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EASE OF ACCESS TO LIST ITEMS IN SHORT-TERM MEMORY DEPENDS ON THE ORDER OF THE RECOGNITION PROBES

Elke B. Lange,
University of Potsdam, Germany

John Cerella, and
Syracuse University, NY

Paul Verhaeghen
Georgia Institute of Technology, GA

Abstract

We report data from four experiments using a recognition design with multiple probes, to be matched to specific study positions. Items could be accessed rapidly, independent of set-size, when the test order matched the study order (forward condition). When the order of testing was random, or backward, or in a pre-learned irregular sequence (re-ordered conditions), the classic Sternberg result was obtained, response times were slow and increased linearly with set size. A number of explanations for forward-condition facilitation were ruled out, such as the predictability of the study order (Experiment 2), the predictability of the probe order (Experiment 1), the covariation of study and test orders (Experiments 1, 2, 4), processes of probe encoding and perception that did not rely on STM access (Experiments 1, 2, 4), specific support of the forward condition by articulatory processes (Experiment 3), or condition-dependent strategic differences (Experiment 4). More detailed analyses demonstrated that fast forward responses could not be accounted for by the effects of input position and output position that modulated random responses, effects that did account for the slower responses of the re-ordered conditions (Experiments 1, 3, 4). A final analysis of probe-to-probe transitions as a function of encoding distance revealed a sizeable single-step benefit in the random condition. We concluded that STM representations were serial rather than spatial, and that forward probes benefited from their serial adjacency.

Suppose that a short list of familiar items (digits, letters, words) is presented in brief succession and studied. How are they subsequently accessed from short-term memory (STM)? If people are asked to recall the list immediately after study, items are reported in a predominately forward order, from first to last, although sometimes the final item or two is reported early on (Lewandowsky, Brown, & Thomas, 2009; Murdock, 1962 cited in Kahana, 1996; Tan & Ward, 2007). This suggests a natural disposition to access STM in a forward order, a disposition reflected in the serial-position curve, which gives accuracy as a function of input position: Performance is best for the beginning of a list (the primacy effect), decreases gradually over subsequent positions with sometimes a slight improvement for the

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Elke B. Lange, General and Biological Psychology, University of Potsdam, Karl-Liebknecht-Str. 24/25, 14476 Potsdam, Germany, elke.lange@uni-potsdam.de.

end of the list (the recency effect). When report order is constrained by the experimenter, accuracy for backward recall is only about 80% of that achieved for forward recall (Farrand, & Jones, 1996; Hinrichs, 1968; Hulme, Roodenrys, Schweickert, Brown, Martin, & Stuart, 1997; Rosen & Engle, 1997).

Findings such as these suggest a specialized mechanism for forward retrieval in free or serial recall. A paradigm introduced by Sternberg (1966) opened another window on STM access, shifting from measures of accuracy ("item availability", to adapt Tulving & Pearlstone's terminology, 1966) to measures of latency ("item accessibility"). In Sternberg's memory-scanning procedure a short list of items is exposed, followed by one or more recognition probes. Participants judge whether or not a probe item occurred in the study list, and their decision latency is recorded. The basic finding from this procedure is that decision latencies increase as a linear function of the size of the list (the load function). Sternberg interpreted the load function as indicative of a serial scanning process, a notion that has been a subject of vigorous debate (e.g., Townsend & Wenger, 2004). Sternberg pointed out (1975) that the combination of a positive load function and a flat serial position function or increasing latencies across serial positions was compatible with the forward access mechanism thought to underlie item access in free recall.

Such converging evidence across paradigms and across measures was exciting at the time, but has been dimmed by later research. Some recognition studies have indeed obtained results suggestive of target-terminated forward scanning, namely increasing latencies across serial positions (Ashby, Tein & Balakrishnan, 1993, Subj. 3; Ellis & Chase, 1971; Klatzky, Juola & Atkinson, 1971; Klatzky & Smith, 1972). These same studies, however, failed to find that target-absent slopes were twice as steep as target-present slopes, a result necessary to conclude that search is self-terminating. In addition, several authors have reported serial-position functions for latencies with a negative slope, indicative of backward scanning (Corballis, Kirby, & Miller, 1972; McElree & Dosher, 1989; Monsell, 1978). This leaves the mechanism of STM access unclear, to say the least.

In the studies reported here, we took up a variant of the Sternberg procedure that has shown a particularly clear benefit for forward access as opposed to random access (Lange, Verhaeghen, & Cerella, 2010). This procedure allowed us to pose a series of questions about what aspects of forward access facilitate retrieval latencies. The answers to these questions have implications not only for our understanding of item recognition memory, but also of memory for serial order. In the Lange et al. study a list of N digits (N = [1 2 3 4 5]) was exposed serially at N different screen locations, arranged in a row from left to right. Each screen location was then probed once, and the probe had to be matched with the digit for that location. Hence, differently from the classical Sternberg task, we probed memory for both item and location. Probing locations in random order produced a positive load function that lay parallel to and above the load function of the control task, a conventional Sternberg condition (probing item memory only). This suggested that STM access was mediated by the same mechanism in these two conditions, with additional time needed to process the positional information. In contrast, when the probe order corresponded to the study order (left to right), the load function was completely flat. The demonstration of rapid, load-free STM access in a forward serial recognition task was a dramatic illustration of STM efficiency, a demonstration that reinforced the conclusion of Lewandowsky, Nimmo, and Brown (2008) that different retrieval mechanisms are involved in forward as opposed to reordered STM access.

The current investigation took up the Lange et al. result and tried to understand it further. What makes the forward order special? The order of retrieval here corresponds to the order of study. This correspondence plays out as a benefit in most models of serial recall: forward retrieval follows in a direct way such memory attributes as item strength (Page & Norris, 1998), or the overlap in context information (Burgess & Hitch, 1999, 2006), or the association chain (Murdock, 1995). In all of the present experiments (Experiments 1 to 4) a forward probe order was compared with a random probe order, to replicate the Lange et al. result, demonstrating the benefit of the forward order.

All other manipulations moved beyond the Lange et al. experiment. We introduced additional retrieval orders to evaluate two explanations of the forward benefit: covariation between study order (input) and test order (output), and predictability of the test order. First, we implemented a backward retrieval order (Experiments 1, 2, and 4), in which input and output positions were perfectly – but negatively – correlated. If covariation of input and output order had a beneficial effect, backward probing would show the same benefit as forward probing, or at least a shallower slope than random probing. Second, we implemented a fixed and pre-trained output order (Experiments 1 and 2) that was “irregular” in that it was uncorrelated with input order. Retrieval strategies that capitalized on encoding neighborhood would be ineffective on the fixed-irregular order, but any benefits due to the predictability of the output sequence would remain. For example, Anderson and Matessa (1997) and Sternberg, Monsell, Knoll, and Wright (1978) proposed that participants pre-load the to-be-reported list into a temporary buffer prior to verbal output, and then engage in a simple buffer read-out. Such preloading was possible in the fixed-irregular order because the retrieval order was known beforehand.

To foreshadow our findings, the results of Lange et al. were replicated, the load function for the forward condition was flat, while the load function for the random condition had a typical Sternberg slope. Moreover load functions for the backward and fixed-irregular conditions were more or less collinear with the random function. Thus rapid forward STM access was unique, and not due to the predictability of the forward-order probes or to the covariation between study order and test order. Subsequent experiments focused further on the source of forward-order facilitation. Expt. 2 sought to determine whether working-memory representations followed a temporal-sequential order (perhaps limited to forward probing) or utilized a spatial-location code (perhaps for random probing). In Expt. 3 we tested for the operation of a phonological loop (perhaps specific to forward probing), and for the marshalling of additional control processes (perhaps for random probing). In Expt. 4 we sought to preclude strategy differences by mixing probe orders from trial to trial rather than holding them fixed for a block. Once all the data were in we undertook several more detailed analyses in the General Discussion. We sought to determine which if any of the fixed probe orders (forward, backward, irregular) could be viewed as nothing more than particular instances of the random probe order. Finally we looked for traces of forward search or associations within the random order.

