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Task conditions and short-term memory search: two-phase model of STM search

***Abstract**: Short-term memory (STM) search, as investigated within the Sternberg paradigm, is usually described as exhaustive rather than self-terminated, although the debate concerning these issues is still hot. We report three experiments employing a modified Sternberg paradigm and show that whether STM search is exhaustive or self-terminated depends on task conditions. Specifically, STM search self-terminates as soon as a positive match is found, whereas exhaustive search occurs when the STM content does not contain a searched item. Additionally, we show that task conditions influence whether familiarity- or recollection-based strategies dominate STM search performance. Namely, when speeding up the tempo of stimuli presentation increases the task demands, people use familiarity-based retrieval more often, which results in faster but less accurate recognition judgments. We conclude that STM search processes flexibly adapt to current task conditions and finally propose two-phase model of STM search.*

***Key words**: short-term memory, STM retrieval, STM search, Sternberg paradigm, familiarity, recollection*

On the role of task conditions in short-term memory retrieval

The seminal paper by Saul Sternberg (1966) resulted in numerous studies aimed at the discovery of processes responsible for short-term memory (STM) retrieval. In its classical version, the task consisted in sequential presentation of a series of items and the participants were asked whether a probe appearing at the end of the sequence was present in the previous set. A typical result shows that response times (RT) of correct responses increase as a function of a number of elements in the set. Sternberg himself believed that this pattern of data suggested that the contents of short-term memory store were scanned serially and exhaustively. Serial scanning involves revision of the stored elements one by one. Serial processing models assume that average processing time for every item is identical regardless of the number of elements stored in STM (set size, SS) and the position of an item in the set. Therefore, these models predict that the set-size function (mean RT as a function of the number of elements in the set) will be linearly increasing with the number of items in the set (van Zandt & Townsend, 1993). This effect was indeed repeatedly confirmed (Sternberg, 1966, 1969, 1975).

Exhaustive search, on the other hand, implies that people investigate the complete list of stored elements even if the correct match is already available. This assumption appears counterintuitive because the search process should self-terminate as soon as a correct match is found (see Ashby, 1976). However, it is usually found that the relationship between RT and the number of elements in a set is linearly increasing regardless of whether the probe stimulus was presented earlier or not (Townsend & van Zandt, 1990; van Zandt & Townsend, 1993). These findings generally confirm Sternberg's arguments that people tend to scan the whole STM store, as if the scanning process, once started, had to be carried out automatically until every possible element is checked.

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However, the examples of cognitive economy principle are plenty. Based on this principle, the exhaustiveness of scanning seems to make sense only in negative trials where the probe was not present and participants have to search the whole STM content to respond correctly. In positive trials, though, where the probe was present in the set, people should search the STM store until the first matching element is found. Interestingly, one should expect a linear increase of RTs in both cases. Although this assumption is straightforward in case of negative trials it is also valid for positive ones since increasing the number of elements in a set should result in longer reaction times as well. However, the RT/SS function should be less steep in the case of positive trials because search items usually appear before the end of the series.

Another interesting question about Sternberg's findings is how exactly participants produce recognition judgments based on STM search processes. Some theories propose that performance in recognition memory tasks (e.g. Sternberg's task) depends on two separate mechanisms: a fast-acting, automatic familiarity process and a slower, controlled recollection process (see: Yonelinas, 2002, for a review). The difference between these two processes is commonly and intuitively understood. It can be illustrated by the experience of recognizing someone as familiar but not being able to recollect who this person is or where he or she was previously encountered. These two processes contributing to recognition have been studied from both cognitive and neurophysiological perspectives (Göthe & Oberauer, 2008).

Yonelinas (1999) assumes that familiarity and recollection stem from different retrieval processes. Familiarity is based on the strength of memory traces. A recognition response is then based on a specific response criterion. Item's recognizability can be thought of as a function of the strength of a memory trace that depends on a stimulus salience. Recollection, on the other hand, includes retrieval of contextual information, such as spatiotemporal context, as well as associations between different components of a study event. If such information is available, recollection dominates recognition judgments. However, when no such information is available to a participant, an item is retrieved below the recollective threshold and the recognition judgments depend only on familiarity. Furthermore, it is assumed that recollection and familiarity act in parallel at the time of retrieval and influence recognition fairly independently (e.g., Jacoby, 1991; Yonelinas, 2002). Familiarity is also thought to be faster than recollection (Yonelinas & Jacoby, 1994, 1996).

