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Is scanning in probed order recall articulatory?

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Abstract

We consider how theories of serial recall might apply to other short-term memory tasks involving recall of order. In particular, we consider the possibility that when participants are cued to recall an item at an arbitrary position in a sequence, they covertly serially recall the list up to the cued position. One question is whether such “scanning” is articulatory in nature. Two experiments are presented in which the syllabic length of words preceding and following target positions were manipulated, to test the prediction of an articulatory-based mechanism that time to recall an item at a particular position will depend on the number of preceding long words. Although latency was dependent on target position, no word length effects on latency were observed. Additionally, the effects of word length on accuracy replicate recent demonstrations in serial recall that recall accuracy is dependent on the word length of all list items, not just that of target items, in line with distinctiveness assumptions. It is concluded that if scanning does occur, it is not carried out by covert or overt articulation.

Is scanning in probed order recall articulatory?

Models of verbal short-term memory have focussed on the serial recall task, which has provided a wealth of data on the representations and processes involved in remembering and recalling ordered sequences of information (for a recent overview, see Lewandowsky & Farrell, 2008). One question is the extent to which those representations and processes generalise beyond serial recall to other tasks that require memory for order, but where recall is not necessarily in forward order. In a number of models of short-term order memory, the order of items is assumed to be carried by the associations of those items with some representation of time or position in the sequence (Anderson & Matessa, 1997; Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1999; Henson, 1998). By virtue of this assumption, in these positional models it is in principle possible to access items directly by providing the appropriate cue and probing for the associated item. In applying their positional model to the probed recall task, Brown et al. (2000) assumed that states of temporal context (i.e., positional representations) were paired with items, and that the positional representations were in turn associated with some token used to access that representation based on the memory task. For example, if an individual was asked to recall an item at a particular position by providing the numerical label for that position (e.g., “the 4th position”, or simply “4”), that label would be used to retrieve a positional representation (i.e., a state of temporal context), which would then be used to cue for the item. A similar mechanism was suggested by Henson (1998) in considering the extension of his start-end model to certain types of probed recall task. One implication of these accounts is that there is nothing “special” about forward serial recall; this order recall task just happens to require participants to probe positional memory in a forward order. In contrast, a class of serial recall models here referred to as *ordinal* models are specialised for serial recall, and cannot provide direct access to items on the basis of positional cues

(Farrell & Lewandowsky, 2002; Page & Norris, 1998b). These models assume that the order of items is represented by a primacy gradient of activation or association strength across list items. To recall the list, an iterative cycle of recalling and suppressing the strongest item is carried out; when recalling the item at the third position, the first two items are likely to have been successfully recalled and suppressed, leaving the third item as the item currently strongest or most active. The only obvious way for such models to model recall in response to an arbitrary position cue would be to enact serial recall from the beginning of the list through to the required position. Page and Norris (1998b) showed that such an assumption allowed their primacy model to account for data from the backward recall task, by assuming that items were recalled by a series of covert list recalls up to the desired position, with that and the preceding item then being “peeled off” for recall.

Evidence from recall latencies supports this notion of “positional scanning”. Sanders and Willemsen (1978) tested participants in a speeded positional probed recall task, in which participants were cued with the position of an item and asked to report the item presented at that position in a preceding sequence. Sanders and Willemsen observed a linear relationship between probe position and correct recall latency for initial and medial positions, consistent with the notion that participants “scan forward” from the start of the list to retrieve an item at a particular position. Similarly, in examining recall latencies in backward recall Thomas, Milner, and Haberlandt (2003) observed a negative, roughly linear relationship between output position (which in backward recall maps on to reverse input position) and recall latency, consistent with the general notion of scanning and the specific suggestion of Page and Norris (1998b). As an exception, the final few list items are assumed to be directly accessed, leading to a drop in latency for the last several list items (Sanders & Willemsen, 1978); a similar effect can also be seen in the backward recall data of Thomas et al. (2003).