Experiment 1

In the first experiment we compared short-term memory access for four probe orders, forward, backward, irregular and random. We expected to replicate the finding of Lange et al. (2010) of a flat access function for forward, and a ramped function for random. If the input-output correspondence was the source of the forward benefit, backward retrieval would result in a linear function with a flat slope (or at least a shallower slope than for the random condition), and the function for the irregular order would match the function of the random order. If predictability was the key to the forward benefit, both, the backward and the irregular order conditions would result in corresponding benefits.

In addition, we included a memory-free control task (magnitude judgment), which encompassed all processes required in the STM task – the shifting of visual attention to each probe, encoding of the digit, a binary decision and a keyboard response – except for STM retrieval and comparison. Comparing load functions from the two tasks allowed us to ascertain the extent to which load effects were due to memory processes alone or to ancillary processes as well (e.g., Heywood & Churcher, 1980).

Lists were of sub-span length, to keep accuracies close to ceiling and drive effects into the latency domain. Short lists also discouraged the spontaneous grouping of items, which can distort latencies (Anders & Lillyquist, 1971; Anderson, Bothell, Lebiere, & Matessa, 1998; Farrell & Lewandowsky, 2004; Maybery, Parmentier, & Jones, 2002).

Method

Participants—Twenty-four undergraduate students (13 women) were recruited for this experiment. Their mean age was 20 years. They received course credits for participating.

Material and apparatus—Memory lists were 3, 4, or 5 items long; for the recognition task each list was followed by an equal number of probes. Items for the memory list were sampled randomly without replacement from the digits 1 to 9; for the magnitude-judgment control task the digit 5 was excluded. Digits (1.0 by 1.3 cm, width/height respectively) were presented visually inside rectangular frames (2.7 by 3.2 cm) on a computer screen. The arrangement of the frames kept the distance between all (and not only neighboring) positions comparable (see Figure 1).

Experimental design—The experiment consisted of two sessions, with the recognition task in one session and the magnitude-judgment task in the other. Each session started with a practice block with probes presented in random order (six trials for $N = 3$, five trials for $N = 4$, and four trials for $N = 5$). Within the twelve experimental blocks the four probe orders were scheduled, forward, backward, fixed irregular, random (chance forward sequences were excluded from the random order). List length was blocked, nested within probe order. All three factors (two tasks, four probe orders, three list lengths) were balanced across the 24 subjects, with the factors of probe order and list length following a Latin square design. Each block consisted of 60 probes, 20 trials for $N = 3$, 15 trials for $N = 4$, and 12 trials for $N = 5$, plus an additional three warm-up trials at the beginning of each block. Within each block 50 % of the probes were positive and 50 % were negative. One-third of the negative probes were digits that were part of the memory list but presented at a different, randomly sampled, location (intrusion probes). The remaining two-thirds of the probes did not occur in the memory list (extra-list probes). When the set-size changed between experimental blocks, a location-recall task was inserted. This was necessary to train the fixed-irregular order, but was included in all conditions to keep the procedure consistent. The number of trials for the location task was determined by the subject’s performance (see Procedure).

Procedure—Two sessions were scheduled no further than two weeks apart, each session no longer than one hour in length. Participants assigned their responses (“yes” or “no”, and “greater than 5” or “smaller than 5”) to the left and right arrow keys on the standard PC keyboard by preference. The four probe orders were diagramed in the written instructions (see Figure 1). The computer gave notice of the probe order and the list length throughout the experiment. Each trial started with N empty frames; stimulus presentation was initiated by pressing the space bar. Each digit in the location-recall and the recognition task was presented for 500 ms with an inter-stimulus interval (ISI) of 250 ms.

In the location-recall task the first digit occurred upon initiation for 500 ms. Then the digit was masked with an X and after the ISI the next digit was presented. This sequence was repeated until N digits occurred, addressing each frame once. Subsequently, the Xs were removed and a cue display (equivalent to the diagrams in the instruction sheet, see Figure 1) occurred for 750 ms, to illustrate the fixed retrieval orders again. Subsequently, the empty frames remained on the screen and participants were required to move a mouse pointer to the frames in the order in which the digits had been presented, clicking each frame once. Digit values were irrelevant, only the order of the addressed frames had to be remembered. The learning criterion was reached when the participant recalled the serial frame order correctly in five consecutive trials.

In the magnitude-judgment task the cue display occurred for 750 ms upon initiation. Immediately thereafter the first probe was presented in one of the frames. The participant had to decide whether the digit probe was smaller or larger than 5 by pressing the corresponding key, whereupon the digit was masked by an X that remained on the screen until the end of the trial. After 200 ms the next probe occurred. Each frame was addressed once.

In the serial-recognition task, the first item of the memory list was presented upon initiation, followed by a masking X and the ISI. Presentation order always followed the forward probe order. After presentation of the memory list the cue display was turned on for 750 ms, followed immediately by the first probe. The participant pressed the “yes” or “no” response key to indicate whether the probe digit matched the study digit for that frame. After the key-press the probe digit was replaced by an X. The next probe appeared after 200 ms. *N* probes were presented in each trial, addressing each frame once. Participants received feedback on their mean accuracy and reaction time after each experimental block.

Analysis—All experiments followed the same guidelines for analysis. The practice block was excluded from analysis. Only correct answers were included into the reaction time (RT) analysis. Values greater than the mean plus three times the standard deviation (based on individual means for task, order condition and positive or negative probe type) or smaller than 100 ms were excluded as outliers. If not reported otherwise, we collapsed across positive and negative probes when computing mean RTs. Accuracy was calculated as the proportion of correct answers per trial. We analyzed the RTs using hierarchical (multi-level) linear modeling, and verified the results with conventional repeated-measures ANOVAs, which are not reported here. We started with a full model, estimating random slopes and intercepts for the forward order, and adding fixed-effects slopes and intercepts for each of the other retrieval orders. To enhance interpretability of the results, memory set-sizes were recoded such that the intercepts indicate RT at memory set-size 3, rather than at set size 0. After parameter estimation for the complete model, we excluded parameters that were not significantly different from zero, and introduced a common parameter for conditions whose means did not differ, as evaluated by a χ^2 test on the log-likelihood values of the nested models.

Results and Discussion

Accuracy in the recognition task was near ceiling for all conditions (range: 95.9 – 97.9 % across conditions), and was not analyzed further. Errors and outliers led to the removal of 5.1 % of the reaction time data.

The role of probe predictability and input-output covariation—The first analyses focused on set-size effects in the recognition task. The hierarchical linear model showed the best fit for a model with three slopes and four intercepts (see Figure 2, Expt. 1, with the model trends superimposed on the data points; see Table 1 for the parameter estimates). We found no set-size effect (slope = 0) for the forward order, but a significant effect for the backward, random and irregular conditions. This result rules out that the benefit for the forward condition was due to predictability. If it were, the forward, backward and irregular condition would all show either zero slopes, or slopes shallower than that of the random order. Nor was the forward-order benefit explained by input-output covariation, because then the forward and backward condition should both have resulted in a benefit, unlike the random and irregular order. This indicated that backward search or associations did not play an important role in our serial recognition paradigm, contrary to what has been demonstrated in recall procedures and reconstruction of order tasks (Kahana & Caplan, 2002;Kahana & Howard, 2005;Lewandowsky et al., 2009).