Time is an important factor influencing the familiarity and recollection processes in recognition judgments in a different way. For example, making accurate discriminations between recently studied and nonstudied items under speeded test conditions is based more on familiarity than recollection (Yonelinas, 1997, 1999). Also, allowed encoding time should influence the contribution of the two processes, since time spent on encoding influences the quality of memory traces in STM. We assume that the shorter exposure of a stimulus set the less information is available for recollection. Conversely, speeding-up the exposure should affect familiarity to lesser extent and therefore we expect familiarity to contribute more than recollection to recognition judgments when items are presented fast enough. Specifically, when items to memorize are presented with enough time to be efficiently encoded we should observe an increase in response latencies as a function of the number of elements to be memorized in a given set. Contrary to Sternberg's original conclusions, we expect that STM search would be exhaustive in case of negative trials whereas it should self-terminate in positive trials as soon as a positive match is found. Therefore, we predict shorter response latencies in the latter case, regardless of set size. However, as exposure times get shorter participants would rely more on familiarity than recollection, especially in case of positive trials where STM search is self-terminating as soon as a positive match is found. This match would automatically trigger a YES response in positive trials. However, when a positive match is not found, participants would still be required to search the whole STM content. The absence of a positive match in negative trials would motivate participants to use more effortful recollection; therefore, we should expect greater set size effect on RTs in negative rather than positive trials.

Additionally, the number of errors is expected to depend on set size, type of trials (positive vs. negative), as well as exposure time. Firstly, the total number of errors is assumed to increase as a function of the number of elements presented in the set. This expected effect would reflect increasing demands on limited memory capacity, which has been confirmed by many researchers. Secondly, error rates are expected to be higher in positive than negative trials, for two reasons. On one hand, self-terminating search in positive trials should result in more errors because of possible similarities between a probe and elements in the set size. For example, number seven is perceptually similar to number one, and therefore it can elicit an incorrect 'no' response when both items are present in memory and one of them is a probe. In such cases, participants' low confidence would lead them to a safer 'no' response. On the other hand, shorter exposure times should result in more errors in general since memory traces are weaker or less salient due to shorter exposure to the elements in the set.

Thus, we assume that set size will affect exhaustive search independently of exposure times whereas the set size effect on self-terminating search will be greater for longer exposure times as compared with shorter durations of item presentations. Also, item familiarity decreases more rapidly than recollection over short retention intervals (Yonelinas, 2002) and therefore for longer exposure times we should observe more reliance on recollection, as the recognition is required later in time as compared to shorter exposure times. Additionally, shorter exposure times and greater set sizes should result in more errors in recognition judgments due to decreased salience of memory traces and STM limited capacity, respectively. Those ideas will be tested in three separate experiments using a modified Sternberg's paradigm.

Experiment 1

Method

Participants

Sixty-two (46 female and 16 male) first year psychology students volunteered to this experiment for course credits. Their mean age was 20.95 (SD = 3.94).

Stimulus material

Stimuli used in this experiment were digits from 0 to 9 (3 cm × 4 cm) presented on the 15” computer screen located approximately 70 cm from participants’ eyes.

Procedure

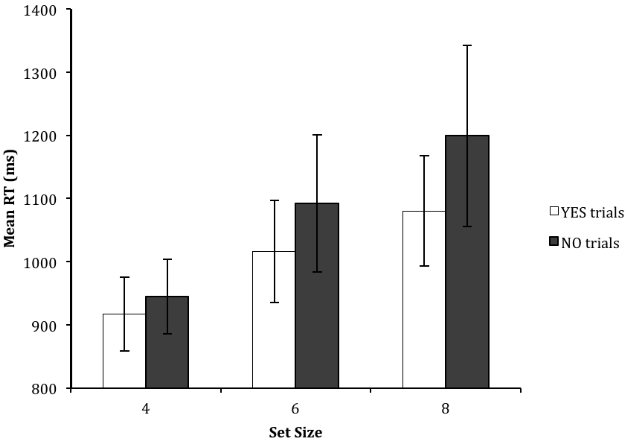
We employed a task called STM-1, based on the classical Saul Sternberg’s procedure. Each trial started with a 1000 ms presentation of fixation point (*) that was followed by a set of digits. Each digit was presented for 1000 ms with ISI = 0 ms. Immediately after last digit’s disappearance, another asterisk appeared for 300 ms, indicating the end of a set. Finally, a probe digit that either was or was not present in the previous set appeared approximately 5 cm above the asterisk and stayed until response. Participants were instructed to indicate whether the probe was presented in the previous set by pressing the relevant response keys (YES vs. NO) on a computer keyboard. Next trial began after the response with ITI = 300 ms.

