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Dual representation of item positions in verbal short-term memory: Evidence for two access modes

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Abstract

Memory sets of $N = 1\text{--}5$ digits were exposed sequentially from left-to-right across the screen, followed by N recognition probes. Probes had to be compared to memory list items on identity only (Sternberg task) or conditional on list position. Positions were probed randomly or in left-to-right order. Search functions related probe response times to set size. Random probing led to ramped, “Sternbergian” functions whose intercepts were elevated by the location requirement. Sequential probing led to flat search functions—fast responses unaffected by set size. These results suggested that items in STM could be accessed either by a slow search-on-identity followed by recovery of an associated location tag, or in a single step by following item-to-item links in study order. It is argued that this dual coding of location information occurs spontaneously at study, and that either code can be utilised at retrieval depending on test demands.

Keywords

Memory search; Memory scanning; Serial recognition; Binding; Short-term memory

How do we encode and access location information for items stored in verbal short-term memory (STM)? The classical task that addresses STM, Sternberg’s (1969) memory-scanning task, sidesteps this question and deals solely with the identity of an item, and not its temporal or spatial position in the study list. In the Sternberg paradigm, subjects are presented with a memory set of N stimuli, after which one or more probes are presented. The task is to decide whether a probe is part of the memory set or not. Response time (RT) is found to increase with set size N —the time to access an item in active memory depends on the number of co-resident items. Often the set-size effect is linear, characterised by a slope

and intercept, although the exact nature of the access process is still unresolved (e.g., Ashby, Tein, & Balakrishnan, 1993). We will refer to this process as load sensitive.

Some recent findings from our laboratory suggest that the situation may be different when items are probed by location. We used a variant of the N -Back task, in which a running series of items are displayed one at a time, and each item has to be compared with the item presented N items back (Smith & Jonides, 1997). Typically, RT for $N=1$ is very fast, likely mediated by a special buffer with a capacity of one item (McElree, 2001; Oberauer, 2006; Verhaeghen, Cerella, & Basak, 2004); values for $N=2\sim5$ reflect the operation of the bulk of working memory. In our studies we found a flat RT-by- N slope over the $N=2 \sim 5$ range (Verhaeghen & Basak, 2005; Verhaeghen et al., 2004), suggesting that retrieval of an item's identity was assisted by knowledge of the item's location, which allowed the system to bypass load-dependent access. We concluded that locations in STM could be accessed in a load-free fashion, and that this access extended to an item's identity if its location was known.

Subsequent work by Oberauer (2006) challenged this conclusion. Oberauer, like Verhaeghen and colleagues, presented the stimuli in N virtual columns on the screen, but instead of probing from left to right, columns were probed in random order. With this procedure, RT was found to increase linearly with N . It appeared that when locations were probed in random order, then access to an item in STM involved a load-sensitive process, perhaps akin to that governing the Sternberg task.

The conclusion would then be that search through STM proceeds not through a single-, but a dual-access mechanism—random-order probes elicit a load-sensitive search, but when locations are probed in first-to-last or left-to-right order (forward order), item access is load free. Before accepting this dichotomy, it would be well to replicate the divergent outcomes of the Verhaeghen et al. and Oberauer studies in a within-subject design—such a replication was undertaken here. Moreover, the N -Back procedure is not an ideal task with which to measure STM access: The updating requirement embedded in the task may alter retrieval (Zhang, Verhaeghen, & Cerella, 2009)—a requirement we dropped in the present experiment. We did, however, keep the arrangement of multiple probes that had to be matched based on their identity and location. Adding another condition, in which items are probed by their identity only (location free), would help settle the question whether items in STM are accessed primarily by location or by identity. Of particular interest was the comparison between the location-free, Sternberg-like procedure and the location-cued random-order task.

Figure 1 depicts four possible outcomes relating slopes and intercepts in the two conditions expected to be load sensitive.

- A. *Location-based search:*** If identity values are associated with particular locations, and locations are the key to STM access (as in Averbach & Coriell's, 1961, and Sperling's, 1960, visual store model; or Conrad's, 1965, box-car model), access time in the random-order condition would be given by the time to access the location, plus a single item retrieval operation and identity check. The Sternberg-like condition will yield a steeper slope than the random-order condition, because

item retrieval operations and identity checks are necessary for all locations visited (on average: $N/2$).