Did non-memory processes contribute to the set-size effect?—We included a magnitude-judgment control condition to measure the effects of several non-memory processes that were involved in the recognition task and which may have contributed to the set-size effect – processes such as attention shifting, visual encoding, decision making, and response execution. Accuracy for the magnitude-judgment task was close to ceiling (range: 97.1 – 97.8 % across conditions); 4.6% of RTs were excluded due to error responses or outliers. As can be seen in Figure 3 (Expt. 1), load functions were all flat, indicating that the costs of shifting attention did not increase with set size. Therefore the latency increases seen in the recognition task can be confidently ascribed to memory-search processes per se. Predictability did have an impact on the control task: Reaction times for the random condition (the only unpredictable condition) were a constant 72 ms longer than those for the predictable conditions. Predictability likely allowed participants to shift their attention and execute a saccade to the next location before the probe appeared. Lastly, the finding that the intercept for the fixed-irregular order matched the intercepts for the other predictable orders strongly suggests that participants learned the fixed-irregular order of probe locations successfully.

Experiment 2

Experiment 2 was a replication of Expt. 1 with one difference: item order (forward, backward, fixed-irregular, random) was manipulated at study rather than at test; the order at test was always forward (that is, upper-left to lower-right). A comparison of the results from the two experiments should give us a handle on the important question: Were item positions in our displays coded temporal-sequentially or spatially? The prevalent assumption for list recall is that items are ordered on a temporal dimension (Brown, Neath, & Chater, 2007; Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1999, 2006) or on an ordinal sequence (Conrad, 1965; Farrell & Lewandowsky, 2002; Henson, 1998; Page & Norris, 1998), but spatial representations have been implicated in cases where re-ordered reports are required (Li & Lewandoswky, 1993, 1995; but see Oberauer, 2003, and Rosen & Engle, 1997). In Expt. 1 the two coding schemes were interchangeable, because spatial locations (upper-left-to-lower-right) and sequential positions (first-to-last) coincided at study. For Expt. 2, the two coding schemes were not interchangeable. If digits were coded spatially at study, then no trace of the original temporal-sequential order of presentation would remain in either the backward, irregular, or random condition. Hence, under spatial encoding, every access function in Expt. 2 would be flat. Thus discordant outcomes across Expt. 1 and 2 would support the conclusion that subjects used spatial coding. Concordant outcomes across Expt. 1 and 2 would point to temporal-sequential coding.

Method

Participants—Twenty-four students (mean age of 24 years, half of them male) participated in the experiment in exchange for a small honorarium.

Material and Procedure—This experiment was a replication of Expt. 1 in all aspects (material, apparatus, design, balancing, procedure) with the important change that probe order was kept constant and input order was varied, taking the forward, random, backward, and fixed-irregular orders from Expt. 1.

Results and Discussion

Accuracy in the recognition task was high (range: 91.7 – 95.9 % between conditions), and was not analyzed further. Due to errors and outlier rejections 8.5 % of the reaction time data were excluded.

Load functions for recognition latencies when study order was manipulated—The best-fitting hierarchical linear model essentially replicated the results of Expt. 1, with a flat slope for the forward condition and ramped functions for the other orders (see Figure 2 and Table 1). Manipulating item order at study rather than at test did not collapse the slopes for all orders, a powerful argument that temporal-sequential coding dominated memory performance, leaving little room for spatially organized representations. These results echoed findings from a study by Oberauer (2003), who de-confounded sequential (first-to-last) and spatial (left-to-right) effects in a visually presented recognition task: Latencies showed only a small effect of spatial position.

Non-Memory Processes—We included the control task from Expt. 1 to enforce the procedural parallel. As can be seen in Figure 3, we replicated the results from Expt. 1: A simple decision task did not lead to a set-size effect, except now for a small effect (a slope of 10 ms/N) in the irregular condition, indicating that visual attentional processes contributed little or nothing to the pronounced set-size effects in the recognition task.

Experiment 3

From Expt. 2 we concluded that item positions were represented by a temporal-sequential code of some sort, rather than by a spatial code. In Expt. 3 we tested for a particular sequential coding scheme, the phonological loop, in which study items are stored in a phonetic buffer in the order of their occurrence and refreshed by sub-vocal rehearsal (Baddeley, 1986; Burgess & Hitch, 1999). This scheme leads naturally to a forward advantage; indeed re-ordered readout is sometimes deemed to involve elaborate work-arounds in the form of multiple forward scans (Page & Norris, 1998). In Expt. 3, the technique of articulatory suppression was used to disrupt sub-vocal rehearsal. If a phonological loop supported forward retrieval, blocking the loop would eliminate the support, and as a result a slope would emerge in the forward condition. Existing studies of articulatory suppression in item recognition have focused on accuracy loss (Henson, Hartley, Burgess, Hitch, & Flude, 2003; Murray et al., 1998; Murray, Rowan, & Smith, 1988). The effects on recognition latencies are less clear; two studies that reported depressed accuracies did not find elevated latencies (Gruber, 2001; Murray, 1986).

The additional cognitive load of articulatory suppression could itself disrupt the recognition task (Barrouillet, Bernadin, & Camos, 2004). To control for this we added a foot-tapping condition. Both of the concurrent tasks demanded the same temporally based coordination of a motor response, but one was articulatory in nature and the other was not. Because of the additional measurements we implemented only one of the reordering conditions: forward probes were contrasted with random probes.

Method

Participants

Participants—Twenty-four students (15 women) participated in exchange for course credits or a small honorarium. The mean age was 19.

Material and apparatus—Experiment 3 corresponded to Expt. 1 in list lengths, stimuli, and apparatus. The display geometry differed. Item frames were distributed in two horizontal rows centered on the screen: an upper row of *N* frames for the presentation of the memory list, and a lower row of *N* frames for the presentation of the probes. The gap between adjacent frames was constant across set sizes. The frame colors for both rows were red, turquoise, green, hot pink, and light grey, from left to right (set size five). Above the colored frames the current distractor task was announced. For the articulatory-suppression condition participants saw ‘Say: “The”’, for the foot tapping ‘Do: Tapping’, for the control condition ‘Do: ---’.

Experimental design and procedure—The experiment consisted of two sessions, with the forward condition presented in one and the random condition in the other. A session comprised nine experimental blocks of 60 probes each, with an additional practice block at the beginning. Set size was blocked within the experimental blocks and its order was balanced between participants. The three dual-task conditions, articulatory-suppression, foot-tapping, and no dual task, were mixed within blocks and occurred equally often in each block. There were 50 % positive probes, 25 % extra-list negative probes, and 25 % intrusion probes per block. Chance forward and backward sequences were excluded in the random condition. The general procedure and event durations were as in the previous experiments. At the beginning of each session participants practiced incanting the word “the” or foot tapping, both synchronized to a metronome which clicked every 375 ms (50 ms sound of 100 Hz with 325 ms inter-sound interval). For tapping the foot contra-lateral to the response hand was assigned. The experimenter remained in the room during the experiment to verify and enforce compliance of correct dual-task performance (enforcement was rarely needed). A series of nine clicks preceded each trial, to help participants to catch the tempo. After memory-list presentation the clicks stopped but the participant continued with the distractor task until the end of the sequence of probes.

Study items were presented in the first row, always in forward order, left-to-right. Recognition probes then appeared in the frames of the second row. Participants had to match a probe with the digit in the study list that occurred in the same column (in the frame of the same color).

