS and latency or accuracy of response for that item) than on MS size curves.

On a basis of our previous results cited above, we expect that individual differences in position curves will appear, and we claim that the proper model of WM search should predict these differences in a very natural way (optimally, with change in only one of its parameters).

Method

23 women and 57 men were examined, with mean age of 17.45 (sd=0.73). We used computerized MST with a pool of 16 consonants as stimuli, each one 2×1.5 cm in size. Four- and eight-items MS sizes were used in an experiment and varied within Ss. Eight trials for each target position (1-4 or 1-8, depending on MS size condition) were presented in positive condition (96 trials total), and another 96 trials in negative condition, on random. An asterisk presented before first stimulus in each trial served as a fixation point. Two presentation times (400 and 800 ms) were varied between Ss. After presentation of MS a mask was shown for 500 ms and then a probe letter appeared inside a rectangle. If Ss decided that a probe was presented in MS in a current trial, they had to press key "Z", in opposite case they were to press "M". Cues on computer screen helped Ss to remember proper response keys. The time for response was limited to 1500 or 3000 ms, varied between Ss. The progress bar shown under each probe indicated how much time was left to respond. The manipulation in time for response independent variable was aimed at changing Ss strategy of search. We expected that a shorter time will result in more parallel search and, thus, less steep position curve. The same relation was expected in case of a presentation time independent variable.

After completing the task, Ss were given a questionnaire, whether they searched memory carefully testing each item, or responded intuitively on basis of familiarity of a probe, or were just guessing. Only data from 71 Ss that filled the questionaire and did choose first or second answer were analysed. In another question, 66,2% Ss admited use of mnemotechnique of silent rehearsal, while remaining Ss reported use of chunking or visualisation. It suggests that a proper model of stimuli encoding in MST has to implement rather general attentional trace-activation mechanism, instead of implementing rehearsal within a phonological loop as the only method of activating traces (which is probably appropriate for modeling serial recall, and in case of long presentation times, see: Huss & Byrne, 2003).

Results and Discussion

Neither time given for response nor time of presentation influenced accuracy dependent variable. Crucial for this research, a position effect in case of accuracy is presented in Figure 1. The effect was highly significant, $F(3, 67)=8.74$, $p<0.001$, $F(7, 63)=27.79$, $p<0.001$, for MS size 4 and 8, respectively. In the most interesting MS size 8 condition, accuracy for all pairs of items on neighbouring positions differed at $p<0.01$ level, except differences for pairs on positions 3-4 and 7-8, which were not significant ($p>0.1$). In case of pair 1-2, the difference indicates strong primacy effect. The 'no' responses were more accurate than average 'yes' responses, $F(1, 69)=38.79$, $p<0.001$. MS size 4 responses were more accurate than MS size 8 responses in both positive, $F(1, 69)=338.78$, $p<0.001$, and negative condition, $F(1, 69)= 44.57$, $p<0.001$.

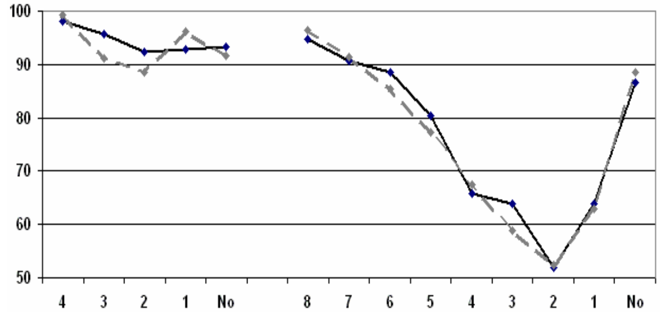

Figure 1: Observed (solid lines) and simulated (dashed lines) accuracy (% correct) for target positions within MS.

Although both factors: time for response and time of presentation, influenced latency of responses (p<0,01), they did not interacted with a target position and then will not be analyzed further. Again, position effect (see: Figure 2), in case of latency of correct responses dependent variable was highly significant, both in MS size 4, $F(3, 67)=19.85$, $p<0.001$, and MS size 8 conditions, $F(7, 63)=28.88$, $p<0.001$. In MS size 8 condition, all item pairs except 5-6 pair differed significantly (p<0.05; for pair 4-5 a difference was marginally significant, $p=0.071$). In case of pair 1-2 the difference indicates strong primacy effect. The 'no' response was faster than responses for target on positions 2, 3 and 4 ($p<0.05$) and its latency was higher than average latency for 'yes' response, both in MS size 4, $F(1, 69)=22.53$, $p<0.001$, and MS size 8 conditions, $F(1, 69)=9.83$, $p=0.003$.