The question addressed here is the nature of this posited scanning process; specifically, the extent to which information about items is accessed during this scanning. Although existing models do not provide any clear specification of the nature of this scanning process, a number of different interpretations can be placed on models that would constrain said models if the appropriate evidence was obtained. One possible explanation for this scanning process is that it is fully equivalent to list recall, such that list items are accessed in order as assumed in serial recall. Although the time to recall an item (measured from the cue to recall) in serial recall (e.g., Dosher & Ma, 1998; Farrell & Lewandowsky, 2004) tends to be longer than the time to recall a specific item in response to a positional cue (e.g., Experiment 2 of Sanders & Willemsen, 1978), in some situations these times are within the same order of magnitude; for example, in Experiment 1 of Sanders and Willemsen (1978), the scanning rates of around 200 ms per item roughly corresponds to the retrieval times in serial recall experiments (e.g. Farrell & Lewandowsky, 2004; Hulme, Newton, Cowan, Stuart, & Brown, 1999). Alternatively, this scanning process might be considered as a form of covert rehearsal of the form assumed in the phonological loop model (Baddeley, 1986) and the primacy model (Page & Norris, 1998b). Although this rehearsal may not be fully equivalent to recall, it should involve the articulation of items in line with the rehearsal assumed in models of short-term verbal memory (Baddeley, 1986; Page & Norris, 1998b). For example, in the computational phonological loop model of Burgess and Hitch (1999), articulatory rehearsal, limited by the articulatory duration of items, acts to strengthen item representations, which in turn may refresh the decaying associations between items and positions. Similarly, to explain the classic detrimental effect of word length on serial recall accuracy, Page and Norris (1998b) assumed that the primacy gradient in their model, which represents the order of a sequence, is maintained by articulatory rehearsal. This rehearsal was assumed to be cumulative, such that it involved repeated rehearsals in strict forward order from the start of the list, and was assumed to essentially be a read-out from memory (Page & Norris, 1998a); this is consistent with overt rehearsal patterns collected in serial recall (Tan & Ward, 2008). Being articulatory in nature, this process was limited by the number of words that could be rehearsed within the time between list items, the number of words being recitable in this period in turn being limited by the length of those words. As mentioned above, Page and Norris (1998a) also assume that a series of covert list recalls of decreasing length underlies the performance of backward recall. Although Page and Norris do not explicitly relate this process to rehearsal, the assumption that it reactivates items, as does rehearsal, suggests some correspondence of the two processes. The alternative is to assume two processes that involve a read-out from memory and are able to reactivate list items: an articulation-based "rehearsal" mechanism, underlying maintenance of recall; and a "covert recall" mechanism used exclusively at recall, and which may or may not be articulation-based.

The possibilities mentioned above assume some access to the identity of list items in the process of gaining access to other items in the sequence. In two other possible schemes, no such access is required. One possibility is that scanning occurs at the level of positional representations. For example, one account that might be advanced in the framework of the model of Brown et al. (2000) is that scanning is performed by "winding forward" the temporal context from the start of the list to the time state related to a particular position (with the exception of the last position, whose temporal context is likely to still be present at the beginning of recall; this would explain the speeded responses to recency items in the experiments of Sanders & Willemsen, 1978). In this case, only the position of the item in the list would affect the scanning rate, with the associations between time states and items only coming in to play once the cued position has been reached. A final possibility is that scanning does not occur when arbitrarily accessing positions; instead, it might be that there is direct access to items through positional representations as implied in a number of models (Brown et al., 2000; Henson, 1998). As discussed above, this was explicitly assumed by Brown et al. (2000) in their account of probed recall accuracy. In this case, the pattern of recall latencies would instead reflect a parallel competition for recall (Farrell & Lewandowsky, 2004; Hulme, Surprenant, Bireta, Stuart, & Neath, 2004), with an approximately inverse U-shaped latency function mirroring the standard accuracy latency position function (see Farrell & Lewandowsky, 2004, for an example for the case of serial recall).