Results and Discussion

Was the load function affected by the dual-task?—Unlike Expt. 1 and 2 there were substantial losses in accuracy across the conditions of Expt. 3. Hierarchical linear modeling established that there was a common intercept for all six conditions (98.1 % correct). As can be seen in Figure 4 the slope for the control and the tapping conditions was independent of probe order: The common slope showed a decrease of 1.3 % in accuracy for each item added to the memory set in these four conditions (forward control, forward tapping, random control, random tapping). With concurrent articulation the slope was also independent of probe order, but the drop was much steeper, a decline of 6.3 % per item. Hence, articulatory suppression had a substantial impact on accuracy, an effect that was equally pronounced for the forward and random orders. This suggests that articulatory codes were used for both probe orders, a result that dovetails with the conclusion from Expt. 2 of temporal-sequential coding. Re-articulation is one mechanism for keeping sequential codes active, a mechanism that appears to have been operating in our multiple-probe recognition task. These results differed from those obtained in two related studies of serial recall: Li and Lewandowsky

(1993,1995) found that undertaking an arithmetic distractor task during encoding disrupted forward but not backward serial recall. Their subjects solved the addition problem out loud, leading to the hypothesis that articulatory codes supported memory performance in the forward condition but not the backward condition, and that spatial codes came into play with the latter.

Turning from accuracies to latencies, the pattern was very different (Figure 2 and Table 1; due to errors and outliers 6.5 % of the reaction time data was excluded). The forward order was characterized by a low intercept and a zero slope, which applied equally to the articulation, tapping and control conditions; the random order was characterized by a high intercept and a steep slope, which applied equally to the three conditions. Neither intercepts nor slopes were influenced by the dual-task manipulation; the sole determinant was probe order. Clearly, the latency benefit of forward probing was not based on articulatory processes. Indeed, retrieval speed was independent of articulatory processes in every order condition. Nor was retrieval speed affected by a non-articulatory load.

The null-effect of articulatory suppression on RT notably dissociated from its effect on accuracy, in agreement with similar split outcomes reported by Gruber (2001) and Murray (1986) (but see Murdock, 1985, and Norman & Wickelgren, 1969). Such splits challenge single-factor STM models that base both accuracies and latencies on the single factor of trace strength (Wickelgren, 1970; Wickelgren & Norman, 1966; see also Kahana & Loftus, 1999, for a discussion). A single memory dimension is insufficient to describe data spanning both measures. Under articulatory suppression fewer items were retained, but those that remained were accessed without impediment.

Experiment 4

Experiments 1 to 3 demonstrated that accessing item and location information depends critically on probe order. Experiment 4 asked whether such differences were “strategic”. Because probe orders were blocked in the previous experiments, conditions were amenable to differential encoding or retrieval strategies. Experiment 4 replicated Expt. 1 with this change: Conditions were mixed on a trial-by-trial basis rather than blocked, and participants were not instructed about the different probe orders. If the forward benefit in the earlier experiments were due to a specific encoding or retrieval strategy, this benefit would be lost in Expt. 4.

Method

Participants—Twenty-four students (16 women) were tested in exchange for class credit or a small fee. The mean age was 20 years.

Material and apparatus—Material and apparatus corresponded with Expt. 3.

Experimental design and procedure—The experiment consisted of two sessions, one for the magnitude judgment task, and one for the recognition task. Set size was blocked and probe orders mixed within each block. The probe orders were forward, backward and random – a fixed-irregular order could not be implemented because pre-training would violate the mixed design. Probe type was balanced for each order condition within a block. The general procedure was the same as in the previous experiments, except that participants were not informed about the three programmed output orders. After the second session participants completed a short questionnaire about their awareness of the repeated orders.

Results and Discussion

Asked whether they realized that the probes were presented in certain orders, seven participants answered “Yes”, nine “No” and eight “Don’t know”. Pursuing these perceptions further, we asked participants to describe the supposed orders. Only one participant correctly described the forward, backward and random order.

Did mixing conditions affect the set size effect?—Accuracy was near ceiling (range: 96.4 – 98.0 %) and was not analyzed further. RT trimming led to an exclusion of 4.8 % of RT data in the recognition task. The data were best described by two intercepts and two slopes (see Figure 2; Table 1). Experiment 4 thus replicated the findings from Expt. 1 and 2: Flat slope for forward probes; ramped slopes for re-ordered probes. The replication from a mixed-order condition demonstrated that memory access in Expt. 1 and 2 was not mediated by order-specific strategies. In particular, fast forward access did not depend on a custom, pre-organized strategy for encoding or retrieval.

Did non-memory processes contribute to the set-size effect?—Accuracy in the magnitude-judgment task was near ceiling (range: 97.3 – 97.7 % across conditions), and was not analyzed further. 4.6 % of RT data were excluded due to trimming. Data were best described by two intercept values (Forward: 595 ms, Backward and Random: 612 ms) and one non-zero slope (Random: 16 ms). The latter was too small to have much practical relevance in face of the much larger slopes of the recognition tasks, and was perhaps no more than measurement noise.

General Discussion

In four experiments we replicated the finding of Lange et al. (2010): When multiple probes had to be matched on their study position, probing the memory set in its order of presentation (forward) led to faster retrieval than probing in any other order. Furthermore, in forward access the set-size effect – typical for STM access – disappeared. Expt. 1 scheduled four output orders (forward, backward, irregular, and random), to test whether this forward benefit could be explained by the predictability of probe order or the correlation between study order and probe order. Only the forward order resulted in beneficial access, ruling out predictability and input-output correlation as suitable explanations. In Expt. 2 we found that the underlying representational format for items and their positions was temporal-sequential and not visual-spatial. In Expt. 3 we tested for the operation of the phonological loop, which should particularly advantage forward retrieval. Item retention fell when articulatory suppression was imposed during presentation and retrieval, but the impairment in accuracy was identical in the forward and random probe conditions. At the same time, access times were unimpaired. This result suggested that items may have been maintained in an articulatory format, but that retrieval speed was not reliant on this phonological loop. Expt. 4 excluded the possibility that the forward benefit was simply due to a different encoding or retrieval strategy. Thus, our experiments demonstrated that forward access to STM is highly efficient, whereas re-ordered access is costly. Having ruled out several plausible explanations of this efficiency, we were led to the following conclusion: Two STM access modes existed, a fast mode limited to forward-order access, and a slow mode allowing access to memory representations in any other serial order.

We have so far examined retrieval times with respect to two independent variables: retrieval order and set size. Other variables are known to affect retrieval times (or accuracies) as well, such as positive or negative probe type (e.g., Sternberg, 1969), serial input and output position (Cowan, Saults, Elliott, & Moreno, 2002; Oberauer, 2003; Ratcliff & Murdock, 1976), input-output lag (Wickelgren, 1970), and probe history (temporally proximate list positions, Schwartz, Howard, Jing, & Kahana, 2005). In the remainder of the Discussion, we take up two of these determinants as they bear on our conjecture of two access modes: serial position effects and encoding proximity.

Serial position effects

If forward and re-ordered retrieval utilized different access modes, the serial position functions for the two cases would differ. This was indeed the case. Figure 5 shows serial position functions for Expt. 1, which were representative of all the experiments. Note that input and output positions were truly independent in the random condition only; input and output plots for the forward condition were identical, and for the two other orders differed only by re-arrangement, and hence are shown for input only.

Strikingly, the forward condition had a relatively flat serial position function, whereas the other order conditions all showed pronounced serial position effects. The forward condition was not completely flat, showing a long first reaction and a small inverted U-shaped effect for the remaining positions. This pattern is notably similar to the serial-position curves for forward serial recall latencies (Anderson et al., 1998; Haberlandt, Lawrence, Krohn, Bower, & Thomas, 2005; Mayberry et al., 2002; Thomas, Milner, & Haberlandt, 2003), suggesting that similar mechanisms may be involved in forward recall and recognition. Long latencies at the first position occurred also for the random output functions, indicating that this was an effect of retrieval and not encoding (see Haberlandt et al., 2005, for a equivalent output effect in spoken backward-recall latencies). Input functions for the backward condition showed a primacy effect similar to those for the random condition; unlike the random data, there was no recency effect. Because the last input position in the backward condition was the first output position, a recency effect in that position was likely confounded with the effect of a prolonged first reaction. Interestingly, the serial position function for the backward condition again matched the serial position function for backward recall latencies (Thomas et al., 2003) (but see Anderson et al., 1998 for a pattern of symmetric forward and backward serial recall functions). The input-order function for the fixed irregular condition followed a zig-zag pattern, with a rather short reaction time for the first position and a long one for the second. The second input position was always the first output position, so we may again be seeing the effect of a prolonged first-response. Regardless of the details, the large modulations seen in the serial position functions from all the re-ordered conditions contrasted with the flattened functions from the forward condition, supporting the assumption of different access modes.