Two independent variables were manipulated within subjects. Firstly, we presented four, six or eight digits in the sets (set size, SS). Secondly, the response required was either YES or NO, depending on whether the probe actually appeared in the set. On YES trials, we also controlled for the serial position of the target digit (identical to the probe) in the set. Namely, the target digits appeared six times in the first position in the set, six times in the second position, and so on. Hence, there were 16 trials where set-size equalled 4 four, 24 trials with six elements in the set, and 32 trials with set size equal 8. Therefore, there were 72 YES trials and they were matched with exactly the same number of 72 NO trials, making altogether 144 trials in the whole task. Additionally, 24 training trials and the instructions for participants preceded the main task. The sequence of trials, as well as the succession of digits in each set, was randomized on a participant basis. Reaction time and accuracy of responses were registered in every trial. However, only the correct responses will be taken into account in all statistical analyses concerning response latencies.

Results

Response times were analysed in a 3 (Set-Size: 4 vs. 6 vs. 8) × 2 (Required Response: YES vs. NO) repeated measures ANOVA. It yielded significant main effects of set-size, $F(2, 122) = 28.46$, $p < .001$, $h^2 = .32$, as well as required response, $F(1, 61) = 11.27$, $p < .01$, $h^2 = .16$. Mean response times increased with set size (931, 1054, and 1139 ms for four, six, and eight digit SS, respectively). They were also significantly shorter on YES trials (1004 ms) compared to NO trials (1079 ms). Those main effects were qualified by the interaction between SS and required response, $F(2, 122) = 3.95$, $p < .03$, $h^2 = .06$ (see Fig. 1). The analyses revealed stronger SS effect on YES trials, $F(2, 122) = 27.47$, $p < .001$, $h^2 = .31$, than NO trials, $F(2, 122) = 20.56$, $p < .001$, $h^2 = .25$, mainly due to a larger variance in RTs in the latter case. Separate comparisons between YES and NO trials for different set-sizes revealed significant effects in case of eight digits, $F(1, 61) = 8.73$, $p < .005$, and six digits, $F(1, 61) = 8.86$, $p < .005$, whereas those difference failed to reach statistical significant for four set-size, $F(1,61) = 3.07$, $p > .05$. Also, planned comparisons unveiled that on both YES and NO trials all differences between set-sizes were significant (all *p*s < .001).

Figure 1. Mean reaction times from Experiment 1 as a function of set-size and required response (YES vs. NO trials). Whiskers represent 95% CI



The overall error rate (ER) was analysed in a similar 3 (Set-Size: 4 vs. 6 vs. 8) × 2 (Required Response: YES vs. NO) within-subject design. It yielded main effects of both set-size, $F(2, 122) = 86.03$, $p = .001$, $h^2 = .73$, and the required response, $F(1, 61) = 11.81$, $p < .01$, $h^2 = .59$. ER increased linearly with set size: from 6.2% of errors in four SS, through 10.4% in six SS, up to 14.4% in eight SS (all *p*s < .001). The differences between ER in four and six SS as well as six and eight SS were also significant, $F(1, 61) = 44.70$, $p < .001$, and $F(1, 61) = 38.38$, $p < .001$, respectively. Also, mean ER was higher on YES trials (11.9%) than on NO trials (8.8%). Set-size and required response did not interact significantly on error rates, $F(2, 122) = 1.02$, $p > .05$, $h^2 = .02$.

Discussion

This experiment conceptually replicates some of the original findings from Sternberg (1966). Namely, we show a linear increase in response latencies and the number of errors as a function of increasing number of elements in the set. However, contrary to his reports, our data show shorter response times on positive trials, where the probe was present in a set, than on negative ones. Moreover, the influence of set size on response latencies was relatively stronger on positive as compared to negative trials. Those effects, in line with findings from other researchers (see Nęcka, 2000; Yantis & Jonides, 1984), suggest that STM search is exhaustive when there is no match between the probe and content of STM, so memory has to be examined thoroughly to produce a correct answer. However, the process self-terminates whenever the match is found (van Zandt & Townsend, 1993; Townsend & Colonius, 1997).