One way to test between these different accounts, and the approach employed here, is to vary the word length of items in a positional probed recall task. Although controversy surrounds the time-based nature of word length effects in short-term memory (e.g., Lovatt, Avons, & Masterson, 2000), it is clear that words containing more syllables take longer to produce during recall (e.g., Cowan et al., 1994; Hulme et al., 1999). If positional scanning is equivalent to recall, or involves articulatory rehearsal processes, longer words should lead to a steeper position-latency relationship for early and medial positions in positional probed recall: recall of an item in response to a positional probe should take longer if that item is preceded by longer words. In contrast, if scanning acts on positional representations, or recall does not involve scanning at all, no such effect of word length on latencies should be obtained. One caveat that applies to direct access to items is that recall may involve parallel competition between items (Farrell & Lewandowsky, 2004) and that this competition is sensitive to word length effects. In such a case, these effects should be symmetric with respect to the balance of long items preceding and following the target; in contrast, the articulatory scanning account predicts that it is specifically the length of items preceding the target that should predict recall latencies.

Experiment 1

Experiment 1 was designed to test the critical prediction that it is the length of the words preceding an item on the list that should be the critical determinant of recall latency for that item. In a positional probed recall task the number of short (1–syllable) and long (3–syllable) words preceding and following the target item (the item for which recall was cued) were independently varied, along with the length of the target item itself.

Method

Participants. Participants were 30 volunteers, all native or fluent English speakers, aged between 18 and 35 years. Participants were reimbursed £7 for taking part.

Materials and apparatus. Seventy 3–syllable (long) words and seventy 1–syllable (short) words were selected from the CELEX database (Baayen, Piepenbrock, & Rijn, 1995) using the N-watch program (Davis, 2005); the words are given in the Appendix along with their phonetic transcription from CELEX. Words were pairwise matched for word frequency across the one and three syllable groups (mean word frequency per million = 47.3). These words were used to generate the experimental stimuli; 140 lists of five words were constructed for each participant, ensuring that there were an equal number of long and short target words. For each target position, each combination of number of long words preceding and following the target item was presented to each participant four times. The assignment of words to lists, and the order of lists, was randomized for each participant.

The experiment was controlled by a PC that presented all stimuli (on a 15” monitor) and collected and scored all responses using a headphone/microphone and the Psychophysics Toolbox for MATLAB (Brainard, 1997; Pelli, 1997).

Procedure. Participants were tested individually in a laboratory. Each trial began with a fixation point (a cross) being presented in the centre of the screen for 1000 ms. This was followed by a blank screen with duration 500 ms, which was then followed by presentation of the memory list. List items were presented one by one on the screen, each for a duration of 1000 ms. A blank screen was presented for 100 ms between the presentation of each new list item. Following presentation of the list there was another blank screen of 1000 ms, followed by the presentation of a digit indicating the target position to be recalled (e.g., '4'). Once the target position appeared on the screen, the microphone started recording and participants gave their response vocally. After 3000 ms, the microphone stopped recording and the program automatically moved onto the next trial.

Two demonstration trials were presented before the experimental session began, in order to familiarise participants with the experiment. A self-paced break was presented after every 16 experimental trials; participants were presented with a message indicating that they should press the space bar to move to the next set of trials. The entire procedure lasted for around 40 minutes.

Data analysis. The identity of the items recalled was determined by listening to the recorded wave files after the experiment. Latencies were scored by a single observer who examined the wave forms in a wave editing program and visually determined the onset of the response for each trial without knowledge of the conditions for that trial (except the length of the recalled item itself).

Results and Discussion

Accuracy. The left panel of Figure 1 shows the mean proportion correct recall at each probed position for short and long target words (i.e., words that should have been produced in response to the probe). Confirming the apparent lack of effect of word length on recall accuracy, a 2 x 5 repeated measures ANOVA indicated a non-significant effect of word length $[F(1, 29) < 1]$ and a non-significant interaction between word length and probe position $[F(4, 116) < 1]$. The effect of probe position was significant $[F(4, 116) = 10.69, p < .001]$. Post-hoc tests using Tukey's HSD test (using the MS error term from the main effect of probe position with $\alpha = .05$) revealed a significant difference between probe position 5 and all positions 2–4, and a marginally significant difference between position 1 and positions 2–4.