The pronounced primacy effect in the serial-position functions for backward and random suggested some underlying commonality between the two conditions, a suggestion reinforced by the parallel slopes of the load functions. An increase of latencies across serial positions is a distinctive feature of self-terminating search models of STM access (Sternberg, 1969). Sternberg noted that this model carries a further prediction, that the slope of the load function taken from negative probes should be double the slope for positive probes. We compared positive and negative slopes taken from all of the re-ordering conditions of the four experiments. Eight out of eleven tests demonstrated parallel slopes for the two probe types, replicating the result reported by Lange et al., 2010. This ruled out a self-terminated search. Alternately, the primacy effect may simply reflect item strengths or association strengths between items, as in the serial-recall theories of Lewandowsky & Murdock (1989) or Page & Norris (1998). In those theories access to items in STM is direct rather than via an item-to-item search, and the efficiency of access is modulated by the memory strengths. These theories are compatible with parallel positive and negative load functions.

We next asked whether the input-output functions of the three fixed probe orders could be predicted by data from the random order taken from corresponding input-output positions.

To this end data from the random condition were assembled into $N \times N$ cell matrices, such that Cell_{ij} contained the response time to item_i queried by probe_j. Data were taken from correct positive probes only, to ensure that a study item had actually been contacted. Each of the fixed orders could be mapped to a subset of N cells in the $N \times N$ matrix from the random order. Probes for the forward order ($N = 4$) mapped to cells $\{\text{Cell}_{11}, \text{Cell}_{22}, \text{Cell}_{33}, \text{Cell}_{44}\}$; for the backward order to cells $\{\text{Cell}_{41}, \text{Cell}_{32}, \text{Cell}_{23}, \text{Cell}_{14}\}$; and for the fixed-irregular order to $\{\text{Cell}_{21}, \text{Cell}_{42}, \text{Cell}_{13}, \text{Cell}_{34}\}$.

Figure 6 shows the data from Expt. 1, which were representative of the other three experiments. The results were clear: as can be seen in the figure the latencies for both the irregular and backward conditions coincided with the random data. Not so for the forward data points, which fell well below the random data points. These impressions were verified by a series of univariate ANOVAs with two-tailed tests performed for each fixed order and set size.[2] Across the four experiments, 17 of 18 tests showed a significant difference between forward and random data, but only two of 15 showed a significant difference between irregular or backward and random. Latencies in the re-ordered conditions were governed by the same input and output effects that operated in the random condition. Latencies in the forward condition, on the other hand, benefited by factors over and above the input-output positions of the probes.

Temporal-sequential encoding proximity

In our final analysis we tested for another plausible determinant of the forward benefit, trial history. Previous research has shown that after a particular item in a memory list has been accessed, access to the next item is facilitated compared to the previous item or the next item plus one (Kahana & Caplan, 2002; Nairne, Ceo, & Reysen, 2007; Schwartz et al., 2005). This has been described as a “successor benefit”. The benefit follows from STM models in which location information is encoded dynamically by associative links between items (the simple chaining model in Murdock, 1995), and likewise from models that link item representations to a dimension that encodes position (Brown et al., 2000, 2007; Burgess & Hitch, 1999, 2006; Henson, 1998). These ideas invited inspection of the “distance function” for the latencies in our random condition. Distance D was given by the difference in position between the current probe and its predecessor. For example if the current probe referenced the first study item, and the preceding probe referenced the third study item, then $D = (1 - 3) = -2$. A successor benefit would be seen as a faster response at $D = +1$ than at any other distance. This expectation was intriguing, because in the forward condition every distance was +1. It raised the possibility that fast forward responses may be simply echoing a minimum in the distance function from random at $D = +1$.

We compiled distance functions from the random data of our experiments, and then looked for a coincidence between forward RTs and the random RT for +1 probes. To be sure that item locations were actually visited, observations were limited to successive pairs of positive probes that were both answered correctly. The random-data distance functions for Expt. 1, 3, and 4 are illustrated in Figure 7 (The input-output reversal made the analysis problematic for Expt. 2). Notable in these functions was the evidence for a successor benefit, a minimum at $D = +1$. These “single-step” transitions in random probe sequences were highly facilitated – the distance functions modulate over 400 ms from their minimum to their maximum. This impression was only partially supported statistically. From 15 tests for the main effect of distance (each set-size and experiment analyzed in a separate ANOVA), 8 tests were significant, 7 were not. The lack of significance here can partially be traced to the large

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[2] Note, that individual participant’s data were incomplete in this (and all further) detailed analysis, which precluded a within-subject design. Instead, the mean reaction time (if any) for each subject for each cell was entered in a between-subject design.

standard errors visible in the figure, due in turn to the sparseness of the data when broken down so finely. Replication of the shape of the function from experiment to experiment convinced us that these distance-induced inflections were nonetheless real.

Superimposed on the distance functions in Figure 7 are the forward data points, positioned on the abscissa at $D = +1$ (Forward data were selected like random data, using the second of two successive positive probes, both correct). Despite the fact that the random distance functions dipped to a minimum at that point, the forward data points fell below the random data points. In 15 *t*-tests the forward-random difference was significant in 13 cases. Thus, the single-step benefit observed in random access was not sufficient to account for fast forward responses. It is possible that the same mechanism nonetheless facilitated responding in the two situations. Here are two rationales that would explain the gap that remained between forward RTs and random RTs at $D = +1$. First, in the random condition the single-step access mode might have been utilized for only a proportion of the eligible probes. On other occasions a costly search took place, because search was necessary for most of the random probes anyway. The demonstrated successor benefit for the random condition would then be underestimated. A second possibility is that the successor benefit may have been enhanced in the forward condition because there any pair of successive probes was always preceded by another single-step transition. The power-set model of Murdock (1995) predicts retrieval enhancement in this situation. In this model remote associations are formed between a given item and every preceding item. Access to a target will accordingly be facilitated when cued by multiple predecessors. Note, however, that the power-set model incorporates backward as well as forward associations, and we did not see a cumulative benefit for backward probing in our data.

There were other exceptionally fast values apparent in the distance functions of Figure 7, those at $D = -3$ for $N = 4$ and $D = -4$ for $N = 5$. Both of these distances denominated jumps from the end of the list to the beginning of the list; they yielded response times nearly as fast as those for a single forward step, $D = +1$. This observation accords with two studies using quite different paradigms: Lewandowsky et al. (2009; reconstruction of order) and Farrell and Lewandowsky (2008; a re-analysis of 14 sets of free recall data). The implication here is of a circular buffer or chain, whose first item is reachable in a single step from its last item.