- B. *Item-based search*: In this type of search, on the other hand, slots would be organised or labelled by item identity (as in Lee & Estes', 1981, revision of their perturbation model, or Coltheart's durable memory, 1984). In this case the response in the Sternberg-like condition can be executed immediately after an identity match and the response time will be determined by the identity-access time alone. In the location-cued random condition the identity search must be followed by a single additional step to check for a location match, creating an intercept difference between the two access functions.
- C. *Link-guided search*: Location information is not directly associated with identity information, but is coded only through an item's temporal or spatial position in the encoding saga (as in Sternberg's scanning-to-locate model, 1969; Lee & Estes's cyclic reactivation model, 1977; and the associative models of Shiffrin & Cook, 1978, or Lewandowsky & Murdock, 1989). For example, location information may be obtained by looping through an ordered set of identity tags and keeping track of position by updating a running count each time an item is accessed. Under this scenario, the observed slope for random-location access—with on average $N/2$ counter update operations per trial—would be steeper than for location-free access, where no counter update is necessary.
- D. *Location-and-identity search*: Location and identity information are both integral parts of an item's STM representation—as soon as one type of information is accessed, the other type is available as well. If so, then RTs from the Sternberg condition and those from the random condition may coincide. Note, though, that retrieval in the random condition is driven by two cues, location and identity, but in the Sternberg condition by identity only. Effective cues would alter predictions shown in Figure 1 depending on probe type. For example, if the cues for random-location access are congruent (a match, or a mismatch in both location and identity), retrieval latencies may be faster for two cues than for one (Anderson, Bothell, & Lebiere, 1998), making the random-order access function in location-and-identity search shallower than the location-free function. If the cues are incongruent (an identity match in the wrong location for the random-order condition), the reverse should be observed.

In sum, in the present experiment, we approached the question how item and location information are accessed by comparing three different search conditions. We adapted a task introduced by Oberauer (2003), in which a set of N probes followed the presentation of the N items of a memory set. In the location-free test condition, each probe digit was compared to all items in the memory set, regardless of position. (This is the *fixed-memory-set* version of the more usual *variable-memory-set* Sternberg task; Sternberg, 1969.) In the two location-cued conditions, each probe was displayed at a particular location, and both its identity and its position must match a target. In the forward-order condition items were probed in the order in which they were presented, akin to the Verhaeghen et al. procedure (2004); in the

random-order condition, items were probed in a random order, akin to Oberauer's procedure (2006).

METHODS

Participants

Thirty-two students of Syracuse University (12 female, mean age 23) participated in the experiment in exchange for course credit or a small honorarium.

Design

Memory lists were composed of one to five digits sampled randomly without replacement from the digits 1 to 9. Stimuli were presented visually on a computer screen. Different fonts were used for memory digits (sans-serif characters, 1 cm wide $\times$ 1.3 cm high) and probe digits (serif characters, 1.2 cm wide $\times$ 1.3 cm high).

The experiment had three probe conditions of 10 blocks each: forward-order location-cued probes; random-order location-cued probes, and location-free probes. Memory-list length was blocked and varied between $N=1$ and $N=5$, with 120 probes for each list length in each condition, divided into two blocks of 60 probes for $N=2$ to 5. Because the task for $N=1$ was the same in all three conditions, the 120 reactions for $N=1$ were distributed across the experiment in six blocks of 20 probes each.

Half the participants started with the forward location-cued condition, followed by the random location-cued condition and the location-free condition; the other half got the reverse presentation order. Three $N=3$ practice trials preceded each condition. The order of blocks with different list lengths followed a complex Latin-square scheme that differed between participants.

A series of N probes followed the presentation of the memory set. Half of all probes were negative. For $N=1$ and for the location-free condition the negative probes were extralist items (digits not in the memory set). For the location-cued conditions, two-thirds of the negative probes were extralist digits, and one-third were digits that were part of the memory set but from a different position (intralist probes).