In Experiment 2, we decreased the exposure time of each element in the set. On one hand, we should observe longer reaction times across all conditions because of higher task demands on memory. However, based on the assumption that less salient memory traced are produced due to shorter exposures to a series of elements in the set, we expect that recognition judgments will be based on familiarity to more extent than in Experiment 1, which should lead to shorter reaction times overall, as familiarity is associated with faster responses than recollection. This effect should be especially visible in positive trials, since a positive match would generate a correct 'yes' response faster when it is based on familiarity than on recollection. At the same time, because familiarity depends on the strength of memory traces (Yonelinas, 2002), which is a function of exposure time, we should find more errors in 'yes' trials in Experiment 2 than in Experiment 1.

Experiment 2

Method

Participants

Sixty-three (43 female and 20 male) first year psychology students participated in this experiment for course credits. Their mean age was 21.01 years (*SD* = 3.47).

Stimulus material

We used identical stimuli as in Experiment 1.

Procedure

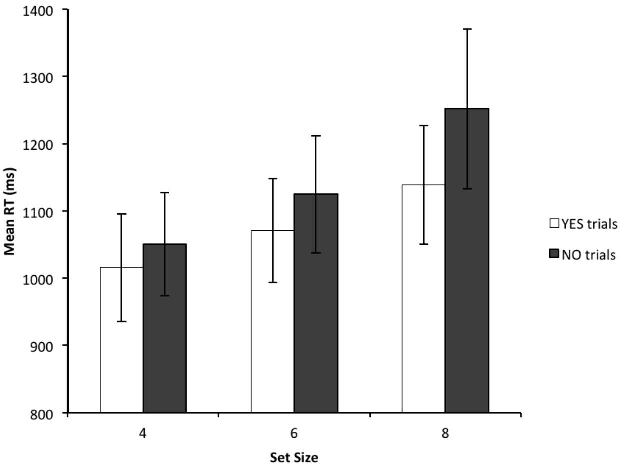
The procedure STM-2 was the same as in Experiment 1 except for the duration with which every single item in the set was presented. This time, each digit remained on the screen for 700 ms.

Results

RTs were analysed in a 3 (Set-Size: 4 vs. 6 vs. 8) × 2 (Required Response: YES vs. NO) within-subject ANOVA that revealed main effects of both factors, $F(2, 124) = 25.16$, $p < .001$, $h^2 = .29$, and $F(1, 62) = 8.32$, $p < .01$, $h^2 = .12$, respectively. Mean RTs were faster when SS included four digits ($M = 1030$ ms) compared to six digits ($M = 1098$ ms), $F(1, 62) = 10.60$, $p < .001$, and eight digit SSs ($M = 1195$ ms), $F(1, 62) = 32.16$, $p < .001$. Also, participants responded faster on six digits SSs than on eight digits SSs, $F(1, 62) = 25.32$, $p < .001$. They also responded significantly faster on YES ($M = 1075$ ms) than NO trials (RT = 1142 ms).

Moreover, the two factors interacted significantly, $F(2, 124) = 3.88$, $p < .05$, $h^2 = .06$ (see Figure 2). The effect of SS on RTs in case of NO trials, $F(2,124) = 21.37$, $p < .0001$, $h^2 = .26$, was stronger than on YES trials, $F(2,124) = 14.71$, $p < .0001$, $h^2 = .19$. All contrasts between the three levels of the SS variable were significant on YES and NO trials (all *p*s < .01). Further comparisons between YES and NO trials, run separately for all SSs, yielded significant differences in RTs on eight digit SS, $F(1, 62) = 12.61$, $p < .001$, as well as six digit SS, $F(1, 62) = 4.00$, $p < .05$, but not on four digit SS, $F(1, 62) = 1.59$, $p > .05$.

Figure 2. Mean reaction times from Experiment 2 as a function of set-size and required response (YES vs. NO trials). Whiskers represent 95% CI



Similar analyses of error rates showed main effects of set-size, $F(2, 124) = 176.98$, $p < .001$, $h^2 = .74$, as well as required response, $F(1, 62) = 26.48$, $p < .001$, $h^2 = .30$. The lowest ER were observed in four digit SS ($M = 4.10\%$) as compared to six ($M = 9.94\%$), $F(1, 62) = 108.87$, $p < .001$, and eight digit SSs, ($M = 14.21\%$), $F(1, 62) = 350.76$, $p < .001$. It also appeared that the percentage of errors was significantly higher on YES trials (11.5%) than on NO trials (7.3%). Additionally, set-size and required response interacted significantly, $F(2, 124) = 3.88$, $p < .02$, $h^2 = .10$. In YES conditions ERs grew up from 5.02% (SS = 4), through 13.05% (SS = 6), up to 16.53% (SS = 8). In NO conditions errors rate increased from 3.17%, through 8.83%, up to 11.90%, respectively. All differences were significant (all *p*s < .01). Further comparisons between YES and NO trials run separately for all SSs yielded significant differences in ERs on eight digit SS, $F(1, 62) = 12.99$, $p < .001$, as well as six digit SS, $F(1, 62) = 36.14$, $p < .001$ and four digit SS, $F(1, 62) = 4.66$, $p < .05$.