One way to break down the accuracy of results is to consider the recall of target items given a) the word length of those target items, and b) the mixture of other items on the list generally. Previous studies have shown that when mixing equal numbers of short and long words on lists, a classic word length advantage is not observed (Bireta, Neath, & Surprenant, 2006; Hulme et al., 2004). Although Cowan, Baddeley, Elliott, and Norris (2003) demonstrated a word length effect in this situation, through a number of demonstrations varying experimental design and stimulus set Bireta et al. (2006) showed that the results of Cowan et al. (2003) were likely due to properties of their stimuli that were correlated with word length (e.g., imageability). Furthermore, Hulme et al. (2006) found that "isolating" single short words on serial recall lists by surrounding them with long words varied their recall little with respect to lists containing only short words; in contrast, the recall of long words was enhanced (compared to pure lists containing only long words) by surrounding them with short words. Table 1 shows a similar breakdown of results for Experiment 1 here. Table 1 replicates the findings of Hulme et al. (2004) and Bireta et al. (2006) in showing a standard word length effect in pure lists, but an absence of word length effect with roughly equal numbers of short and long words (number of long words = 2 or 3). In replication of the results of Hulme et al. (2006) and Bireta et al. (2006), Table 1 also shows that the recall of short words was not enhanced by isolating them on a list of long words (comparison of short word recall in rows 4 and 5: $t(29) < 1$), whereas recall of long words was enhanced by surrounding them with short words (comparison of long word recall for rows 1 and 5: $t(29) = 7.39, p < .001$) leading to a reverse word length effect.

Overall, the accuracy results from Experiment 1 and previous experiments are consistent with the pattern of results found by Bireta et al. (2006), which show that regardless of the stimulus set used, there is little consistent effect of the nature of background items on the recall of short items (short word column in Table 1), whereas long words show a consistent increase in accuracy as the number of surrounding long words is reduced (long word column). In comparison to the results from the standard serial recall task, the results from this probed recall experiment can be assumed to be less affected by output delay effects (Avons, Wright, & Pammer, 1994) and thus give a clearer picture of these other effects of word length at play. Together with previous results, these probed recall results are problematic for item-level accounts of the word length effect (Brown & Hulme, 1995; Neath & Nairne, 1995) and suggest alternative global accounts of word length effects in short-term memory (Cowan et al., 2003; Hulme et al., 2004; see General Discussion).

Latencies. The right panel of Figure 1 shows the mean latency for correct responses at each probed position for short and long words. As for the accuracies, a 2 x 5 repeated measures ANOVA indicated a non-significant effect of word length [$F(1, 29) < 1$]. The effect of probe position was significant [$F(4, 116) = 26.32, p < .001$], and the interaction between word length and probe position was close to significance [$F(4, 116) = 2.22, p = .072$]. Post-hoc tests using Tukey's HSD test revealed that recall at position 1 was significantly faster than that at positions 2, 3 and 4; that the response at position 2 was significantly faster than that at position 4; and that recall at position 5 was significantly faster than that at positions 3 and 4. To determine the metrics of the suggested scanning mechanism, a linear mixed-effects model was fit to individual latencies from the first four serial positions. This gave a fixed-effects estimate of slope of 80.5 ms/position [$t(2196) = 3.52, p < .001$].

The left panel of Figure 2 plots mean latency of correct recalls according to the number of preceding long items, while the right panel plots latencies of number of following long items. A linear mixed-effects regression analysis was applied to the data with the proportion of preceding (*predens*) or following (*postdens*) items that were long as a predictor, and log(*latency*) as the dependent variable. The use of mixed-effects modelling here is advantageous in allowing for regression to be applied at the level of individual participants, but also allowing for a more powerful analysis than alternatives such as slopes-as-outcomes regression (see Hoffman & Rovine, 2007, for an introduction to, and the merits of, multilevel modelling). As indicated by Figure 2, neither the effect of *predens* [$t(2717) < 1$] or *postdens* [$t(2704) < 1$] was significant.

