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Individual differences in Sternberg's memory scanning task

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ABSTRACT

This study provides a new perspective on both the cognitive processes actually implemented and the effect of a simple experimental control – the recall constraint – in Sternberg's memory scanning task. These findings were highlighted by adopting a new approach based on the comparison of qualitative and quantitative results.

The analysis of individual processing, on 72 adults, each participating in one of two experimental conditions (with or without sequence recall), highlighted a large variability in quantitative results as well as qualitative procedures. Based on the participants' retrospective verbalisations, two categories of strategies were identified: (1) the procedures used to memorize the sequence of digits, and (2) the procedures used to compare this sequence with the test digit, which includes strategies for coding the items and processes for searching them in memory. The analysis of the strategies shows that their frequencies of use depend not only on the experimental condition, but also on the participants, the level of task difficulty and the interaction between participants and level of difficulty. This variability questions the accuracy of Sternberg's mean model. Furthermore, this approach suggests some answers to the old debate concerning the exhaustive search pattern for the *yes* response. Indeed, our results show three types of strategies that can be identified according to the different models of search suggested in the literature. The "exhaustive" search, that would only be involved in the recall condition and only for some of the participants, the "self-terminating" search and the "immediate" strategy, which can be identified with a model of parallel search with limited resources. Thus our study suggests that the different search models are appropriate but depend on both the specific experimental conditions and participant's strategy. Our results should help to improve the interpretation of data collected with this paradigm in cognitive and neuroscientific studies of memory.

1. Introduction

Numerous studies have relied on Sternberg's memory scanning paradigm in the past, in general psychology (e.g., Baddeley & Ecob, 1973; Burrows & Okada, 1973; Corballis, Kirby, & Miller, 1972; Monsell, 1978; Theios, Smith, Haviland, Traupmann, & Moy, 1973) and differential psychology (e.g., Hunt, 1978; Hunt, Frost, & Lunneborg, 1973). However, despite many studies using Sternberg's paradigm, no consensus exists on the processes really implemented in this task (e.g., Monsell, 1978; Townsend & Roos, 1973). For example, there is still an active discussion about the kind of search that this task involves: serial exhaustive (e.g., Sternberg, 1966, 1975; Wingfield & Branca, 1970), serial self-terminating (e.g., Theios et al., 1973; Townsend & Roos, 1973), parallel with resource limited search (e.g., Atkinson, Holmgren, & Juola, 1969; Burrows & Okada, 1973; Townsend, 1971) or direct access without search (e.g., Baddeley & Ecob, 1973; Burrows & Okada, 1971; Corballis et al., 1972; Monsell, 1978). Recently, the Sternberg paradigm has been implemented in cognitive neuroscientific studies of memory (e.g., D'Esposito, Postle, & Rypma, 2000; Jensen, Gelfand, Kounios, & Lisman, 2002; Rypma, Berger, Genova, Rebbechi, & D'Esposito, 2005).

Given the lack of a consensual model to account for the results observed during the execution of Sternberg's memory scanning paradigm, we propose to use Marquer and Pereira's (1990a) approach to understand better the processes involved in this task. This approach assumes that a given task can be performed in several ways and that subjects differ in their choice and in the combination of processes. Consequently a single "mean model" cannot adequately reflect this variability. Analyses of individual data are used to generate individual models. Subjects are then classified into groups on the basis of similarities between individual models. A mean model is generated for each of these groups, which summarizes features shared by all subjects in the group. The validity of these mean models is tested by means of other independent

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sources of information (Marquer & Pereira, 2002). In previous research using other paradigms (e.g., Marquer, 2005; Marquer & Pereira, 1990a, 1990b, 2002), by adopting this approach, it was found that participants actually implemented much more varied cognitive processes than the literature suggests. Moreover, most of the strategies implemented in the experimental tasks can be adequately described by one of the previous mean models found in the literature. Thus, there would not exist one best model in general but each of these models would yield the best fit to the results of different groups of participants. However, Marquer and Pereira's (1990a) approach had never been used with Sternberg's paradigm.

1.1. Sternberg's Memory Scanning Paradigm

The varied-set procedure of Sternberg's "memory scanning" paradigm consists of presenting a sequence of 1 to 6 digits ("the positive set") among all digits between 1 and 9. Participants are instructed to memorize the sequence. After a signal, a test digit is presented and the participant has to decide whether or not the digit had occurred in the memory set. Then, to verify that the participants memorized the sequence, they are asked to recall the digits in their order of presentation.

Based on an analysis of mean response times, Sternberg derived two general findings (1966, 1969): (1) mean response time increases linearly with sequence length, and (2) the slope of the line is the same for *yes* and *no* responses. On the basis of these results he proposed an exhaustive serial search model of short-term memory retrieval.

Drawing an analogy with the computer, he explained that digits 1–9 could be regarded as locations in memory. During sequence presentation, a marker is placed in the location assigned to each digit in the sequence. The test digit is then compared to each marked location. If it is identical to one of them, the match is detected by a comparator and a *yes* response is activated. The linear increase in response time (first general finding) is explained by the assumption that the rate of checking locations, estimated by calculating the slope of the function, is constant. Because the *yes* response slope is the same as the *no* response slope (second general finding), Sternberg assumed that the search is exhaustive: that is, it continues until all marked locations have been checked, even if a match has already been detected. A *yes* response is not given until the memory scanning process has been completed. If the process stopped when a match is detected – in other words, if the search were self-terminating – the slope for *yes* responses would be lower than for *no* responses. Moreover, another argument that allows Sternberg to support the idea of an exhaustive search is the fact that there is no effect of the serial position of the test digit in the memory set on response times (RTs).

In addition to the slope, the regression of response time on sequence length is used to determine the zero intercept, which Sternberg interprets as the duration of the encoding and motor response process, assumed to be independent of sequence length.