Summary

Using a recognition paradigm on short lists of digits we replicated the finding of Lange et al. (2010), that STM items could be accessed in a rapid and load-free manner when the order of testing matched the order of study. When the test order was random, access times were slower and increased linearly with memory-set size in the manner of Sternberg (1969). By comparing load functions under different test orders (forward, backward, fixed-irregular and random), tasks (recognition judgement or magnitude judgement), designs (mixed versus blocked), and dual-task conditions (articulatory suppression, foot tapping), we ruled out a number of possible explanations for the forward benefit, including study-test covariation, test predictability, encoding strategies, representational differences and ancillary processes of task execution. We demonstrated further that differences between forward and random test orders extended to the level of the study-position (input) and test-position (output) functions. Moreover, we found that forward-order latencies did not match random-order latencies taken from corresponding study-plus-test positions, whereas latencies for backward and fixed-irregular orders were well predicted by latencies from the random condition. In total, this suggested that STM access was governed by a common set of processes in the three re-ordering test conditions that were substantially different from those for forward-order access. Some speculations about the nature of these processes were inspired by a final analysis of the random data. An analysis of probe-to-probe transitions as a function of encoding distance revealed a sizeable single-step benefit in the random condition (as in

Schwartz et al., 2005), suggesting that fast access might be explained by forward chaining. Slow access on the other hand, might be driven by an activation gradient imposed on the memory set by the study order (as in Page & Norris, 1998) or might utilize chaining associations differently than in the forward condition. Such a conclusion was supported by the primacy-weighted serial-position functions, together with parallel slopes of the load functions for positive and negative probes (ruling out the alternatives of exhaustive or self-terminated scanning). More study is needed to pin down these distinctive modes of STM access further.

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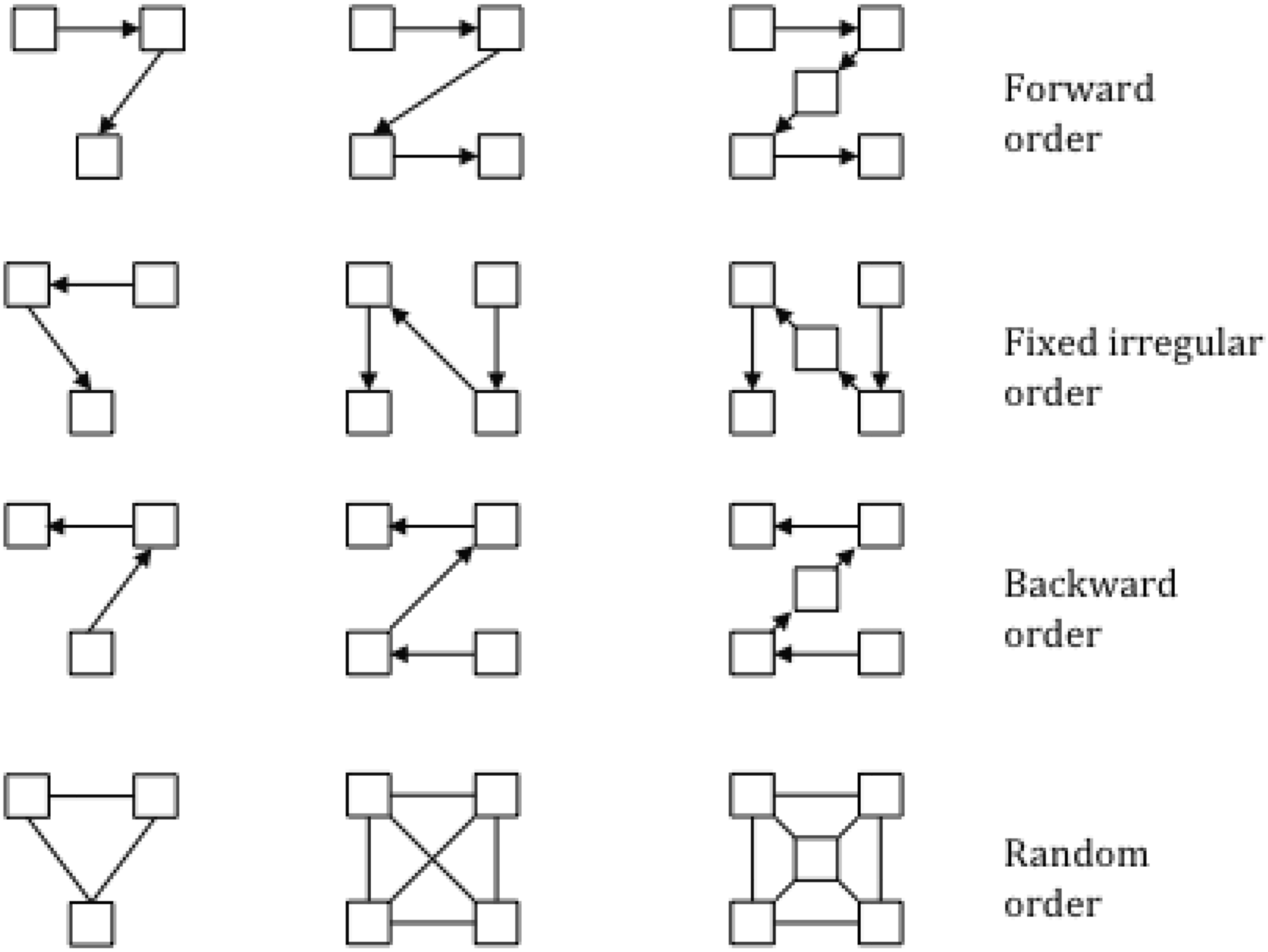

Figure 1.
Schematic order of serial locations of Experiment 1. Adapted from Lange and Verhaeghen (2009), Fig. 1.

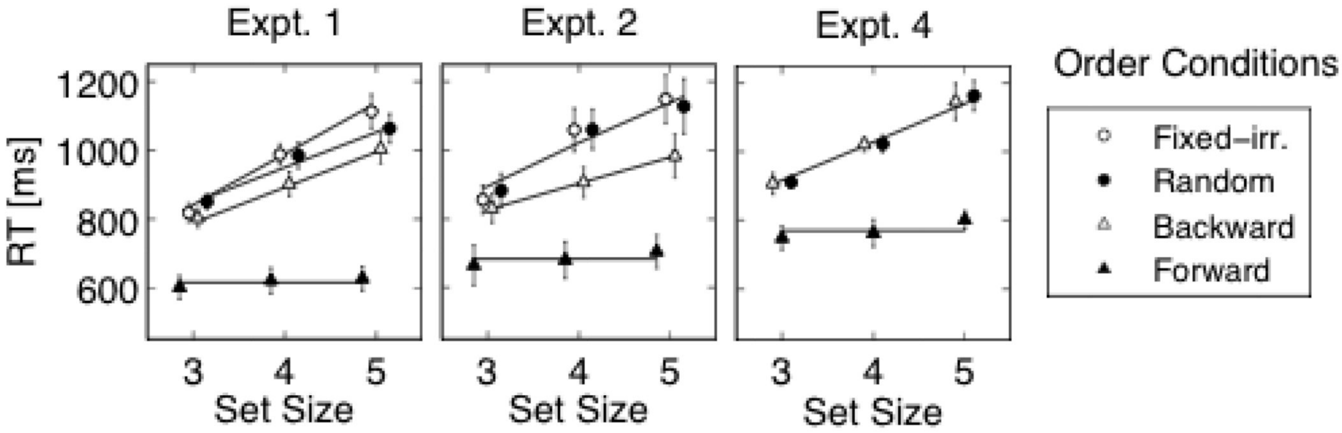

Figure 2.

Reaction times in the recognition task as a function of condition (probe order) and set size. Expt. 1: Blocked order conditions manipulated at test. Expt. 2: Blocked order conditions manipulated at study. Expt. 4: Mixed order conditions at test. The means are accompanied by regression lines established by hierarchical linear modeling.[1]

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[1] Error bars represent the 95 % confidence interval corrected for within-subject measure as proposed by Bakeman & McArthur (1996).