The results of Experiment 1 provided no evidence for an effect of word length on scanning times in positional probed recall; recall times were identical regardless of the number of preceding (or following) long words in the sequence. There was an effect of the overall number of words preceding or following in terms of target position, with increasingly longer recall latencies across all serial positions except the last. The approximately linear increase in recall latencies across earlier list positions replicates previous findings (e.g., Sanders & Willemsen, 1978) and is consistent with scanning models of positional access. The drop in recall latencies for the last position also replicates those previous studies, and is consistent with some form of direct access for the last item. We defer consideration of the exact nature of this direct access to the General Discussion.

The lack of a latency effect here casts doubt on one possible mechanism for the word length effect in probed recall. Although probed recall has been assumed to minimize the influence of output delays (Avons et al., 1994), the lingering effect of word length in previous probed recall studies may have reflected the longer time taken to access items in lists of long words. That is, because longer items needed to be scanned through in order to recall the probed items, there may have been an increased delay of recall on lists of long words. The failure to find an effect of word length of preceding items on latencies here allows us to discard this as a likely explanation of the word length effect in this paradigm.

Experiment 2

Experiment 2 aimed to replicate Experiment 1 using a more powerful manipulation. On each list, words were either all long (3 syllables) or all short (1 syllable). Varying all preceding items to be either long or short constitutes a more powerful manipulation of the length of items. Additionally, this allows for replication of the latency results in Experiment 1 under conditions previously used to examine the effects of word length on accuracy in probed recall (Avons et al., 1994).

Method

Participants and design. Participants were 30 volunteers, all native or fluent English speakers, aged between 18 and 35 years. Participants received £7 for taking part. Each participant completed trials in all cells of the 2 (word length: long vs short words) x 5 (serial position: 1–5) design.

Materials, apparatus, and procedure. Materials were as for Experiment 1, with the exception that lists were constucted of either all long or all short words (no mixed word length lists). Each stimulus appeared once in each of four lists, with the assignment of words to lists, and ordering of lists, otherwise being randomized for each participant. Apparatus and procedure were identical to Experiment 1.

Results and Discussion

Figure 3 shows serial position curves (SPCs) for accuracy (left panel) and latency (right panel). For the accuracy SPC, a 2 (word length: long vs short) x 5 (serial position) repeated measures analysis of variance (ANOVA) revealed a main effect of serial position [$F(4, 116) = 67.45$, $p < .001$]; the SPCs show clear primacy and recency effects in the data. Post-hoc examination revealed a significant quadratic contrast for serial position [$F(1, 29) = 189.35$, $p < .001$], reflecting the approximately symmetric U-shaped functions in Figure 3. A main effect of word length [$F(1, 29) = 101.83$, $p < .001$] was found, with lists comprised of short words being more accurately recalled than lists of long words. The interaction between word length and serial position was also significant [$F(4, 116) = 2.76$, $p < .05$], with a significant quadratic contrast [$F(1, 29) = 17.01$, $p < .001$] for this interaction reflecting the greater decrement for long words at medial serial positions.

A main effect of serial position on latency of correct responses was also found [$F(4, 116) = 123.59$, $p < .001$], with steadily increasing latencies across serial position with the exception of the last list items where responses were faster (see right hand panel on Figure 3). Post-hoc tests using Tukey's HSD test (using the MS error term from the main effect of probe position with $\alpha = .05$) revealed significant differences between all consecutive serial positions for short word lists, and for all consecutive serial positions with the exception of the comparison of items 3 and 4 on the long word lists. This supports the view that there is a cost associated with recalling later list items; each additional serial position prior to the probe cumulatively increases response latency (with the exception of the final one or two list items). No main effect of word length was found [$F(1, 29) = 1.35$, $p = .25$] and the interaction between word length and serial position was not significant [$F(4, 116) = 1.26$, $p = .29$].