1.2. Mean models and individual differences

This classical paradigm has given rise to numerous studies and interpretations of the processes involved in this task and their organization. Indeed, some authors have replicated and generalized Sternberg's results (e.g., Burrows & Okada, 1973; Chase & Calfee, 1969; Clifton & Tash, 1973; Foss & Dowell, 1971; Wingfield & Branca, 1970). Others have highlighted phenomena that are incompatible with the model proposed by Sternberg, such as a serial position effect, recency and primacy effects, an effect of the type of responses or even nonlinear functions of RT (e.g., Burrows & Okada, 1971; Corballis et al., 1972; Klatzky & Atkinson, 1970; Townsend & Roos, 1973; Wingfield, 1973). As we have seen above, several models were then proposed to account for these results. They have mainly characterized the search process: exhaustive vs. self-terminating, serial vs. parallel, limited vs. unlimited capacities (e.g., Atkinson et al., 1969; Burrows & Okada, 1973; Theios et al., 1973; Townsend & Roos, 1973); without forgetting the alternative models of "direct access" (e.g., Baddeley & Ecob, 1973; Corballis et al., 1972; Monsell, 1978). For example, Townsend and Roos (1973) found that the models of self-terminating search can easily predict the results, often associated with an exhaustive search process, but exhaustive search models are unable to predict the serial position effects and the differences in slopes found in the literature (regardless of whether the processing being serial or parallel). In the same way, parallel models with limited capacity could mimic serial models (e.g., Townsend, 1971; Townsend & Fific, 2004). Thus, despite the large amount of data on the Sternberg's paradigm, there is no unequivocal model (e.g., Monsell, 1978; Townsend & Roos, 1973).

However, although inter-individual variability on Sternberg's parameters has been emphasized in correlational studies (Chiang & Atkinson, 1976; Hunt et al., 1973; Puckett & Kausler, 1984) and in a few studies that have observed unexpected results (e.g., Atkinson et al., 1969; Corballis et al., 1972; Townsend & Roos, 1973), the possible variability of the strategies implemented by individuals has not yet been examined. In fact, even though some authors such as Chao and Knight (1996) or even Lemaire (2005), suggest the existence of different processes that can be used by an individual performing the task, the systematic study of the strategies involved in Sternberg's paradigm was never conducted. Chao and Knight (1996), based on Sternberg's four-stage model proposed that it is possible for individuals to compare the target to each item in short-term memory (STM) and decide if the target is one of the items in STM, in different ways. They thus defined three strategic processes: (1) a strategic process in parallel in which individuals simultaneously compare the target with all the items in STM, (2) a "self-terminating" strategy in which individuals stop comparing the target with the items as soon as a match is found, and (3) a serial exhaustive search in which all comparisons are made before reaching a decision.

We can note that these different strategies, defined in a theoretical way, correspond to the different mean RT models of search in STM provided in the literature, to which the decision models, based on the concept of trace strength, must be added. However, no research has sought to demonstrate experimentally the existence of these different strategies.

The first aim of this study is to see whether Marquer and Pereira's (1990a) approach, based on the analysis of individual procedures and the comparison of quantitative and qualitative results, can enhance our knowledge of the cognitive processes actually implemented during Sternberg's memory scanning task.

1.3. Effect of the recall constraint

In addition, we note that numerous past and current studies on the memory scanning paradigm differ from Sternberg's original one. Indeed, in his initial study with the memory scanning task, Sternberg (1966) showed participants a sequence of one to six digits and asked them first to decide whether a given test digit was in the sequence, and then to recall the digits in the order in which they had been presented. This last instruction is a serial recall demand used to ensure that subjects memorize well the presented sequence of digits. Since then, most studies using this paradigm have omitted this second part of the task, or have not mentioned it.

In a previous experiment (Corbin & Marquer, 2008), we studied the effect of the recall constraint on RTs. Concerning Sternberg's first general finding, our results showed that Sternberg's linear model fit equally well in both conditions (linear regression explained 98.7% and 98.1% of variance, respectively, in recall and no-recall condition). As for Sternberg's second general finding, our results replicated his findings in both conditions: there was a non-significant interaction between sequence length and type of response. Moreover, the analysis of response accuracy showed very low error rates, as Sternberg found, with a significant increase according to sequence length (ordered from 0.43% to 2.95%) but no differences between the two conditions. Thus, our data support Sternberg's general findings even when the participants did not have to recall the digit sequence.

However, our previous results showed that the participants in the no-recall condition answered faster than those in the recall condition. The longer latency in the serial recall condition can be explained by the fact that this constraint slows down execution of the main task by requiring additional attention to information order. Our results showed also an interaction between conditions and sequence length, which was only significant for the *yes* responses. We interpreted the latter finding in terms of differences between response trends. In the no-recall condition, for *yes* responses, the linear trend accounted for 97.1% of the variance but was not the only significant trend; the quadratic trend was significant too but only accounted for 2.7% of the variance. It seems that in the no-recall condition, the increase in RT for *yes* responses became less marked as the length of the sequences increased, approaching a plateau. For this condition and for this type of response, the logarithmic fit was as good as the linear fit. An interpretation in terms of exhaustive serial memory scanning may not be the only possible one, contrary to what was generally assumed in the literature (see Van Zandt & Townsend, 1993).

In a second analysis of the results, we tested the effect of the recall constraint on the nature of the task. With his experimental procedure, which requires recalling the sequence, Sternberg defined the task as a memory task. All results and the conclusions Sternberg and other authors draw from them are grounded in this definition. But is this task still a memory task if the recall constraint is not applied?