Discussion

The general pattern of results observed in Experiment 2 is very similar to what had been obtained in Experiment 1. We replicated the data showing exhaustive STM search in negative trials and self-terminating search in positive trials. The increase in RTs and error rates as a function of set size was also confirmed. Therefore, we show that recognition judgments based on searching the STM content depend on both response type and the number of elements to be examined.

We can conclude that decreasing exposure times proved to be more demanding in terms of encoding the stimuli. At the same time we did not observe any differences in the RTs dependence on set size between the experiments. If familiarity-based strategies of responding would contribute to recognition judgments in this study more than in the previous one, we should observe faster response times in general and less steep relationship between RT and set size in positive trials. None of the above was found in the data. Also, the expected increase of error rate in positive trials was not observed. A possible reason for the lack of such differences is that the difference in exposure times between Experiment 1 and 2 (1000 ms vs. 700 ms) was too little to allow for a significant change in the processes determining recognition judgments. We therefore decided to run another study, in which exposure time would be significantly reduced (to 300 ms) in order to investigate how recognition judgments in positive and negative trials depend on familiarity and recollection.

Experiment 3

Method

Participants

Seventy-one high school students (42 female and 29 male) volunteered to this experiment with no compensation. Their mean age was 16.8 (*SD* = 0.41).

Stimulus material

Stimulus material did not differ from Experiments 1 and 2.

Procedure

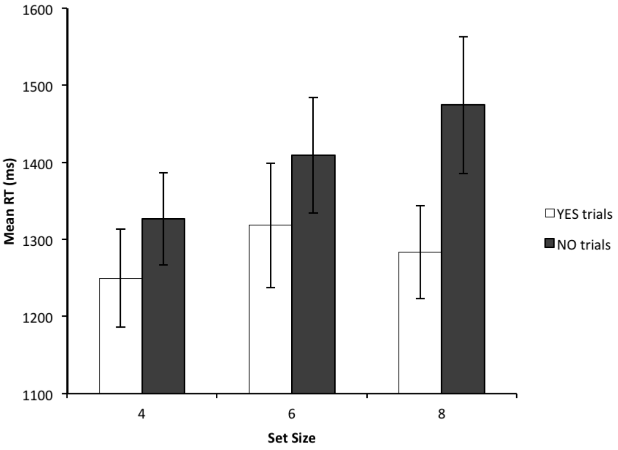
The procedure STM-3 was the same as in Experiment 1 and 2, but with one exception. The time of presentation of each digit in the sequence was set up for 300 ms.

Results

Response times were analysed in a 3 (Set-Size: 4 vs. 6 vs. 8) × 2 (Required Response: YES vs. NO) within-subject ANOVA. The analysis revealed main effects of set size, *F*(2, 140) = 5.07, $p < .01$, $h^2 = .07$, and required response, *F*(1, 70) = 35.85, $p < .001$, $h^2 = .34$. The set size effect was powered by the difference in RTs between four digits (*M* = 1283 ms) and six digits SS (*M* = 1341 ms), *F*(1,70) = 4.07, $p < .05$, whereas the increase between six and eight (*M* = 1370 ms) digits SSs failed to reach statistical significance, *F*(1, 70) = 1.44, $p > .05$. It means that the relationship between SS and RT was curvilinear, to the effect that it became less and less steep as the set size increased. The difference in RT between YES (*M* = 1269 ms) and NO (*M* = 1394 ms) trials was highly significant this time.

There was also a significant interactive effect between SS and required response, *F*(2, 140) = 3.57, $p = .05$, $h^2 = .05$ (see Figure 3). Additional analyses revealed a significant effect of set-size in case of NO trials: *F*(2, 140) = 6.71, $p < .05$, $h^2 = .09$, but not on YES trials, *F*(2, 140) = 0.38, $p < .05$, $h^2 = .005$. Detailed comparisons between set-sizes in case of NO trials showed a significant difference between four and six digits SSs, *F*(1, 70) = 4.73, $p = .05$, and between four and eight digits SSs, *F*(1, 70) = 12.93, $p = .001$ (all other *p*s > .05). Further analyses contrasting YES and NO trials separately for all SSs showed significant differences in RTs on eight digit SS, *F*(1, 70) = 28.70, $p < .001$ and on six digit SS, *F*(1, 70) = 8.22, $p < .01$, but not on four digit SS, *F*(1, 70) = 3.13, $p < .05$.