The lack of an interaction effect in Experiment 2 is worth commenting on given the strong manipulation of contextual word length: the items preceding a target were either all long or all short. Although the use of multilevel modelling in Experiment 1 minimizes any concerns about power, the manipulation in Experiment 2 represents a strong experimental manipulation. One specific cause for concern with respect to power is the extent to which articulation times, as opposed to other durations during recall (specifically, retrieval times), dominate recall. If the large proportion of recall latencies come from processes not affected by articulation, then perhaps a large affect of articulatory length would not be expected. A persuasive suggestion that this is not the case comes from the work of Hulme et al. (1999), who recorded the durations of item pronunciations and inter-item pauses in serial recall of span-length lists (around 4–5 items). Their data show that the duration of pronunciation of short words was over three times longer than the pauses between words, the latter being assumed to reflect non-articulatory memory processes given their insensitivity to word length. Although it might be argued that covert articulation is substantially faster than overt articulation, analyses by Baddeley and Andrade (1994) show that this is not the case. In comparing articulation rates of their stimuli and those of Caplan, Rochon, and Waters (1992), Baddeley and Andrade (1994) showed articulating items covertly rather than overtly led to a speed up in articulation rate of only 10%. Together, this suggests that even under covert articulation, a large proportion of the recall latency should involve articulation of items if this is involved in scanning to positions.

As for Experiment 1, word length affected the accuracy of item recall, but had no apparent effect on the latencies of recalls. Critically, there was no apparent interaction effect involving word length and target position, which is problematic for a theory in which preceding items take longer to scan through, and which thus predicts such an interaction.

General Discussion

The lack of effect of the word length of items preceding a target item on recall latency in probed recall suggests that any scanning taking place in this paradigm is not articulatory in nature. Although the latencies of recalls are suggestive of some form of scanning taking place (as reflected in the approximately linear increase in latencies across all but the last few positions in probed recall), several models have difficulty accounting for the lack of word length effect here (Baddeley, 1986; Page & Norris, 1998b), as their assumed rehearsal mechanisms are required to be temporally sensitive to word length in order to explain the standard detrimental effects of syllabic word length on serial recall (e.g., Baddeley, Thomson, & Buchanan, 1975; Service, 1998). Although the critical results are null effects, the lack of interaction of word length with target position stands in stark contrast to the highly significant effects of target position on recall latencies, and the effects of word length on accuracy of recall.

Word length effects on accuracy

Looking first at the accuracy results, in Experiment 1 there was no effect of the length of the target was found on recall accuracy, but accuracy was affected by the length of preceding and following items. This is consistent with the finding in serial recall that the structure of the list modulates the word length effect: when short and long words are mixed together on a list, the word length effect is reduced (Bireta et al., 2006; Cowan et al., 2003) or abolished (Hulme et al., 2004) for individual items. Together with those findings, a similar lack of effect here, including the lack of effect of the length of target items on recall accuracy in Experiment 1, is problematic for item-based accounts of the word length effect. For example, Neath and Nairne suggested that word length effects on accuracy follow from the increased probability of making an error in reconstructing longer words, given the assumption that longer words contain more segments. This predicts no effect of the length of surrounding words, in discord with our results. The relative effect of word length observed here is generally consistent with the assumption that long words are less distinct than short words. Hulme et al. (2004) suggested that this was the case because long words are of greater phonological complexity, and that the differences between long words are therefore less easy to apprehend. Additionally, there must be a role for relative distinctiveness: placing a long word on a list of short words will make that long word more discriminable, as it differs from all the short words on the list. As a consequence, mixing long and short words on a list will increase the relative distinctiveness of both classes of items. This theory also explains the effect of word length in Experiment 2 using pure lists of short or long words, which is quantitatively similar to that observed by Avons et al. (1994) in their examination of word length effects in probed recall. However, Hulme et al. (2006) note that quantitative application of these assumptions cannot account for the full pattern of word length effects on accuracy, in particular the finding, replicated here, that isolated long words are better recalled than isolated short words.