Studying the link between Sternberg's parameters and other abilities, we showed that the correlations differ considerably across the experimental conditions and factors considered. We found substantial differences between the two conditions, particularly regarding the involvement of short-term memory capacity (measured by the digit span task), which only exists in the recall condition ($-.29 < r < -.43$ for recall condition and $.14 < r < -.14$ for no-recall condition) (Corbin & Marquer, 2008). These results are congruent with those of earlier studies that did not use the recall constraint and found no significant correlations between span and scan rate within a class of material (e.g., Brown & Kirsner, 1980; Chiang & Atkinson, 1976; Puckett, 1982; Puckett & Kausler, 1984).

In summary, our previous results showed that, at first, this constraint did not seem to have much of an effect from a quantitative standpoint. This may explain why the authors who have used this paradigm have not taken an interest on the impact of the recall requirement. However, our previous results also highlighted that the recall constraint in Sternberg's memory scanning task has an impact not only on task execution but also on its nature. Finally, these previous results, obtained from a strictly quantitative analysis, revealed some phenomena that deserve further attention.

Thus, the second aim of the current research is to see whether the comparison of qualitative and quantitative analyses can shed light on the effect of the presence or absence of the recall constraint. This comparison should provide insight into how participants organize their processes into cognitive strategies and whether or not these strategies are the same regardless of the condition.

These questions about the nature and the processes really implemented in this task are particularly important given that this paradigm has not only been used in the past in the traditional experimental psychology but is widely used today as a memory task in neuroscience research.

Thus, our study had two objectives: first, to examine the cognitive processes actually implemented during the Sternberg memory scanning task by adopting Marquer and Pereira's (1990a) approach; and, second, to see whether such analyses can shed light on the effect of the presence or absence of the recall constraint.

2. Method

The experiment consists of two sessions each lasting about 45 minutes. The first session was used to obtain participant scores on a number of ability tests including a span measurement; the second, two weeks later, was devoted to the Sternberg paradigm. To avoid a task-interference bias, the two sessions were held at least two weeks apart.

2.1. Participants

Seventy-two third-year psychology students at Paris Descartes University volunteered to participate in the experiment (66 women and 6 men). They were between 20 and 35 years old (mean age 22.3 years, standard deviation 3.23) and all were native speakers of French.

2.2. Sternberg's paradigm

During the second experimental session, the participants performed Sternberg's memory scanning test. For the purpose of our study, participants were divided into two experimental groups. One group worked in the conditions defined by Sternberg (digit-sequence recall condition); the other group was not asked to recall the sequence (no-recall condition).

2.2.1. Construction of the two experimental groups

We have shown previously a link between the digit span task and Sternberg's tasks. Therefore, to make the two groups as equivalent as possible, during the first session, the participants' memory capacity was assessed using the classical digit span subtest (Wechsler Adult Intelligence Scale III, 1997/2000). On the basis of their span, participants were then assigned to conditions in order that the mean scores of the two groups did not differ significantly (17.1 vs. 16.5; $F(1,70) < 1$, NS).

Furthermore, it was assumed that the participants would use a variety of strategies to perform the digit span subtest. Thus, to make the two groups as equal as possible, we also verified that the strategies were equally represented in the groups. For this reason, participants were asked a number of preset questions right after the test, and their verbalisations were recorded. The questions were designed to determine as precisely as possible what strategy each participant had used to carry out the task; as a precaution, the experimenter did not request any inferences from the participants, and stressed that they should only say what they were sure of and should not make up anything (Kail & Bisanz, 1982). Finally, the two groups did not differ in terms of age (21.9 vs. 22.6, $F(1,70) < 1$, NS).

2.2.2. Experimental procedure

The participants were seated comfortably about 60 cm from the computer screen. First, the experimental task instructions were displayed on the screen. At the beginning of each trial, the word "Attention" was displayed, after which the participant saw a sequence of one to six digits long (L). The items in the sequence were presented one by one in the middle of the screen for 1.2 s each. Sequence length varied randomly across trials. After the last digit in the sequence, a warning signal was displayed in the centre of the screen for 2 s and was then replaced by a test digit. Participants had to decide as quickly and as accurately as possible whether this digit had been in the sequence just presented. To answer, they had to use their dominant hand to press one key on the keyboard if they thought the test digit was in the sequence, and another key if not. As soon as one of the keys was pressed, a one-word feedback message about the answer ("correct" or "incorrect") appeared on the screen to encourage the participants to respond quickly while keeping their error rate as low as possible. To complete the trial, participants in the recall condition had to recall the sequence aloud in the order in which the digits had been presented. Participants in the no-recall condition went directly onto the next trial. The duration of the inter-trial interval was thus longer in the recall condition, than in the no-recall condition. In order to be as close as possible to experimental procedures in typical studies that do not use the recall condition, we decided to not provide an equivalent inter-trial interval in the no-recall condition. Indeed, in research using Sternberg's paradigm without the restitution constraint, the participants complete trials successively without any delay. We chose this procedure in order to be able to compare our results and conclusions with others in this type of research.

Each participant was trained on a practice block of 24 trials, and then performed three experimental blocks of 48 trials. For each value of *L*, items for which the answer was *yes* and items for which the answer was *no* were equally frequent. Each digit appeared the same number of times in each block and was the test digit equally often, both for *yes* responses and for *no* responses. Every sequence in every block was drawn at a random from the list of items. Thus, for each participant, there was a random item-presentation order that was different each time.

Each participant's RT was measured for each item. RT began when the test digit appeared on the screen and ended when the participant responded by pressing a key. The correctness or incorrectness of each answer was recorded.