Procedure

Participants were tested individually in a single, hour-long session. In all conditions participants saw three rows of rectangular frames, 3 cm wide $\times$ 4 cm high, separated horizontally by 3 cm and vertically by 4 cm. The upper row contained a single white frame; the second and the third row contained N frames. The colours of the frames in the second and third row, from left to right, were blue, red, green, hot pink, and yellow in the case of $N=5$. For $N<5$ the first N colours from the list were used.

At the start of a block the length of the study list was indicated by a display of N empty frames in the second and third row. Participants initiated the presentation of the memory set in the second row by pressing the spacebar. N memory items were presented inside the frames, one at a time, from left to the right, in the second row. Presentation was self-paced

by the spacebar. Each item of the memory set was replaced by an “X” when the next item appeared. After presentation of the last memory item, one more barpress triggered the presentation of the first probe item.

In the location-free condition the N probes were presented successively in the top frame; the participant indicated whether or not the probe was part of the memory set. In the forward-order location-cued condition the N probes were presented successively in the frames of the third row, from left to right; the participant indicated whether or not the probe had been presented in the memory set at the same horizontal location. In the random-order location-cued condition probe locations were selected randomly. Each location was probed once. The participant pressed the right or left arrow key to indicate a Yes or No answer in response to a probe. Following a response the probe was replaced by an “X”. The next probe occurred after 200 ms. Upon completion of the N probes of a trial, the next keypress initiated presentation of the next trial.

Participants were instructed to be as fast and accurate as possible. At the end of each block participants were provided with feedback: mean encoding time, mean probe response time, and the number of correct answers. An alpha level of .05 (two-tailed for paired comparisons) was set for all statistical tests.

RESULTS

Accuracy was close to ceiling for all conditions (ranging between 98% and 96%) and was not analysed further.

Encoding times

As can be seen in Figure 2, RTs to the presentation of the memory set increased with set size. A two-factorial ANOVA yielded a significant main effect of set size, $F(4, 124) = 42.32, p < .001, \eta_p^2 = .577$; neither the main effect of condition, $F(2, 62) = 1.97, p > .10, \eta_p^2 = .060$, nor the interaction between set size and condition, $F(8, 248) = 1.50, p > .10, \eta_p^2 = .046$, reached significance. One implication is that potential differences in response times between conditions cannot be an artefact of differential encoding time.

Response times by condition

Only correct responses were analysed. RTs longer than the mean plus three standard deviations as well as those shorter than 100 ms were removed as outliers, excluding 4.8% of the observations. The remaining data are presented in Figure 3. An ANOVA on the $N=2\sim5$ range revealed significant main effects of condition, $F(2, 62) = 87.22, p < .001, \eta_p^2 = .738$, and set size, $F(3, 93) = 83.85, p < .001, \eta_p^2 = .730$, as well as a significant interaction, $F(6, 186) = 43.73, p < .001, \eta_p^2 = .585$.

Figure 3 suggests that the RT×Set-size slope is flat for the forward-order condition, and that the other two conditions have equal slopes. This was confirmed in a hierarchical linear modelling analysis (HLM). HLM is a regression model in which the hierarchical nature of

the data set (i.e., the slopes and intercepts for each condition for each subject) is taken into account, which allows for a more precise estimation of error variance. It was applied here to yield accurate estimates of the slopes and intercepts of our three conditions, as well as to test more precisely the potential equality of slopes and intercepts across conditions. The latter test takes the form of fitting a series of models with increasing restrictions on the data structure; because these models are nested, the difference from one to the next can be tested using a χ^2 statistic on the difference between the log-likelihood fits of the successive models (Snijders & Bosker, 1999).

Three models were tested (Table 1). The first model included three separate intercept parameters and three separate slope parameters, one for each condition. Model 2 was a pruned version of Model 1, with all nonsignificant parameters from Model 1 fixed to zero. In Model 3, we imposed equality on the slope values for the location-free and the random-order conditions. The log-likelihood difference between Model 1 and 2 did not reach significance, $\chi^2_{\text{diff}}(2)=2.70, p>.20$, nor did the difference between Model 2 and 3, $\chi^2_{\text{diff}}(1)=0.001, p>.20$. In the final model, the forward-order and location-free conditions share the same intercept (714 ms); the intercept for the random-order condition is significantly higher (855 ms). The forward-order condition has a statistically flat slope; the slopes for the location-free and random-order condition coincide (82 ms/N).