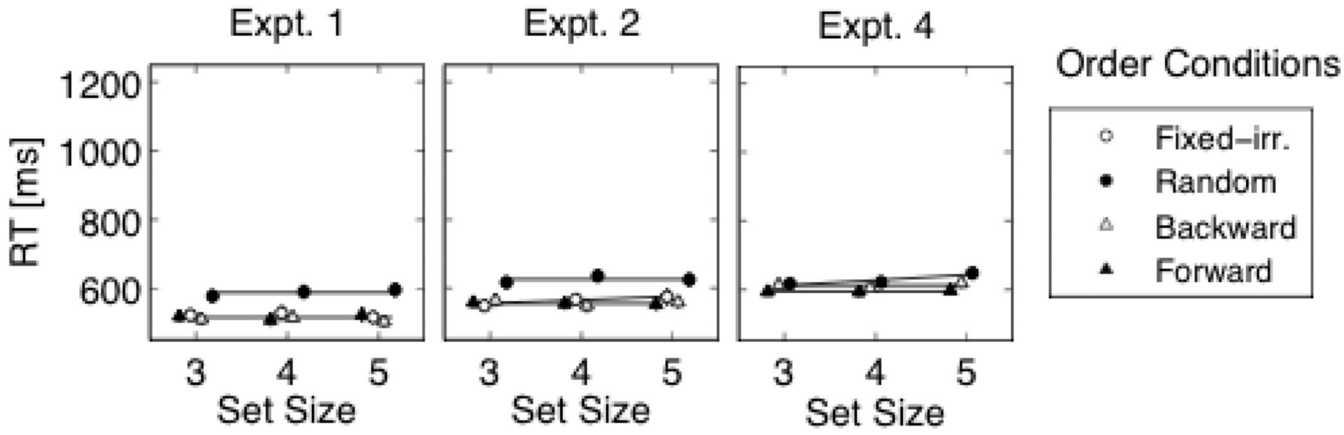

Figure 3.

Reaction times in the magnitude judgment task as a function of condition (probe order) and set size, Experiment 1, 2, and 4. The means are accompanied by regression lines established by hierarchical linear modeling.[1]

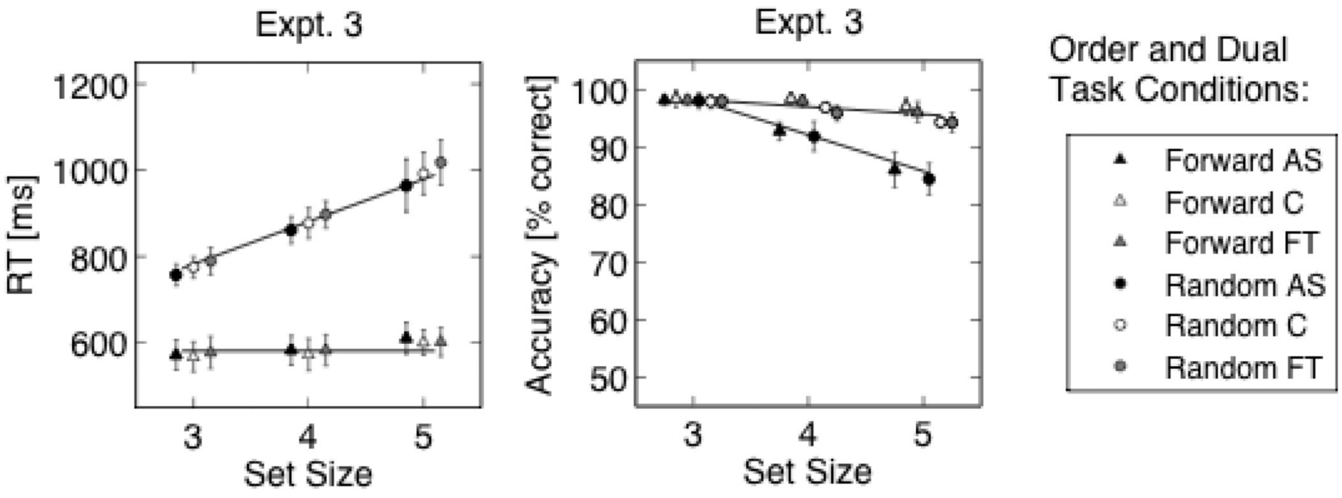

Figure 4.

Reaction times and accuracies as a function of probe order, set size and dual-task condition for Expt. 3 (recognition task).[1] The right panel shows accuracies, the left reaction times. Accuracies with foot-tapping (FT) and in the control-condition without dual-task (“C”) were high and virtually unaffected by set size; accuracies with articulatory suppression (AS) dropped substantially with larger set sizes. In neither case did outcome depend on probe order (Forward, Random). Response times were unaffected by dual-task condition, but differed dramatically with probe order.

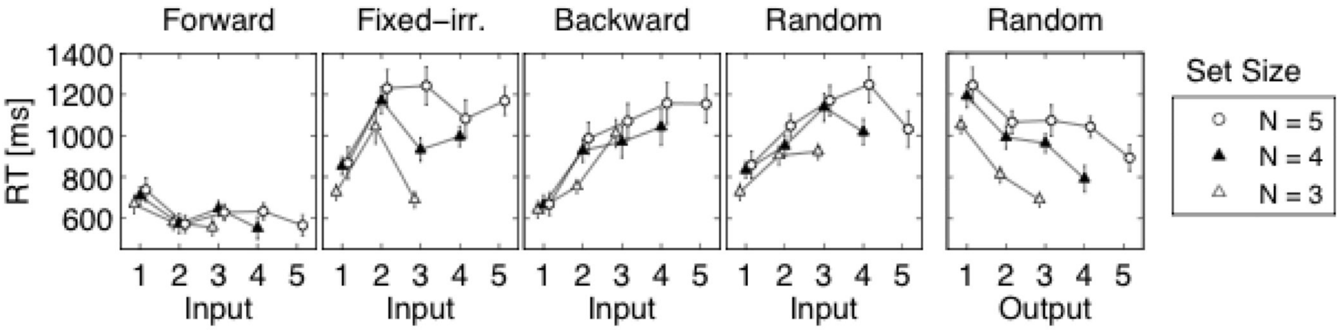

Figure 5.
Mean RTs for Expt. 1 plotted as a function of input (study) or output (test) position, for each probe order, parameterized on the memory-set size *N*. Whereas the input function for the forward condition was relatively flat, functions were highly modulated for all the re-ordered conditions.[1]