As soon as a test block was finished, the experimenter stopped the experiment to register the participant's retrospective verbalisations about the task which she/he had just completed, in order to identify the strategies that she/he adopted. These retrospective verbalisations are not the same as post-experimental interviews, reported in some research on Sternberg's paradigm (e.g., Clifton & Tash, 1973; Sternberg, 1969; Townsend & Roos, 1973), because of their planning and organization. This technique of strategy identification by retrospective verbalisations has been criticized, for example, Nisbett and Wilson (1977) express doubts about individuals' capacity to analyse and explain how information is processed, but all these criticisms do not seem justified (see Caverni, 1988). Indeed, Ericsson and Simon (1980) and Kail and Bisanz (1982) show that verbalisations may be valid under certain conditions. The most important is that the experimenter must take care not to ask any inference or any explanation on the procedures used. Thus, for Sternberg's task, as for the digit span subtest (WAIS III), we asked a series of preset questions while trying to keep the amount of inference requested from the participant as low as possible.

Finally, one last argument concerning the validity of verbalisations comes from empirical research that showed similar results between the data from verbalisations and other sources of information collected jointly, such as RT, number of errors or even eyes movements (e.g., Carpenter & Just, 1986; Marquer, 2005; Siegler, 1987).

3. Results

For each experimental block, only the response times for which a correct answer was given were retained for analysis. RTs three standard deviations or more above or below the mean were discarded. The discarded RTs represented only 1.35% of the total number of items in the three experimental blocks.

3.1. Variability of the individual response times

On average, our data replicate well Sternberg's results as we show a linear increase of RT according to sequence length as well as similar slope of the regression line for both types of responses and this, regardless of the condition (see Fig. 1). Indeed, the linear

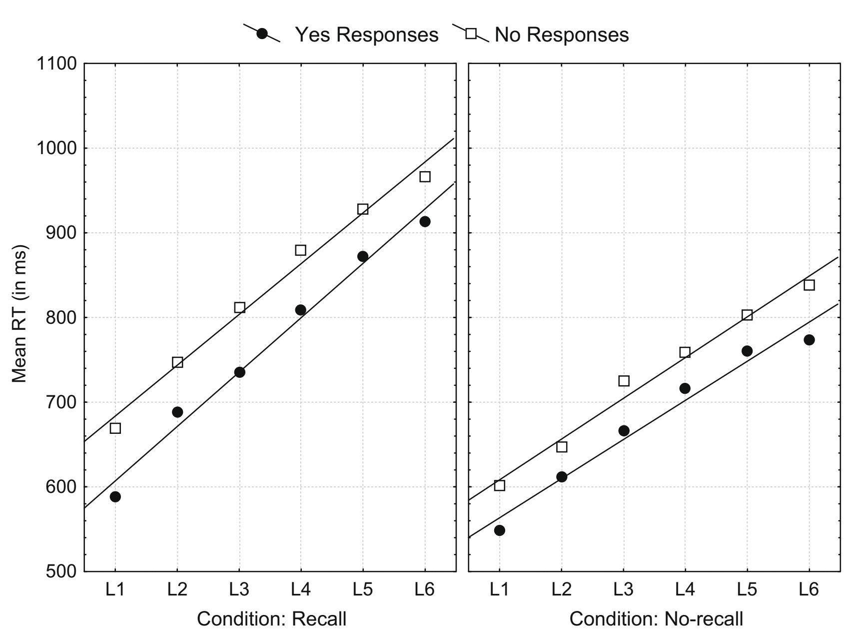

Fig. 1. Mean response time (RT) in millisecond, by sequence length (length one: *L1* to length six: *L6*) and type of response (*yes* or *no* responses) for the recall condition (left) and the no-recall condition (right).

fit, the only significant trend, explained 98.7% and 98.1% of the variance for, respectively, the recall and no-recall condition (two response types pooled) ($F(1,175) = 566$, $p < .0001$; $F(1,175) = 370$, $p < .0001$, respectively). The data indicated a difference between the two slopes of 4.23 ms for the recall and 1.93 ms for the no-recall condition, which are not significant ($F(5,175) < 1$, NS for the two conditions). Moreover, there is no effect of the serial position of the test digit regardless of the experimental condition (respectively, for recall and no-recall condition: $F(4,10) = 1.29$; $p > .10$ and $F(4,10) < 1$; NS).

We descriptively analysed the variability of the degree of linear fit to individual RT curves as a function of sequence length, as well as the variability of the slopes and the zero intercept of these curves. In both experimental conditions, the degree of linear fit varies between 14% and 99%, according to the participant and the type of answer; the same is true for the other parameters with individual slopes ranging from 6 ms to 139 ms and intercept from 210 ms to 1055 ms. Thus, our data show a large variability of the difference in slope between the *yes* responses and the *no* responses. These individual results seem to be consistent with Sternberg's general findings for only a few participants (only 12.5% of participants show parameters in line with the two general findings).

The individual curves show very diverse shapes. Under the no-recall condition, in particular, many show a plateau or a decline in their RT for the last sequence lengths. This type of curve seems to explain the secondary quadratic adjustment found for the *yes* responses of the no-recall condition (58.3% of the participants for *yes* responses and 50% for *no* responses in the no-recall condition; 38.9% and 33.3% for, respectively, *yes* and *no* responses in the recall condition). Indeed, if we remove from the analysis the individual curves that show a plateau or a decline in average RT between the "five digits" and "six digits" sequence lengths, the quadratic trend disappears (the residual of the linear trend is non-significant, $F(4,56) = 1.99$, $p > .10$). The analysis of the verbalisations should allow the explanation of this phenomenon.

Finally, to measure the homogeneity vs. heterogeneity of the processes involved in the different sequence lengths, we established the matrices of common variance percentages ($r^2 \times 100$) between the individual RT data. This analysis involves correlating the individual RTs obtained for each sequence length and each type of response and this, for each condition.

The coefficients are relatively low and heterogeneous in the no-recall condition (see Table 1). This result suggests that different processes are implemented depending on sequence length and response type. On the contrary, in the recall condition (see Table 2), the percentages of common variance are higher and homogeneous, which suggests that the processes involved are more similar, regardless of the sequence length and the response type. Moreover, the "one digit" length (L_1) seems to have a particular status, in both conditions.