Response times by probe type

Breaking down the data by probe type sheds additional light on the access process. Figure 4 shows the access functions for positive (Panel A) and negative (Panel B) probes in the load-dependent conditions. We obtained a main effect for probe type, $F(4, 124)=46.47, p<.001, \eta_p^2=.600$, and for set size, $F(3, 93)=126.76, p<.001, \eta_p^2=.803$, but no interaction, $F(12, 372)=1.35, p>.10, \eta_p^2=.042$. The load functions for all five probe types were parallel, a hallmark of Sternberg's (1969) exhaustive-scan retrieval model. For the positive probes, there were main effects for probe type, $F(1, 31)=50.90, p<.001, \eta_p^2=.622$, and set size, $F(3, 93)=111.44, p<.001, \eta_p^2=.782$, and no interaction, $F(3, 93)=2.22, p<.119, \eta_p^2=.067$. For the negative probes, there was no interaction between probe type and set size ($F<1$). A planned contrast between the extralist probes in the random-order and location-free conditions did not reach significance, $F(1, 31)=3.74, p=.062, \eta_p^2=.108$. A planned contrast between extralist and intralist probes within the random-order condition was significant, $F(1, 31)=93.65, p=.001, \eta_p^2=.751$: rejecting an intralist probe took 190 ms longer than rejecting an extralist probe.

Turning to the load-free forward condition, a repeated-measures ANOVA on the three probe types showed a main effect for probe type, $F(2, 62)=83.09, p<.001, \eta_p^2=.728$, and set size, $F(3, 93)=9.64, p<.001, \eta_p^2=.237$, and no interaction, $F(6, 186)=1.95, p=.105, \eta_p^2=.059$. The set-size effect was quadratic in origin, $F(1, 31)=25.20, p<.001, \eta_p^2=.444$; the linear trend was not significant, $F(1, 31)=2.70, p=.111, \eta_p^2=.080$. A hierarchical linear model confirmed that the linear slope of these access functions did not differ from zero. An

ANOVA showed that intralist probes took longer than extralist probes, $F(1, 31)=108.85$, $p<.001$, $\eta_p^2=.778$, by 90 ms.

DISCUSSION

Our experiment revolved around a standard Sternberg condition in which a memory set of $N=1\sim5$ digits was displayed sequentially in N locations from left to right across the screen, followed by a series of N recognition probes presented at centre screen. We obtained a standard result, the time taken to access an item in STM was proportional to the STM set size, resulting in a ramped load function when RT was plotted against N . We went on to ask what would happen in a comparison condition in which each probe was displayed in one of the N screen locations and participants were required to match both the identity and the location of a study item. The answer depended critically on the order in which the probes were given. When the probe order was random, akin to the standard Sternberg condition, we found that the location requirement increased the intercept of the load function, but not its slope (Figure 3). This result favours clearly the alternative (B) identity-based search, outlined in the introduction, and mirrors the predictions shown in Figure 1B. STM access appeared to proceed in two steps: Participants performed a Sternberg-like identity search first (responsible for the slope of the load function), followed by a discrete, load-independent location check (responsible for the increase in the intercept).

Besides accounting for the increment in response times to positive probes, this two-step, identity-then-location access model makes sense of the negative probe times. RTs to extralist foils did not differ with condition (extralist foils can be rejected on the basis of an identity mismatch alone), whereas rejection of intralist foils required additional time (190 ms), due to the necessity of a location check (Figure 4B). These results argue against several alternatives: the supposition that search in working memory involves a match on location first and then the retrieval of an identity tag (Scenario A: location-based search), or that identity and location are integrated in a unitary representation (Scenario D: location-and-identity search).

This interpretation of the retrieval sequence aligns with response-deadline investigations of the dynamics of retrieval. Two studies have found that access to identity information occurred earlier in the retrieval cycle than access to location information (Gronlund, Edwards, & Ohrt, 1997; McElree & Doshier, 1993). Several accuracy-based experiments suggest an identity-plus-location representation as well. Fuchs (1969) assessed individual differences after simultaneous presentation of a set of five words, followed by a position cue for recall of the cued item. Good and poor subjects did not differ on the likelihood that a word from the study list would be recalled, but this word was less likely to be from the correct position for poor subjects. Jahnke (1968) obtained a parallel result via an experimental manipulation. Supraspan lists of six, ten, or fifteen words were presented successively, and subjects undertook serial recall. The number of words recalled regardless of location did not change with list length, but the number of words that were correctly localised fell with list length. These results suggest a robust set of “primary” memory traces defined by item identities, coupled to a more tenuous set of “secondary” traces containing

location information, traces that are weaker in poorer subjects and more vulnerable to interference (and possibly to decay).