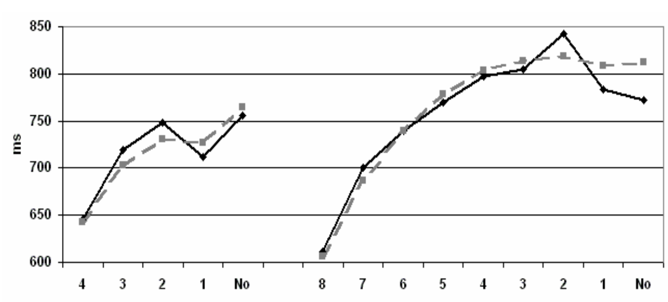

Figure 2: Observed (solid lines) and simulated (dashed lines) latencies for target positions within MS.

The most important conclusion from presented data is, that position curve for MS size 8 is steep for 5 most recent target positions (198 ms difference between latencies for items on positions 1 and 5), while it is rather flat for remaining positions (with position 2 as exception, see Discussion), with strong primacy effect observed.

To search for individual differences in a way people searched WM, we computed a difference between average latency for four least recent positions minus average latency for four most recent positions (position curve slope indicator, PCSI). With application of this method, in general, one can expect four results. First, Ss may not differ significantly, then position curves for low- and high-PCSI Ss would be more or less parallel. Second, low-PCSI Ss may have higher latencies for recent positions than high-PCSI Ss, but lower – for least recent ones. Then position curves would cross. Third and fourth, both curves may be parallel at only one (start or end) part of the curve. And this is the case we have found: both groups did not differ in response latency for four most recent target positions, but for the rest of positions low-PCSI group appeared to have flat position curve, while the curve of high-PCSI group was rising ($p<0.001$) up to position-2 point. This indicates that low-PCSI Ss search for the least recent positions is probably done in more parallel-like way.

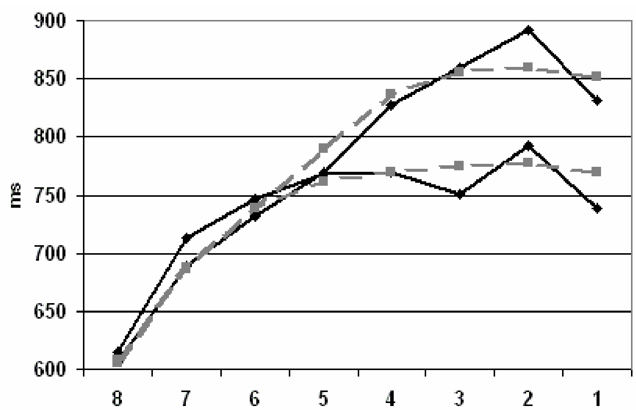

Figure 3: Observed (solid lines) and simulated (dashed lines) latencies for target positions for both groups.

Modeling MST in ACT-R

ACT-R cognitive architecture (Anderson et al., 2004) is a theory of mind expressed as central control structure operating with procedural knowledge (productions) on chunks of information available in buffers of several specialized modules (e.g. visual, auditory, goal, and declarative memory modules). Working memory in ACT-R may be defined in two ways: as a subset of highly active elements of declarative memory or as a process of spreading source activation (i.e. attentional resource) from current goal to declarative elements strongly linked with that goal. These two conditions are often strongly correlated: memory traces are highly active due to additional activation being spread from the goal. Two other factors affecting trace accessibility are: a learning process (strengthening its link to the goal or rising its base activation) and decay of activation in time.

Within ACT-R there are two methods of trace retrieval from working memory (Anderson, Bothell, Lebiere, & Matessa, 1998). In some specific conditions (like time-pressure), most active memory element is retrieved and tested against a probe. Target element may not be the most active one, so a negative response in positive condition (error of omission) is probable. Alternatively, a production may try to retrieve an element identical to the probe. The higher activation of successfully retrieved element, the lower latency of retrieval. Due to the partial matching mechanism, an element similar but not identical to the probe may be retrieved and, by an error of omission, accepted as a target. If there is no target or target-like element above certain threshold at all, retrieval failure with long latency occurs.