3.2. Analysis of the verbal reports

In an attempt to identify the processes implemented in both experimental conditions, we analysed the verbal reports collected after each experimental block.

3.2.1. Procedure inventory

An inventory of the different procedures used by the subjects in the Sternberg task was compiled. These procedures were classified in two categories: the procedures used to memorize the sequence

Table 1

Percentage of common variance ($r^2 \times 100$) between RTs according to sequence length and response type for the no-recall condition (coefficients >70% in bold; coefficients <40% in bold italics).

	L2*Yes*	**L3*Yes***	**L4*Yes***	**L5*Yes***	**L6*Yes***	**L1*No***	**L2*No***	**L3*No***	**L4*No***	**L5*No***	**L6*No***
L1*Yes*	63.71	57.80	55.75	49.51	47.95	47.32	***37.99***	***31.99***	***18.11***	***26.79***	***19.18***
L2*Yes*		66.63	69.42	**73.17**	69.15	50.69	59.34	59.72	43.61	52.46	***36.15***
L3*Yes*			**84.83**	**71.14**	65.43	52.79	58.43	59.56	43.50	54.73	43.59
L4*Yes*				**77.63**	68.30	53.44	65.78	62.21	49.36	60.27	57.39
L5*Yes*					**76.37**	55.57	66.06	63.79	58.18	68.97	52.84
L6*Yes*						41.22	51.77	56.84	52.92	63.17	56.82
L1*No*							60.67	51.25	***29.97***	48.79	***36.23***
L2*No*								**77.15**	58.44	67.07	57.31
L3*No*									**77.30**	**78.26**	59.95
L4*No*										**78.48**	67.62
L5*No*											67.40

Note: L1 to L6 is the sequence length, i.e. the number of digits in the sequence (one to six). *Yes* and *No* represent the type of responses, i.e. if the test digit was in the sequence (yes responses) or not (no responses). For example, the first coefficient: 63.71 is the squared correlation between the individual RTs for *yes* responses on sequence of length one and individual RTs for *yes* responses on sequence of length two.

Table 2

Percentage of common variance ($r^2 \times 100$) between RTs according to sequence length and response type for the recall condition (coefficients >70% in bold).

	L2*Yes*	**L3*Yes***	**L4*Yes***	**L5*Yes***	**L6*Yes***	**L1*No***	**L2*No***	**L3*No***	**L4*No***	**L5*No***	**L6*No***
L1*Yes*	69.37	56.40	53.31	40.76	43.65	**73.04**	63.77	47.03	53.44	48.57	40.72
L2*Yes*		**77.33**	**81.78**	64.80	**78.22**	**70.46**	**89.71**	**71.31**	**73.10**	**72.55**	**70.17**
L3*Yes*			**83.51**	**80.57**	67.04	54.49	**76.19**	**84.06**	**79.45**	**71.64**	58.98
L4*Yes*				**78.35**	**77.56**	61.03	**84.16**	**86.74**	**88.98**	**76.37**	67.48
L5*Yes*					**71.16**	45.70	**61.50**	**76.39**	**80.18**	67.88	59.95
L6*Yes*						47.11	**76.02**	**70.40**	67.08	**72.53**	**73.26**
L1*No*							65.34	52.40	59.77	45.75	48.12
L2*No*								**77.22**	**78.13**	**80.55**	**70.39**
L3*No*									**83.67**	**75.48**	66.04
L4*No*										**76.28**	57.88
L5*No*											**76.24**

Note: L1 to L6 is the sequence length, i.e. the number of digits in the sequence (one to six). *Yes* and *No* represent the type of responses i.e. if the test digit was in the sequence (yes responses) or not (no responses). For example, the first coefficient: 69.37 is the squared correlation between the individual RTs for *yes* responses on sequence of length one and individual RTs for *yes* responses on sequence of length two.

Table 3
Definitions and examples for each strategy found during Sternberg's memory scanning task. Examples with the sequence: 2/7/6/9/■/6 which lead to a *yes* response.

			Definitions *"The participant …*	Examples
MEMORIZATION	During the Sequence	*Visualise*	*… visualises digits as one goes along."*	"2/7/6/9"
		Pronounce	*… pronounces digits as one goes along."*	"two/seven/six/nine"
		Repeat	*… repeats the digit sequence."*	"two/two, seven/two, seven, six/two, seven, six, nine"
		Chunk	*…makes digit chunks."*	"two hundred … /seventy … /six/nine"
		Search for Relationships	*… searches for relationships between digits."*	"two/seven, as in my birthday/six/nine, as my county number"
	During the Cross	*Visualisation*	*… visualises the digit sequence."*	"2, 7, 6, 9"
		Repetition	*… repeats the digit sequence."*	"two, seven, six, nine"
COMPARISON	Coding	*Visual*	*… visually compares the test digit with the digit sequence."*	When the test digit "6" appears, the participant compares this picture with that of the digit sequence.
		Phonological	*… phonologically compares the test digit with the digit sequence."*	When the test digit "6" appears, the participant pronounces "six" and compares this sound with that of the digit sequence.
		Dual Coding	*… compares the test digit picture with the digit phonological sequence."*	When the test digit "6" appears, the participant looks at it and compares this picture with that of the digit phonological sequence.
		Conceptual	*… compares all characteristics (sound, picture, signification…) of the test digit with the digit sequence."*	When the test digit "6" appears, the participant pronounces and looks at it and compares all its characteristics with those of the digit sequence.
	Search	*Immediate*	*… compares immediately the test digit with the digit sequence."*	When the test digit "6" appears, the participant answers immediately "*yes*"
		Self-Terminating	*… retrieves the memorized digit sequence until the match occurs."*	When the test digit "6" appears, the participant retrieves the sequence: "two, seven, six" → "yes"
		Exhaustive	*… retrieves the whole memorized digit sequence even if the match occurs before the end."*	When the test digit "6" appears, the participant retrieves the sequence: "two, seven, six, nine" → "yes"

of digits and the procedures used to compare this sequence with the test digit. The latter category includes strategies for coding the items and processes for searching them in memory (see Table 3).