Conceived more generally, two-level, *identity-primary* representations accord with other reaction-time results in the STM literature, findings that broaden the range of the model to secondary associates beyond location. For example, Crain and DeRosa (1974, uncued condition) presented memory sets of 1 to 6 digits with coloured surrounds. On a given trial one, two, or three colours were used. They reported that load functions for multicolour sets were governed by the size of the total set, not the size of the same-colour subset matching the probe. Additional colours increased the intercept of the load function—a result in agreement with an identity-then-colour access sequence.

Category information appears to be similar to location or colour information in STM, unavailable until an item has been accessed on the basis of its identity. Several studies have found that search of mixed sets of letters and digits is exhaustive, no different than search of pure sets (all letters or all digits, Clifton & Brewer, 1976; Darley, described in Atkinson, Herrmann & Wescourt, 1974; Kaminsky & DeRosa, 1972). Search through lists of words drawn from several semantic categories is similarly exhaustive, rather than restricted to the subset of words that match the probe category (Homa, described in Atkinson et al., 1974; McCormack, Carboni, & Colletta, 1975).

The sum of this research suggests that digits, letters, or words are organised in STM on the basis of their semantic identities, to which other attributes such as location, colour, or category are linked via one-way associations. In situations where items could be reached via multiple attributes, the primary search key was invariably identity, with additional item information then extracted in a secondary step. Hence, there is compelling evidence for our *identity-based* “two-step” model of STM access. How this scheme would apply to items without semantic attributes, such as abstract symbols or visual patterns, is another question.

Returning to the question of how location cues affect a Sternberg slope, we got a completely different answer from the forward-order condition. When probe order matched study order, first-to-last, the load function was flattened—there was no increase in access time with set size, while the $N=1$ or $N=2$ intercept was unchanged. How can we account for this result in our framework?

One possibility is that the two-step, identity-then-location model applies to the forward condition as well as the random condition. The model assumes that access to STM is serial, one item at a time. Typically a further assumption is made, that items are accessed in encoding order. If we make one more stipulation, that on receipt of a new probe the STM buffer is entered at the point where search left off from the previous probe, then the forward-order result follows. When the probe order matches the study order (as in the forward condition), only a single search step is needed to reach the target item. This means that access times will be independent of the memory-set size, and that the $RT \times N$ function will be flat.

Notice that this last stipulation, that search for the current probe starts where search for the previous probe stopped, implies that search in the forward condition is target-terminated. As

noted in the Results, search in the random condition appears to be exhaustive (parallel slopes for positive and negative probes). So if STM organisation and access does follow the identity-then-location model in both conditions, one aspect of the search strategy appears to change between conditions, a shift from exhaustive to self-terminated search. Such a shift accords with speculations of Sternberg (1969). He presented evidence that time-per-item is much less for an exhaustive search than for self-terminated search, and argued that participants will adopt the latter only if it leads to substantial savings of some other sort. The forward condition affords just such savings (the difference between n search steps and one search step), and so induces the change in strategy.

Another possibility is that the entire STM model changes between conditions. Earlier we made the assumption that search order follows encoding order. But suppose that the set of identity tags at the heart of the identity-then-location access model is essentially unordered. If that were the case there would be no difference between random and forward access under the identity-then-location model. A flat function for forward seems to demand that the memory set be ordered. The *link-guided search* model described here provides this ordering in a natural way. That model supposes that identity tags are linked location-to-location at the time of encoding, and are accessed by following the links. Forward probes allow the chain to be traversed one link at a time; access to the next item is consequently unaffected by the length of the chain.