One alternative direction towards explaining these results comes from the principle of feature overwriting (Nairne, 1990; Oberauer & Lange, 2008).[1] When items are presented successively to be memorized, a form of interference may occur whereby items may overwrite or "steal" features from other items, in that those features are lost from the overwritten representations. If it is assumed that feature elements in a word are temporally arranged, such that short and long words overlap on earlier features and only long words overlap on later features (Lewandowsky & Farrell, 2000), then as the number of long words on the list is increased, there will be an increasing opportunity for the elements in a particular long word to be overwritten by other long words. Additionally, this offers to explain superior recall of long isolates compared to short isolates: first, long isolates will suffer from less overwriting than short isolates; and second, a redintegration mechanism of the sort assumed in the model of Lewandowsky and Farrell (2000; see also Brown & Hulme, 1995) could produce an advantage for long words. This explanation requires that "overwriting" is symmetric (i.e., that words can overwrite both preceding and following elements), as some unreported analyses showed that both the number of preceding and following long words contributed to the mixture effects shown in Table 1. Additionally, this does not explain where the overall negative effect of word length comes from. One possibility is that elements in the first segment are particularly robust, either in terms of initial encoding or a lessened susceptibility to overwriting. The assumption of a differential role for different syllables in a word in contributing to memory performance is consistent with the observation that varying redundancy in the beginning, middle, or end of multi-syllabic words leads to different levels of recall decrements (Luotoniemi, Service, & Maury, 2007; Service & Maury, 2003). However, until a well-specified model of serial recall is presented that explicitly instantiates the representations of words of different length (Lewandowsky & Farrell, 2000, notwithstanding), and which accounts for the full range of effects of word length on recall accuracy (e.g., Bireta et al., 2006; Cowan et al., 2003; Cowan, Saults, & Nugent, 1997; Hulme et al., 2004, 2006), this must remain speculative.

Word length effects on latency

The latency data speak to a number of possible models of arbitrary positional access. Models such as the primacy model and the phonological loop model cannot account for lack of effect of word length on recall times, particularly in light of the clear effects of syllabic length on accuracy. The latency data also rule out possible models in which the scanning process is identical to recall, on two counts. First, the lack of word length effects on latencies here stands in contrast to the effects of word length on pronunciation durations in overt serial recall (e.g., Hulme et al., 1999); since these durations will form part of the cumulative recall time to an item, they should result in the predicted interaction between recall latency and serial position. Second, the rate of recall in the standard serial recall task is around 500 ms/item for serial recall of digits (e.g., Farrell, 2008; Farrell & Lewandowsky, 2004) and around 750 ms/item for 1-syllable words (Hulme et al., 1999). The slope relating recall latency to serial position here (Figures 2 and 3) gives an estimated scanning rate of 80-100 ms per item, which clearly does not accord with the timing estimates from serial recall.

One alternative is that positional access in this probed recall task involves scanning, but a form of scanning that is insensitive to the nature of items. A candidate mechanism is the scanning mechanism suggested by Cowan and others (Cowan, 1992, 1999; Hulme et al., 1999). Cowan (1992, 1999) and Hulme et al. (1999) suggested that the pauses between words in serial recall reflect a search of working memory, and that this search mechanism also serves the process of reactivating, and thus maintaining, items for short-term recall. Cowan (1992) identified his scanning mechanism with that posited by Sternberg, Monsell, Knoll, and Wright (1978), and suggested that it was unlikely to be articulatory in nature given the lack of effect of word length on latency in the standard recognition scanning paradigm (Clifton & Tash, 1973) and ordered output (Sternberg et al., 1978; see also Hulme et al., 1999). Additionally, the search rate of approximately 80 ms per item is within the range of search rate estimates reported for item recognition: Hulme et al. (1999) found scanning rates of 76 ms and 56 ms per item for 1– and 5–syllable words, and Cavanagh (1972) reported a rate of around 50 ms/item on the basis of a number of previous studies. However, the scanning mechanism suggested by Cowan and Sternberg on the basis of such results does not plausibly account for the results here, as Cowan (1992), following Sternberg et al. (1978), suggested that the order of search of memory is random; items cannot be accessed in forward order, but are instead paired with serial position tags, with positional access being accomplished by finding the item whose tag matches the position of current interest. Such an account would predict a flat function relating recall latency to serial position.