In both categories, there are multiple strategies, particularly with regard to memorization for which we observe almost as many methods as participants if we go into detail. However, five broad categories of strategies can be identified (memorization by Visualizing the digits, by Pronouncing them, by Repeating them, by Chunking them or by Searching for Relationships between them). Concerning the procedures for comparison, we identified four categories of strategies for coding (Visual, Phonological, Dual Coding and Conceptual) and three for search (Exhaustive, Self-Terminating and Immediate[2]).

3.2.2. Procedural categories

We attempted to establish an individual model for each participant which would represent the sequence of processes she/he implemented during a trial. However, we were confronted with a large intra-individual procedural variability, even during the last experimental block. Inter-individual procedural variability is very large too, as well concerning strategies of memorization, coding methods and search processes for comparison strategies as well as combinations between these classes of strategies. This intra- and inter-individual variability can easily be explained by the fact that Sternberg's task takes place in three stages (memory, time interval before the test digit and comparison) with six different sequence lengths and two possible types of responses, leading to many potential combinations of procedures. This memory scanning task is therefore not as simple as it might seem. Thus, this diversity makes it difficult to construct and analyse RT and performances of sub-groups with a sufficient number of homogeneous participants regarding the strategies used.

Nevertheless, to account for this procedural diversity, we examined histograms of the frequencies of use for each category of procedures as a function of sequence length and experimental condition.

3.2.2.1. Processes of memorization. Fig. 2 shows that, to memorize the sequence, participants in the recall condition use a strategy of repeating the whole sequence more frequently than participants in the no-recall condition. Participants in the no-recall condition are more likely to use all the possible memorization strategies and especially the one that consists of only pronouncing the digits.

We can suppose that this difference in frequency of use is due to the obligation of participants in the recall condition to recall the sequence. Moreover, we note that one of these memorization strategies, the "chunking" strategy, is usually found in rehearsal studies.

Moreover, our results show that most of these memorization procedures seem very close to those identified in the digit span subtest; they are actually identical for certain participants. For example, 71.4% of the participants in the recall condition, who use the repetition strategy in Sternberg's paradigm already used it in the digit span task; 78.1% for the participants in the no-recall condition (for the visual strategy: 66.7% for the recall condition and 58.8% for the no-recall condition; for the "chunking" strategy: 66.7% for the recall condition and 50% for the no-recall condition).

3.2.2.2. Coding methods for the comparison strategies. Fig. 3 shows the frequency of the various coding methods, during the comparison of the test digit to the sequence. Regardless of the condition, the visual comparison strategy dominates for short sequence lengths – in particular for L1 – then decreases as the sequence length increases, to be replaced by the "phonological" and "double coding" strategies. This pattern of frequencies may explain the low percentages of common variance between the L1 length and the other lengths, in both experimental conditions.

However, the increase in the use of the "dual coding" strategy with sequence length is greater in the recall condition. This strategy consists of comparing the test digit picture on the screen with the phonology of the pronounced and/or repeated digits during the sequence presentation. Consequently it is the most complex strategy among those that we have identified. The no-recall condition

[2] Headings of the identified strategies were selected to best reflect the procedures described by participants as we then try to link them to more theoretical concepts.

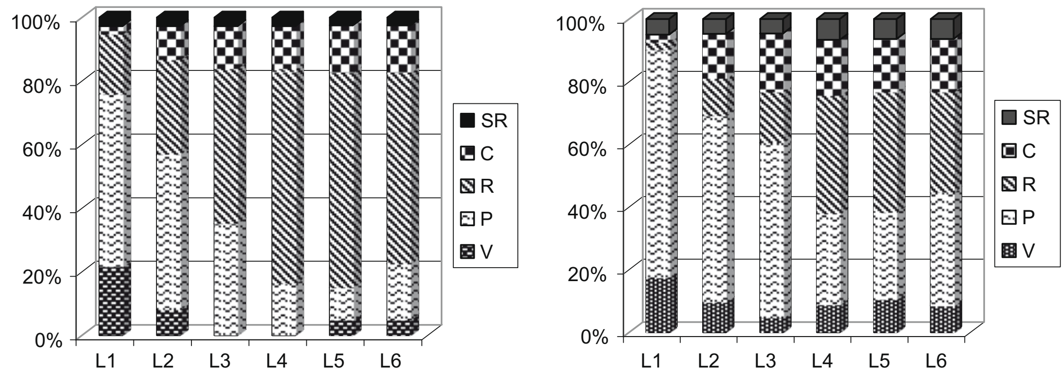

Fig. 2. Frequency of the use of each memorization strategy, according to sequence length, in recall (left) and no-recall (right) conditions. *Caption:* The participants memorize the sequence by Visualizing the digits (V), by Pronouncing them (P), by Repeating them (R), by Chunking them (C) or by Searching for Relationships between them (SR). L1 to L6 is the sequence length, i.e. the number of digits in the sequence (one to six).