In either of these possibilities, RTs for extralist and intralist probes should not differ in the forward condition: A No response can follow an identity mismatch in either case with no location check. Contrary to prediction, responses to intralist probes were slower than responses to extralist probes. The 90 ms intrusion cost, however, was substantially less than the 190 ms cost observed in the random-probe condition, $F(1, 31)=36.74$, $p<.001$, $\eta_p^2=.542$, a condition where location checking was more likely to have separated responses to the two probe types. One explanation that would save both accounts, the immediate-access and the chaining account, is to suppose that intralist foils sometimes triggered a weak identity match, and that on those occasions subjects performed a follow-up check on location. If this happened on about half the intralist trials, it would account for a mean of 90 ms additional processing time.

Together, these results replicate the divergent outcomes of the N -Back studies of Verhaeghen et al. (2004) and Oberauer (2006)—flat load functions when items were updated sequentially, and ramped functions when items were updated randomly. The same bifurcation was obtained here in a within-subject design, and in a discrete-trial procedure that rules out STM updating (or extensive practice) as a critical variable. The implications for STM models are substantial. We have proposed two alternatives: Search may be based on a two-step identity-then-location mechanism (the identity-based search model). When representations of this sort are accessed in encoding order search is self-terminated; when accessed in random order search is exhaustive. Alternatively, two STM models may be implicated (the identity-based search and the link-guided search model of this paper), models that differ both in the representation of items—unordered sets versus linked lists, and in retrieval method—search-by-identity versus search-by-location.

Our introductory survey considered only what may be regarded as *single-process* retrieval models. Several *dual-process* models were neglected, falling outside the survey. These models are especially suggestive, because multiple outcomes arise naturally from them. Perhaps they can provide another perspective on the two retrieval patterns seen in our data. We take up two models here. One very current model assumes that two factors underlie recognition judgements: a fast process based on the familiarity of the item, and a slower process of recollection (for details see Mandler, 2008; Yonelinas, 2002). It is tempting to see the flat slope for forward as being driven by the familiarity process, and the ramped slope for random as due to recollection. An experiment by Banks and Atkinson sets a precedent (1974, high-accuracy condition). They found a shallow search slope when memory sets and negative probes were drawn without replacement from a large set of never-repeated words, and a steeper slope when memory sets and negative probes were drawn with replacement from the same set of 12 words throughout the experiment. In the first condition negative probes may have been so unfamiliar as to allow a strength-based decision; whereas in the second condition all probes, both positive and negative, would have high familiarity values due to repeated exposures, necessitating an explicit scan of the memory set. But in our experiment the same set of nine digits was used throughout the forward and random conditions. Familiarity values would all be close to saturation, as in the second of the Banks and Anderson conditions. Our outcome difference cannot be explained by an appeal to familiarity differences between conditions.

In another sort of model, dual-access routes arise from the structure of STM, which is subdivided into two buffers. The dynamic-stack model of Theios is one instance (1973, as developed analytically by Treisman & Doctor, 1987); the expectancy model of Shiffrin and Schneider is another (1974). The two models are very similar; both partition STM into a single “priority” item, and a multi-item “residual” store. Retrieval in these models is a contingent process: The priority item is checked first, and if no match is found then a serial scan is performed on the residual buffer. The dual-buffer models generate divergent load functions that are driven apart by manipulation of probe frequency or expectation. Our results appear to lend themselves to interpretation on just these lines. Forward probes were perfectly predictable. The next probe position could always be anticipated and prepositioned in the priority buffer, available for immediate access. Random probes would be anticipated on only $1/N$ of the trials on average; on the remaining $(N-1)/N$ of the trials a residual scan would be required. There are, though, two problems with this application of the dual-buffer model. First, the model predicts a flat slope only for positive probes in the forward condition. Negative probes should show a steep slope equal to that from the random condition—whereas both positive and negative slopes were flat in our data. Second, the dual-buffer models failed to fit other datasets reviewed by Shiffrin and Schneider, nor did they fit new data collected by Treisman and Doctor. Both groups of authors were led ultimately to reject the two-buffer models.