Figure 3. Mean reaction times from Experiment 3 as a function of set-size and required response (YES vs. NO trials). Whiskers represent 95% CI



Error rates were analysed in the same design as RTs. The analysis unveiled main effects of both set-size, *F*(2, 140) = 40.63, $p <.0001$, $h^2 = .37$, and required response, *F*(1, 70) = 63.59, $p <.0001$, $h^2 = .48$. The lowest ER were observed in four digit SS (*M* = 11.74%) as compared to six (*M* = 15.26%), *F*(1, 70) = 28.62, $p < .0001$, and eight digit SSs, (*M* = 17.73%), *F*(1, 70) = 84.97, $p < .0001$. Error rates were significantly higher on YES trials (19.17%) than on NO trials (10.65%). Additionally, set-size and required response interacted significantly, *F*(2, 140) = 6.40, $p < .005$, $h^2 = .08$. In YES conditions ERs grew up from 14.73% (SS = 4), through 19.60% (SS = 6), up to 23.18% (SS = 8). In NO conditions errors rates increased from 8.74%, through 10.92%, up to 12.29%, respectively. All differences were significant ($p < .01$) in YES condition, whereas in NO condition only the difference between four and eight elements set sizes reached significance. Further comparisons between YES and NO trials run separately for all SSs yielded significant differences in ERs on eight, *F*(1, 70) = 67.37, $p < .0001$, six, *F*(1, 70) = 38.50, $p < .0001$, as well as four digit SS, *F*(1, 70) = 22.52, $p < .0001$.

Discussion

The results of the third experiment allow the conclusion that there are different strategies of search of the STM store depending on which response is expected in a given trial. If the probe is identical with the target, participants are supposed to give a positive decision. In this situation the search seems to be based on familiarity. In other words, people respond with the same speed, regardless of how many digits they have to inspect in order to find a target. Since the familiarity response is occurring shortly after the probe, the reaction time does not depend the number of elements to be search in the STM. If there is no target identical with the probe, participants are supposed to give a negative decision. In such a situation, the recognition judgments seem to be based on effortful recollection rather than automatic familiarity process, so the more digits have to be inspected the more time is needed for that. It is important to remark that these differences in strategy of STM retrieval became evident only in the third experiment, in which the pace of stimuli presentation had been speeded up to 300 ms per item. However, traces of such differences were visible to some extent in Experiment 2 as well, although they were not strong enough to allow convincible conclusions.

Although the analysis of response time seems to be the best way to examine cognitive strategies, the data concerning accuracy are also of great importance. It is therefore worth mentioning that error rate was always linearly dependent on set size, regardless of the YES/NO factor and regardless of the pace of stimuli presentation. Moreover, error rate was always higher in the YES condition as compared to the NO condition. This finding confirms our expectation that in positive trials participants rely on fast familiarity impressions more than on slow recollection of encoded material.

General Discussion

In three experiments we investigated processes underlying the short-term memory search and recognition judgments that follow this search. We looked for differences in retrieval processes engaged in recognition over short retention intervals. Specifically, we assumed that retrieval based on familiarity and recollection would differently contribute to recognition depending on exposure time and a type of required response.

The results obtained for longer exposure times (700 and 1000 ms) do not allow us to identify the architecture of STM search unambiguously, because a linear increase in reaction time as a function of set size is acceptable both in sequential and parallel models, as long as we adopt the assumption of limited efficiency of the system (Van Zandt & Townsend, 1993). The differences in reaction times between positive and negative trials together with different slopes of the RT/SS function allow us to cautiously conclude about the exhaustive search rule in the negative condition and the self-terminating rule in the positive one. What prevents us from drawing strong conclusions about the strategies is the fact that in large sets some of the memory traces might have been gone before search processes start to operate. Therefore, our conclusions should in fact be limited to assessing that probably more items are searched in the negative condition that in the positive one.