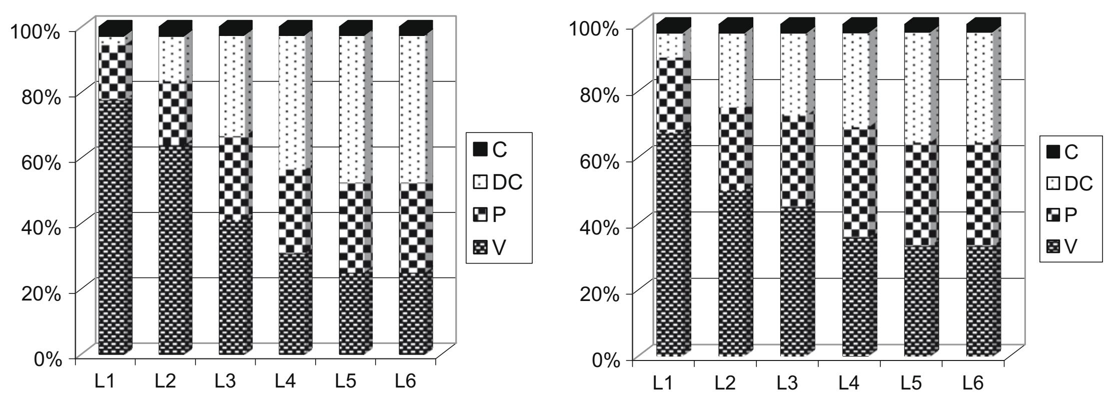

Fig. 3. Frequency of the use of each coding procedure of the comparison strategies, according to sequence length, in the recall (left) and no-recall (right) conditions. *Caption:* The participants compare the test digit to the digits of the sequence by a Visual coding (V), a Phonological coding (P), a Dual coding (DC) or a Conceptual (C) coding. L1 to L6 is the sequence length, i.e. the number of digits in the sequence (one to six).

participants are more likely to use simpler comparison strategies (visual or phonological comparison) and to continue doing so until the end.

3.2.2.3. Search processes for comparison strategies. Fig. 4 shows that "immediate" comparison is the most used search strategy regardless of sequence length and condition. This strategy consists of comparing immediately the test digit with the digit of the sequence without re-repeating or re-visualizing the sequence.

However, the use of this type of search, which requires less cognitive resources, decreases much more for the recall condition participants, and is replaced by a "self-terminating" or "exhaustive" search which entails going over the sequence to compare it with the test digit, therefore involving additional time and effort. Conversely, the majority of the no-recall condition participants continue to use an "immediate" search process and even though some give up this strategy for a "self-terminating" search, none uses an "exhaustive" search.

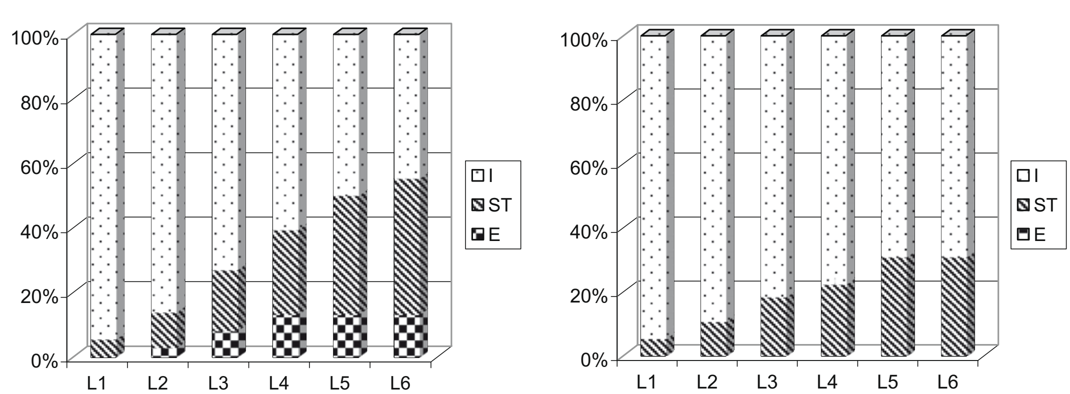

Fig. 4. Frequency of the use of each type of search, according to sequence length, in the recall (left) and no-recall (right) conditions. *Caption:* The participants compare the test digit to the digits of the sequence by an Exhaustive search (E), a Self-Terminating search or an Immediate search (I). L1 to L6 is the sequence length, i.e. the number of digits in the sequence (one to six). *Note:* for L1, a ST search process means that the participants repeat the sequence digit before comparing it with the test digit.

We mentioned above that many participants present individual curves with a plateau or a decline in mean RT between the "five digits" and "six digits" lengths. These particular curves, which seem at the origin of the quadratic trend (observed in addition to the main linear trend), correspond, mainly to the participants who say they used an "immediate" search process for all sequence lengths; this is especially true of the no-recall condition participants.

According to their verbalisations, none of the participants seem to have proceeded by successively comparing the test digit with each "location" in memory, marked by the digit sequence presentation, as presumed by the Sternberg model. On the other hand, five participants in the recall condition seem to have used an exhaustive serial search strategy. Indeed, starting from a certain length, these participants repeated the previously presented sequence at the same time as they compared it with the test digit. The fact of having to recall the order sequence encouraged them to continue until the end of their repetition before answering, even if they had already found a match.

None of the participants in the no-recall condition claimed to have used this strategy. The exhaustiveness of search thus appears to be closely related to the sequence recall constraint even though, within this framework, this strategy is used by only a minority of participants.

In further analyses, we calculated the quantitative results associated to each strategy. Given the small number of subjects per group we could not go as far as we wanted in this analysis. Nevertheless, we found in the recall condition (the only condition in which some subjects declared to have used an "exhaustive" search), a hierarchy between the execution speeds of the different search strategies: the slopes of the regression lines increase with the complexity of these strategies (55.8 ms for "immediate", 59.5 ms for "self-terminating" and 81.1 ms for "exhaustive" search); the same is true for mean RTs (727 ms for "immediate", 770 ms for "self-terminating" and 825 ms for "exhaustive" search). Furthermore, our results show that the participants who reported using an "exhaustive" search have weaker performance in the digit span subtest than others (15.80 vs. 17.26). However, due to the small number of subjects (only five for the exhaustive strategy), these effects are not significant.