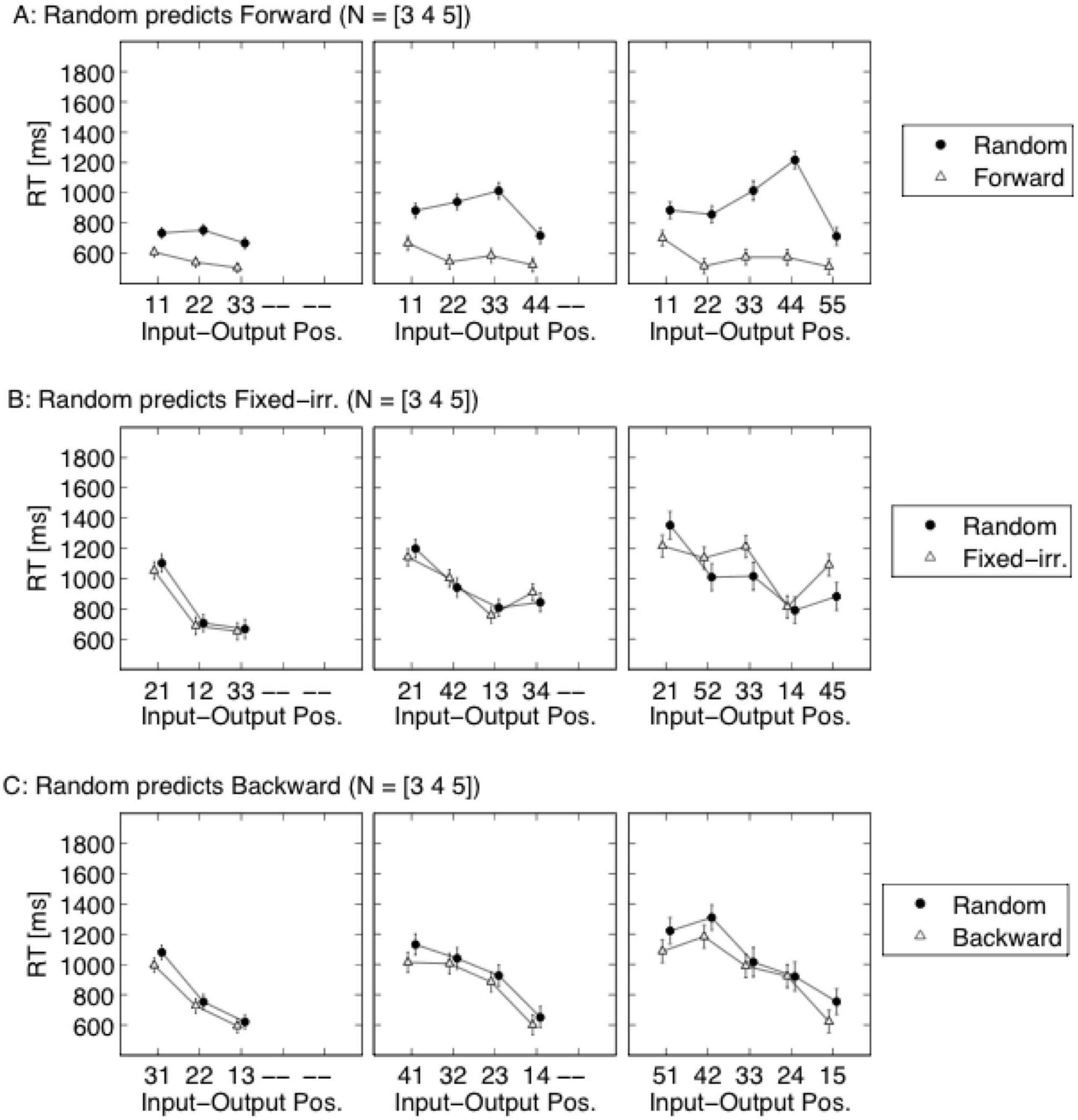

Figure 6.

Latencies from the random condition matched to the fixed-order conditions by their input and output position for Expt. 1. Latencies for forward were substantially faster than matching random latencies (top row). Latencies for fixed-irregular (middle row) and backward (bottom row) were statistically equal to matching random latencies. Differently from Figures. 2 to 4, data were treated as a between-subject design, hence error bars represent usual standard errors. Only positive probes were tallied.

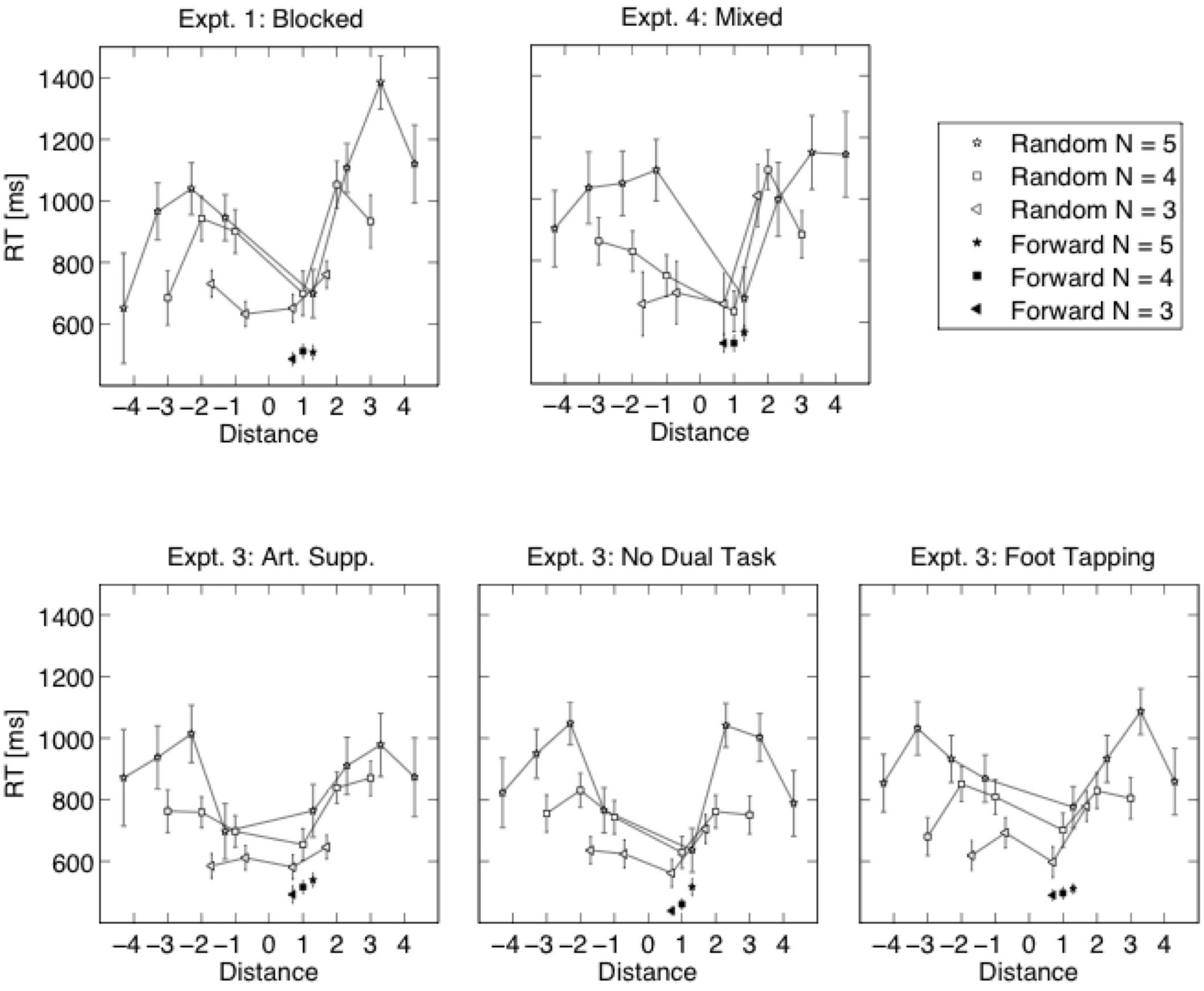

Figure 7.

Latencies from the random condition (open symbols) are plotted as a function of the difference in study position between two successive positive probes (“Distance”) for Experiment 1, and 4, and in three secondary-task conditions of Expt. 3. Data were treated as a between-subject design, hence error bars represent usual standard errors.

Table 1

Parameter estimates (intercept and slope) of the hierarchical linear model fits for different order conditions for all four experiments. Only Expt. 3 utilized three dual-task conditions: Control (no dual task), AS: articulatory suppression, FT: foot tapping.

	Expt. 1		**Expt. 2**		**Expt. 3**			**Expt. 4**	
	Inter-cept [ms]	**Slope [ms]**	**Inter-cept [ms]**	**Slope [ms]**		**Inter-cept [ms]**	**Slope [ms]**	**Inter-cept [ms]**	**Slope [ms]**
Forward	602	0	684	0	Control/AS/FT	582	0	747	0
Fixed-irregular	813	150	888	135	-	-	-	-	-
Backward	790	105	831	76	-	-	-	897	113
Random	850	105	888	135	Control/AS/FT	773	108	897	113