For short exposure times (i.e. 300 ms) we initially assumed that the architecture of the search process is parallel in positive trials, as indicated by the flat RT/SS function, and sequential in the negative trials. At the same time, from the differences in reaction times and in the slopes of the RT/SS function between positive and negative trials, we can infer that there is an exhaustive search in the negative condition and a self-terminating search in the positive condition. While the conjunction of sequential architecture and an exhaustive stopping rule within a single process is acceptable, parallel architecture excludes a self-terminating stopping rule. Since the system has simultaneous access to all the items, the search encompasses the whole (accessible) set. Therefore, it should be concluded that for short exposures the search is parallel and exhaustive.

However, there is another problem here. The cognitive system is not able to identify the type of trial (positive vs. negative) before the search is finished, so how could it “know” which type of search it should launch: sequential (in negative trials) or parallel (in positive ones)? The cognitive system “learns” about the type of trial only after the search is finished, and only if it has been correct. Thus, it seems that the architecture of the search process must be fundamentally the same in positive and negative trials.

In dual-process theories it is sometimes assumed that the searches based on familiarity and recollection are launched simultaneously and are conducted in parallel until one of them returns a result (Yonelinas, 2002). The data obtained in our research could be explained by assuming that the flat RT/SS function results from the fact that a response is generated exclusively on the basis of familiarity assessment and encompasses all the accessible items in parallel. Recollection, on the other hand, would be the source of response in the negative condition, and would generate an increase in RT for larger sets. This would explain the results for the 300 ms exposure condition, including recognition accuracy which was lower in the positive condition (probably resulting from the use of a more unreliable process of familiarity assessment in the search). However, this explanation raises some doubts. First, it involves the assumption that the system in the positive condition does not use recollection, and in the negative condition – it does not use familiarity. This seems to contradict conclusions drawn by Oberauer (2001) who argues that in larger sets that exceed the capacity of the focus of attention and the direct access area, familiarity is the only mechanism of access to the oldest elements with trace activation. Therefore, it is not the type of trial that decides which process – familiarity or recollection – provides cues triggering the decision to response, but it results from the level of activation of the searched area.

Second, shortening the exposure time was to disrupt the process of encoding distinctive features, without which recognition cannot take place. This, of course, applies to both positive and negative trials. The assumption that such manipulation leads to disruption of encoding only in the positive condition (but not in the negative one) is illogical. Thus, if the results in negative trials indicate the recollection process, then certain distinctive features of the stimuli must be accessible in both conditions.

Third, it would be necessary to explain why familiarity may be the only basis of a response in shortly presented positive trials, whereas it is the recollection that becomes important for longer presentation times. In order to maintain this explanation, one would have to assume that the manipulation of exposure duration launches fundamentally different mechanisms of WM search. And finally, fourth, the mere assumption about parallelism of two processes seems to be quite exotic. Simultaneous initiation of two processes having the same goals, as well as control and integration of their results (they might be contradictory after all), would be a very effortful task of the kind the cognitive system tries to avoid.

Theoretical model

An inspiration in the search for a noncontradictory explanation concerning both the architecture and the mechanism of the search, proved to be the theories of perceptual field search involving attention. These are theories that divide the search into two phases (e.g. a model of segregation of features guiding attention, Wolfe, Cave, & Franzel, 1989; Cave & Wolfe, 1990; two-stage conception of visual-spatial processing, Schneider 1999; feature integration model, Treisman & Gromican, 1988). For example, Wolfe (1994; Wolfe et al., 1989) considers that in the perception of objects some of their features are encoded pre-attentively and can parallelly "guide" attention in the search for a specific object in the perceptual field. The efficiency of this search is determined by the quality of cues obtained in the first, parallel phase of the search. The authors identified two components of the parallel processing: bottom-up and top-down. During the search of the field, the bottom-up and top-down components operate independently, separately for each of the features of stimuli. The bottom-up activation comes from the physical features of stimulation. The top-down activation is based on expectations, for example, coming from an earlier presentation of the target or from earlier knowledge about its features. Both processes cause activation of all the representations of particular features that are known to characterize the stimulus. These two sources of activation produce the so-called general activation map. It does not contain information about the source of activation, but only directs attention to the most active regions, that is the places with the highest combined activation of bottom-up and top-down components. In the second phase of the search, attention is being shifted – sequentially – between the most activated regions of the map, until the target is found (i.e. until a complete match of activation coming from bottom-up and top-down components for all of its features). If the target is not found, activation decreases and below a certain threshold the search is self-terminated.