To summarize, the comparison of the two experimental conditions, in terms of the processes used to memorize the sequence, the coding procedures, and the type of search, highlights the fact that the participants in the recall condition use strategies that are more complex but also safer, as the sequence length increases, than the no-recall condition participants. These results could be explained by the fact that the recall constraint makes the execution of the principal task more difficult.

4. Discussion

Our approach underscores the high level of variability in quantitative results and qualitative procedures depending on the experimental condition but also on participants, task difficulty and the interaction between participants and difficulty level. This can be explained by the fact that Sternberg's task is very complex because it involves six sequence lengths associated with two types of responses, which increases the number of possibilities of procedures. Such variability suggests that Sternberg's mean model might not be able to adequately reflect the cognitive processes actually implemented during the experimental task.

However, even if this procedural diversity did not enable us to specify the profiles of RT or abilities associated with the various strategies, this approach also allows us to propose some explanations of several phenomena that occurred during our earlier study.

First, the longer processing times in the recall condition can, of course, be explained by the fact that this constraint slows down the execution of the principal task by requiring additional attention to information order. These longer processing times may also be due to the fact that these participants tend to use more complex procedures, which allow them to make fewer errors.

The significant secondary quadratic trend for the yes responses in the no-recall condition seems to be explained by the presence of many individual curves that present a plateau or a decline in RTs over the last sequence lengths. The analysis of the verbal reports indicates that this type of curve is associated with the use of an "immediate" search process, regardless of the sequence length.

The greater heterogeneity of the percentages of common variance in the no-recall condition can be linked to the greater diversity of the coding methods in this condition.

Finally, the particular status of the "one digit" length highlighted by the matrices of common variance percentages could be explained by the predominance of the visual comparison strategy for this length.

Furthermore, our approach suggests an answer to the old debate over the use of the exhaustive search pattern for the *yes* response. If, like Sternberg, we ask participants to recall the sequence, some of them actually implement this type of search "to keep this sequence in memory". We note that these participants have memory capacity lower than others. If, however, like those authors who claim that an exhaustive search has no meaning for *yes* responses, we do not ask participants to recall the sequence, then none of the participants implements this kind of search. According to our study, the exhaustiveness of search appears to be closely related to the sequence recall constraint. Indeed, some participants, whose memory capacities are lower, could use an exhaustive search in order to keep the entire sequence in memory and then, to recall it. However, even if this type of research only appears in the recall condition, it is not the dominant strategy as it is used by a small number of subjects.

Moreover, our results show three types of search strategies that correspond to those proposed at the theoretical level by Chao and Knight (1996) or Lemaire (2005). (1) The "exhaustive" strategy, only in the recall condition, in which all comparisons are made before a decision, (2) the "self-terminating" strategy where individuals stop comparing the target with the items as soon as a match is found, and (3) the "immediate" strategy that can be identified as a strategic process in which individuals compare simultaneously the target with all the items in STM. Thus, our study allows us to verify experimentally the theoretical assumptions made by these authors without having tested them. Moreover, these search strategies can be identified with different models of search suggested in the literature: serial exhaustive search model (e.g., Sternberg, 1966, 1975), self-terminating search model (e.g., Theios et al., 1973; Townsend & Roos, 1973) and the model of parallel search with limited resource (e.g., Townsend, 1971; Van Zandt & Townsend, 1993). Thus, the different search models are appropriate but depend on both the specific experimental conditions and participant's strategy. We can notice that Townsend and Fific (2004), studying whether the search in memory is serial or parallel with Sternberg's paradigm, arrived at the same conclusion: that depends on the participant and experimental condition.

So, using Marquer and Pereira's (1990a) approach on the Sternberg paradigm would leave to the same conclusions as for other paradigms on which it has already been used: there does not exist one best model in general, but rather different models which each corresponds to a group of participants (e.g., Marquer, 2005; Marquer & Pereira, 1990a, 1990b, 2002). It also shows how it is dangerous to average across participants as we do not ensure that all subjects use the same procedures (e.g., Marquer & Pereira, 1990a, 1990b, 2002; Newell, 1973; Townsend & Fific, 2004).

However, unlike these previous studies, we were unable to establish patterns of RT or accuracy for each category of strategies. This can be explained by the fact that, despite its apparent simplicity, the complexity of the task leads to much greater variability than in other paradigms. So, in order to characterize more precisely these various strategies, further research with a greater number of participants is needed. Moreover, this can also be explained by the fact that this task allows us to measure only one RT, the time for comparing the test digit to the sequence. This measure does not therefore provide information on the strategies of memorization. To remedy this lack, another measure that is directly linked to the processes involved in the first stage of the task should be devised. We could, for example, imagine a system in which participants paced, by pushing themselves on a button, the presentation of each digit of the sequence. This would separately measure the time for memorization and the time for comparison. With this type of device, we can expect that the different memorization strategies give different times for memorizing. Finally, these future studies may allow us to use more advanced techniques for testing the various strategies by rigorous mathematical models (e.g., Nosofsky & Kantner, 2006; Townsend & Fific, 2004; Wenger & Townsend, 2006).

The memory scanning paradigm is widely used today in neuroscientific research, both in studies on the neural bases of this task in healthy participants (e.g., D'Esposito et al., 2000; Jensen et al., 2002; Pelosi, Hayward, & Blumhardt, 1998; Singhal & Fowler, 2004; Ward, 2003), and in research on short-term memory deficits and impairments (e.g., Ahn et al., 2003; Archibald et al., 2004; Karrasch et al., 2006). Most of these studies use the paradigm without a recall condition, yet the conclusions they draw are generally based on Sternberg's interpretation of the various parameters in his general model (*with* recall). The results of this study show that this task is not necessarily a memory task; it depends on the experimental conditions and participants' strategies. Thus, this study suggests that caution is required when using Sternberg's paradigm as a typical memory task.

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