A simple ACT-R model of word recognition memory was proposed by Anderson et al. (1998, pp. 222-225). It retrieves the most active word trace as a candidate and checks whether it is identical to a probe. Source activation is being spread from the probe to a corresponding trace in memory. The model predicts almost linear relationship between the number of elements in a list and their recognition latency (ibidem, Figure 7.7). Thus, the model does not fit some recent data described previously in this paper: flat SS curves of fast responding Ss (Chuderski & Orzechowski, 2005) or log-like SS curves (Jou, 2000). It is neither coherent with the data presented in last section: the slope of position curve for five most recent items in Anderson et al. (1998, Figure 7.8) is approx. 80 ms only, while the same slope observed in our data is 198 ms. Shorter latencies of accurate negative responses than of positive responses to less recent stimuli, observed in our data, cannot be easily predicted with existing ACT-R model, either. In negative condition (a foil) it always retrieves less active chunk or reaches retrieval threshold, what causes long retrieval, and thus long response latency. Any parameter manipulation (for example in latency factor), undertaken in order to rise steepness of a position curve, would probably increase the difference between foil and target latency, making the model even less fitting our data. Finally, existing MST model predicts rather good accuracy of response, while our data shows that also low (60-70%) or random level (50%) accuracy may be observed, depending on position of a target item in MS.

Relying on retrieval from active part of declarative memory, as modeled by Anderson et al. (1998), is probably a very reasonable strategy in case of semantic material (words), that is presented for long time (1.5 s) and can be intensively rehearsed. However, with the use of small set of letters, huge level of interference within declarative memory appears quickly and the task becomes very difficult. Relying on automatic access to declarative memory may then lead to very low accuracy. Engle (2002) proposes, that in such circumnstances controlled attention, that preserves important information in active and interference-secure state, has to be involved in storage of memorized material. It seems that existing ACT-R MST model cannot be generalized to such conditions. More attentional processes have to be implemented within a proper model of MST with limited number of non-semantic stimuli.

As position curves presented in previous section indicate, within the scope of five most recent elements, MST (with varying MS size) has similar characteristics to n-back task, where latencies and number of errors grows with increasing n-back. The only difference is, that in exclusive n-back tasks (McErlee, 2001) a stimulus, to become a target, must be repeated at exact n-back position, while in MST it may occur at any position

An ACT-R model of n-back task was presented by Lovett, Daily, and Reder (2000). The most interesting observation is that two different strategies were exploited by subjects. Some Ss used an 'activation' strategy for encoding stimuli in WM: they were just activating a current stimulus during its presentation. In a decision phase, their responses were based on subjective familiarity of a new element. Individually modeled attentional resource parameter (*W*) did not influence observed accuracy. Other subjects used 'update' strategy – they actively maintained and updated recent stimuli in WM. Efficiency of this updating process was highly dependent on individual *W* value.

A Two-Phase Model of WM Search

As Ss are probably able to update only a few elements in WM, they are not able to maintain actively all elements in eight stimuli version of MST, as low accuracy in 2-, 3- or 4-position condition in our data indicates. Thus, all Ss must use 'familiarity' decisions for elements exceeding their active part of WM, which is often referred to as a focus of attention (FA; Cowan, 1995) or an area of direct access (Oberauer, 2002).

We introduced the idea of attentional focus (or, more strictly, the idea of Oberauer's direct access area) into our model of WM search. However, in relation to other aspects of WM structure, our model was not designed in any intentional compliance with (much more general in their scope) Cowan's nor Oberauer's theories. We assume that only elements in WM focus of attention may be volitionally updated, and that individual differences in current WM focus of attention capacity, resulting in differences in stimuli encoding, affect memory search process and explain results presented earlier in this paper.

WM Focus of Attention During Encoding

Like most ACT-R models of WM, our model also encodes simulated stimuli, "presented" on a computer screen during MST, into episodic memory traces. In case of this study, these traces are chunks encoding information that particular letter appeared in the current list. However, according to ACT-R theory, making a new trace, without additional effort to hold it active in memory, results in almost immediate decay of chunk's activation below threshold. To achieve a satisfactory accuracy, a cognitive system runs processes (productions in our model) aimed at activating the traces until the probe arrival. This may be done with a focus of attention. Its average capacity is estimated on about four elements (Cowan, 2000), but attention can also be surely intensively focussed on just one element (McErlee, 2001).

In our model, process of activation consist on retrieval of the most active trace from declarative memory (maximally twice in a row) and placing it in the goal buffer, which works as an attentional focus. Its capacity is limited (a model parameter), so if this capacity is overloaded, a chunk placed in the stack least recently is overwritten by the most recently activated chunk. No spreading of activation from goal buffer to declarative memory occurs, focus is treated as structurally distinct part of WM.