Returning to the single-process models, our data convince us that two such models, or at least two access modes in one model, are needed. At the same time, data as sparse as ours (i.e., load functions) can contribute little beyond a broad specification of model requirements. The nature of identity-based access, for example, is unresolved despite nearly

half a century of research on Sternberg scanning (Ashby et al., 1993). Our data do address one other issue: Do differences in representation arise from differences in strategy? Our study encouraged strategy differences, both by blocking the probe conditions and by self-pacing study times. Study times, however, did not differ by probe condition (Figure 2). If participants constructed location tags only in the random condition, and interlocation links only in the forward condition, and neither in the Sternberg condition, then these encoding differences were not reflected in study times. We recently repeated the random-probe/forward-probe conditions in the context of an ageing study (Lange & Verhaeghen, 2009; there was no Sternberg condition). In that study blocked probe orders were compared with mixed probe orders. The ramped-slope/flat-slope outcomes reported here were replicated in the blocked condition, and were essentially unchanged in the mixed condition. These observations make it unlikely that the retrieval differences in either of these experiments were due to encoding differences—apparently, list representation does not differ with different probe orders.

We venture a tentative conclusion. Order or spatial information (either dimension could have been the basis for location discrimination in our study) may be doubly represented in STM, once in the form of an attribute tied to an identity tag, and once in the form of a link connecting two identity tags. If location information is needed, one code or the other is utilised at retrieval. If the memory set is queried in forward order, links are utilised; if the queries are random, location tags are utilised. Lewandowsky, Nimmo, and Brown (2008) arrived at a similar conclusion regarding the representation of sequence information in STM as assessed by accuracy in a reconstruction-of-order test. In their study an arrhythmic sequence of seven letters appeared to be encoded both ordinally (“y after x”) and temporally (“y 500 ms after x”—the interval varied from letter to letter). The key finding was that both types of information appeared to be available at test, and subjects utilised one or the other to reconstruct list order, depending on constraints imposed at test, not at encoding. The parallel between their results and ours is intriguing—it remains to be seen if the stimulus dimensions can be aligned across the two studies.

Why dual representation in STM? We offer some speculations. Location tags may be supported by a general-purpose tagging system, useful for capturing other item attributes as well. Access to tags, however, requires prior access to the target item, and that access is inherently slow, perhaps via a serial scan. Location-to-location links, on the other hand, offer fast access to items, but only in the order in which they entered STM. That kind of serial recall must be important enough to warrant a specialised system, perhaps tied to the perception or production of language or behaviour.

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Figure 1.

Predictions from four STM models: (A) location-based search, (B) item-based search, (C) link-guided search, and (D) location-and-identity search. For each model, probe RT is shown as a function of memory-set size and two search conditions: search for item identity and location in the location-cued random condition, and search for item identity only in the location-free condition.

Figure 2. Encoding times for different conditions and set sizes. Means connected by lines are shown. Error bars represent the 95% confidence interval corrected for within-subject measure as proposed by Bakeman and McArthur (1996).

Figure 3.

Reaction times as a function of condition and set size. The means are accompanied by regression lines that resulted from the hierarchical linear modelling account. Error bars represent the 95% confidence interval corrected for within-subject measure as proposed by Bakeman and McArthur (1996).

Figure 4.

Set-size effects in RTs for the location-free and the random-order location-cued condition split by (A) positive and (B) negative probes. The means are connected by lines. Error bars represent the 95% confidence interval corrected for within-subject measure as proposed by Bakeman and McArthur (1996).

TABLE 1

Parameter estimations of Models 1, 2, and 3

	Model 1	Model 2	Model 3
Forward-order intercept	713.05* (34.23)	713.91* (33.17)	713.91* (33.17)
Difference of forward-order intercept and location-free intercept	4.44 (16.81)	—	—
Difference of forward-order intercept and random-order intercept	134.88* (16.81)	140.99* (13.78)	140.72* (9.80)
Forward-order slope	−9.63 (7.61)	—	—
Difference of forward-order slope and location-free slope	85.12* (10.42)	81.87* (5.71)	81.78* (4.69)
Difference of forward-order slope and random-order slope	89.84* (10.42)	81.61* (7.66)	81.78* (4.69)

Table shows means with standard errors in parentheses. Model 1 comprises three different intercepts and slopes. Model 2 comprises two different intercepts and three slopes: common intercept for forward-order and order-free intercept. Model 3 comprises two different intercepts and two slopes: common intercept for forward-order and location-free intercept; common slope for location-free slope and random-order slope.

* indicates that the parameter is significantly different from zero.