Drawing inspiration from the above theoretical model, we propose a two-phase model of short-term memory search. During the sequential presentation of stimuli, a temporal representation of each of them is created. Both the rate of exposure and the type of material significantly affect the process of its encoding. If the rate of exposure is fast, the encoding may be disrupted, and that means either selective encoding of the features of objects (a mechanism that would rather apply in relation to non-verbal stimuli, because they are defined by many features), or some difficulty of verbalization, e.g. in the case of digits, letters or words. The presentation of the target stimulus initiates the search process, which is closely related to the accessibility of the material. Time or interference, especially in the case of larger sets, may effectively reduce accessibility. The first, parallel phase of the search process, analogous to familiarity, consists in determining the order of items, according to which the proper process of recollection will be conducted. Thus, the first phase would be a process of indexing stimuli. Two factors would "guide" this indexing stimuli as candidates for the target. The first is the level of activation, understood as the strength of excitation of representations. If stimuli are equivalent, i.e. there are not any salient stimuli among them, then the search proceeds from the most active stimulus (that is, the most often recently presented), to the least active. Thus, it seems that the search order is determined by the level of activation of stimuli, and consequently, their accessibility. The second factor that could serve as a guide in indexing stimuli is the similarity of the elements in the set to the target, assessed – in the first phase – globally and in parallel. This assessment is carried out in relation to the discriminative features, and that appears especially important in the case of complex stimuli, e.g. non-verbal, that do not lead to an automatic excitation of existing representations, as in the case of familiar letters or digits. In contrast to the assumptions made by dual-process theories, the first phase, which may be considered as equivalent to a search based on familiarity assessment, does not lead to generating a response.

Information coming from the first stage – delivered very quickly, as a result of a parallel process – is "only" a cue for the second, sequential phase of the search. The latter consists in a thorough comparison of the "candidates" – selected in the first phase – for the target. This second phase would be essentially what other researchers call recollection. In this phase, the bottom-up activation, coming from the map of indexed stimuli, is being sequentially compared – taking into account discriminative features of stimulation – with the top-down activation, coming from the probe. We postulate, therefore, a strict temporal succession of two phases: the first phase of parallel indexing of stimuli and the second phase of the sequential comparison of the stimuli with the probe. Information from the first phase would be used in the subsequent one as a cue concerning the search order. The efficiency of this type of search is highest, when the level of activation or similarity of the probe to the target is not related to its position in the set.

It seems that the proposed model copes well with all the obtained results, including apparent anomalies in the search process showed for 300 ms exposure duration. In the proposed model, the architecture of the search process is the same in positive and negative trials. In both cases, it starts with a phase of parallel indexing of stimuli that in positive trials proves to be an important cue for the search, therefore even the first (or one of the first) comparisons of the probe with properly indexed WM content may – in the second phase – demonstrate their match. In the case of negative trials, the cues from the parallel phase are being successively falsified, leading ultimately – after the search of all the accessible material – to a negative response. Therefore, generally negative responses are significantly slower than positive ones.

If the exposure time in Sternberg's task is significantly shorter than optimal, there is a disruption of the encoding process, which means a shallow encoding that in an extreme case can be based on a single, distinct feature of the stimulus. The important thing is that this feature may not be important in the discrimination process. Then the only cue available in the phase of sequential search is the general level of activation, resulting from indexation in the first phase. Sequential search process, not having any other sources of information, is using only this cue, and already in the first comparison of the element best matching the probe, it generates a response. This happens regardless of the size of the set of elements. That is why the RT/SS function "appears" in this condition as parallel, although in fact it is always an effect of combining the first parallel indexing phase and a single – regardless of the set size – comparison in the sequential phase. Unfortunately, with the increasing cognitive load (set size), this mechanism leads to a growing number of errors due to limited access to a larger and larger part of the material. In the negative condition, the information delivered from the first phase to the second phase also provides information about the general level of activation, however, due to a lack of correspondence between the general bottom-up and top-down activation, the search continues for all the accessible items. This process is dependent on the set size, so the RT/SS function monotonically increases. Nevertheless, due to the disruption of the encoding process caused by a short exposure duration, the effectiveness of this process is also relatively low, as indicated by a high number of errors.

The proposed dual-phase model of STM search is not only supported by – perhaps distant – attentional theory of search in the perceptual field. A few theories propose similar mechanism also in relation to working memory, e.g. the model of two-stage search of visual working memory (Gilchrist & Cowan, 2014). In this model, the first, fast stage of the search focuses on assessing novelty of the probe stimulus. If the level of novelty is low, then the second, slower stage is launched, that consists in an exhaustive comparison between the probe and the contents of visual working memory. There is also a theoretical possibility that these mechanisms are in fact identical; of course, this is just a speculation, but worth considering in further studies.

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