When a capacity parameter is set to one element, model's encoding is similar to 'activation' strategy of Ss from Lovett et al. (2000). Just one (most probably currently presented) chunk is just activated as much as presentation time allows, and loaded into the goal buffer. So, the more recent stimulus is, the greater chance for it to be the only element held in the focus. When capacity parameter is set to greater value, lets say 3 or 4 elements, this may be treated as implementation of 'update' strategy from Lovett et al. – Ss constantly keep and update in attentional focus significantly more elements than one.

Two-Phase Search Process

As letters used in our experiment can probably be perfectly distinguished one from another, and they are almost void semantically (in comparison with words, syllables, and images), we assume that, along with spreading of activation, also partial matching mechanism may be switched off. However, in case of more meaningful material, our model is able to implement ACT-R activation spreading (from a probe to items in memory that are similar physically or semantically to this probe), and partial matching (of these similar items).

When the probe is presented, the model starts searching memory traces for the one identical with the probe. Instead of just retrieving the most active memory trace, as in Anderson et al. (1998), our model runs two phases of memory search. In a first phase, traces in the focus of attention are checked serially, one by one, starting from the most recent one. The model's focus represents stable, probably self-activating, representations. So, in the model, these representations (like goal chunks in ACT-R) can be directly reached by search-process productions, at no additional time. At each test of focus contents, traces already checked are marked. In accordance to Oberauer's (2002) theory of WM structure, the model must switch from attending to the first element in focus of attention, to the remaining elements, and in such case one additional production has to be fired.

If the model uses 'activation' strategy, i.e. capacity parameter is set to one or two elements, only the most recent element(s) are checked in the first phase, in less than 100 ms on total. If 'update' strategy is used, due to longer process of serial testing of contents of the focus, the first phase may last up to 200 ms (in case of four traces held in the focus), depending on the exact value of parameter representing time to access each element in the focus. As we believe, this value should be oscillating around 40 ms (i.e. a little bit faster that default firing time for regular productions).

If a result of focus test is negative, the model may run a second, parallel phase of WM scanning. However, the second crucial parameter – probability of stopping the search after the first phase, controls if the second phase runs at all. When the number of elements checked in the first phase is relatively high (large capacity of the focus of attention), and the MS size is relatively low, the additional errorful parallel phase of search would yield little probability of success, but would take huge amount of time. In such case, in time-pressured conditions, sometimes it is much more reasonable to generate the negative answer immediately after the first phase. This phenomenon may result in correct negative responses that are faster than positive responses generated after the second phase. We believe that the parameter regulating the chance of running the second phase may be strategically altered by Ss on basis of their current attentioanl capacity, of the size of MS, and of experimental conditions in which the search task is applied. However, this hypothesis must be experimentally verified in future research.

When the second phase runs successfully, the model tries to directly retrieve, from a declarative memory, the trace with a 'letter' slot equal to the probe letter. The standard mechanism of ACT-R is exploited: the more often and more recent the trace was being activated (i.e. retrieved) during encoding phase, the better and faster it is available for retrieval. If an activation of the trace looked for is not above the threshold (because it decayed or a target was not presented at all), long latency retrieval failure occurs. However, such a case does not determine negative response of the model. Sometimes, especially when MS size is large, model tries to guess an answer, with some chance for a positive answer. This is based on an assumption, that Ss are probably aware, when many letters were presented, that a unsuccessful retrieval may indicate the fact that they forgot the element as well as the fact that there was no such element presented at all. In consequence, the third model's parameter controls probability of guessing 'yes' when the second phase fails to retrieve any memory chunk.

So, when attentional capacity is set to some higher value, after a probe is presented the model has a opportunity to rely its search process on fast but serial access to chunks actively maintained in the focus of attention. When current attentional capacity is low, instead of scanning the focus (which in this case is almost empty), relatively slow but parallel retrieval from declarative memory is executed.

Simulation Results

Simulated data were generated in 5000 runs. Three default ACT-R values: 50 ms for time to fire a production, 0.5 for decay parameter, and 0.0 for base level constant, were used. Three parameters were optimized to produce the best fit to empirical data: retrieval threshold (0.63), activation noise (0.08), and latency factor (0.17). The time for accessing focus of attention was set to 40 ms. Time needed to decode a stimulus was set to 150 ms, while time to activate a trace was set to 300 ms.

The first and most important model specific parameter, a capacity of a focus of attention, was randomly varied from 1 to 2 elements in 4-item MS size condition, and from 1 to 4 elements in 8-item condition. The second specific parameter, the probability of stopping the search after the first phase, was set to 0.03 for the 4-item MS size condition and to 0.25 for 8-item condition. Last specific parameter, i.e. marginal probability of guessing 'yes' in case of retrieval failure, was set to 0.035 for each additional item outside a focus of attention.

The rationale for using different values for 4- and 8-item conditions is, as we believe, that in short MS case, which is relatively easy, people do not need to rely on updating of their focus of attention. In such case, data pattern generated by our model, with its specific parameters set to low values, is very similar to pattern obtained from Anderson et al.'s (1998) model. Accuracy is high, negative condition response is the longest one, while the steepness of position curve – moderate. However, in much more difficult case of a longer, 8-item list, high values of these parameters switch on additional processes of first-phase serial attentional search, while stopping retrieval from declarative memory in significant proportion of model runs. And this results in obtaining pattern of data characteristic for longer lists: low accuracy for the least recent items, log position curve, and negative responses faster than some positive ones. In consequence, with 14 parameters set, 28 empirical data points are predicted with very good fit: R^2 equals to 0.968, and RMSD – to 2.7, in case of accuracy, while R^2 equals to 0.934, and RMSD – to 17.0, in case of latency. Simulated accuracy is presented in Figure 1 (dashed lines), latency – in Figure 2 (dashed lines).

Crucial for testing the model is an apt simulation of group differences in chronometric pattern of WM search. In case of 8-item condition, when two separate simulations were run: one with focus capacity parameter varied between 1 and 2, and the other with parameter varied between 3 and 4, all other parameters unchanged, the model predicts observed individual differences in RT position curve for low- and high-PCSI Ss (Figure 3, dashed lines) with following values of goodness of fit measures: R^2=0.948, RMSD=17.4.

Summary and Conclusions

The proposed model has very good fit to the empirical data. One and only significant prediction deviation in accuracy consist on simulated but not observed primacy effect in 4-item MS size condition. As such effect was often observed in other our experiments (e.g. Balas et al., 2005), we decided not to modify the model in order to eliminate it. The mechanism of negative responses generation has to be corrected, as Ss negative responses are faster than model's responses. The drop in R^2 in case of latency prediction (both for average results and PCSI groups) is also caused by a significant rise in RT for responses to items on position 2. We also observe sometimes such deviation in case of second-in-row stimulus in our experiments (unpublished data), and we speculate that origin of this phenomenon may lie in processes outside the scope of WM search model. For example, due to high probability that the first stimulus in a list captures subject's attention for about 500 ms, processing of second stimulus in a row may be often impaired.

We conclude that the proposed model is a new and apt proposal explaining how WM search processes may be organized. The model captures some phenomena, previously mentioned in this paper, that seem to lay outside the scope of existing ACT-R model of Anderson et al. (1998). The easily obtained, i.e. only with a small change to a value of focus of attention capacity parameter, prediction of individual differences observed in case of a RT position curve is a very strong argument in favor of the model.

We suggest that the idea of working memory focus of attention – implemented as highly active, easily accessible, and general purpose structure distinct from declarative memory, which stores information currently operated on (i.e., that has just been processed by some cognitive processes, or is just being prepared for processing), should be exploited in ACT-R models to a greater extend. As WM attentional focus may be involved in numerous memory, attention, cognitive control, and decision making tasks (Cowan, 2000; Engle, 2002), more intensive exploitation of focus of attention construct within ACT-R may increase aptness of this theory and provide better understanding of many cognitive phenomena. For example, another model developed in our lab – a model of flexible control in task switching (Chuderski, submitted), explains with the use of WM focus of attention why during random task sequences successive task repeat trials are faster (because of activation boost in task rule retrieval, as all task rules are stored in declarative memory), while during predictable sequences repeat trials latencies are constant (due to fast access to FA, where proper task rule is usually loaded in switch trial).

Our work contributes also to the serial vs. parallel memory search debate by suggesting the central role of individual differences in chronometric characteristics of search process. We believe, that although there really exist pure serial and pure parallel phases of search, the process as a whole is a mixture of both types of processing – a mixture that is different for different people.

By now, the model presented in this paper is particularly suitable for predicting data obtained from experiments where longer stimuli lists, that include items with low semantic associations (i.e. letters, digits, geometric figures, etc.), are used, and from research conducted in time-pressured experimental conditions. The work aimed at generalization of the model onto search among semantically related items, probably involving the process of spreading activation, will be an interesting area of future research. As in real life people probably more often search for meaningful material in their WM, such future model seems to be more ecologically plausible.

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