We may also ask whether the scanning examined here bears a relation to the rehearsal assumed in a number of theories of short-term memory (e.g. Baddeley, 1986; Page & Norris, 1998b). As discussed, the lack of effect of word length clearly mitigates against articulatory rehearsal. An additional reason for thinking that articulatory rehearsal is not involved is that the rate of scanning is much faster than could be accomplished with covert articulation; for example, the analyses of Baddeley and Andrade (1994, Table 1) suggest a covert rehearsal rate of around 300-350 ms per word, which is much slower than the rates observed here. However, there is reason to think that some form of rehearsal might relate to the scanning discussed here. First, as noted above, a number of authors have assumed that a consequence of scanning is the reactivation and maintenance of list items that are yet to be recalled. Second, recent work by Tan and Ward (2008) suggests a close relationship between rehearsal and recall. Tan and Ward (2008) asked participants to overtly rehearse during presentation of stimuli in a serial recall experiment. Supporting the assumptions of Page and Norris (1998b), participants were found to cumulatively rehearse the list in a forward order, with rehearsal tending to switch to repetition of the just-presented item for later serial positions. For slower presentation rates, Tan and Ward also found that participants with better serial recall performance tended to produce longer rehearsal sequences. Regardless of the role of rehearsal in their experiments, these patterns suggest that recall is critically involved in rehearsal, and is a limiting factor for rehearsal. This would be consistent with a framework in which scanning is effected by recall and takes part in the classic operations of rehearsal (that is, reactivation of list items). However, it is not clear that the rehearsal of the type described actually plays any constructive role in short-term memory. Tan and Ward (2008) found similar serial position functions regardless of whether or not cumulative rehearsal could be reasonably accomplished (i.e., irrespective of presentation rate). Oberauer and Lewandowsky (2008) found that a number of models, when fit to their serial recall data, produced proportionately small estimates for the amount of rehearsal occurring in their experiments. They pointed out that rehearsal, if limited by recall, can only impair order memory since it can only be as good as, or worsen, the memory of the list existing prior to rehearsal (in the same way that photocopying a photocopy will reduce image quality further). Accordingly, we see the major role of scanning here to be the positional access of items, and its functional role as a rehearsal mechanism to be minor at best (although it may be co-opted to produce rehearsal sequences in experiments where rehearsal is requested or assumed on the part of the participant).

More generally, these data take us closer to extending models of serial recall to other paradigms such as probed recall. By eliminating articulatory scanning as a mechanism of random positional access, three likely possibilities remain. The first is that items are accessed directly, with the latency-position functions shown in Figures 2 and 3 reflecting standard serial position functions for accuracy, including extended primacy and recency effects. As shown by Farrell and Lewandowsky (2004), a number of assumed mechanisms of serial recall can easily produce inverse U-shaped latency serial position functions in serial recall; a case may be made that the same mechanisms apply here. Similarly, Hulme et al. (1999) noted that their suggested memory search mechanism may not be serial in nature, but may reflect parallel search of memory of the type explored by Ratcliff (1978). Second, the latency patterns may reflect scanning through positional representations without accessing items. This would account for the lack of effect of word length on putative scanning times, and could be accomplished in a number of models (e.g., Burgess & Hitch, 1999; Brown et al., 2000) by assuming that the latency patterns reflect the time to wind temporal context forward to the position of recall. The final possibility considered here is scanning of the nature suggested by Cowan (1992), but that involves forward search from the start of the list. This could be accomplished in models of serial recall by assuming that participants covertly conduct forward recall from the start of the list, but at a level that is not sensitive to the phonological aspects of items themselves. For example, a number of models assume that processes of reconstructing and outputting items are separate and downstream from those responsible for the access of order of items (e.g., Burgess & Hitch, 1999; Henson, 1998; Lewandowsky & Farrell, 2008; Page & Norris, 1998b).

Whether forward scanning occurs across positional representations or items themselves, it is not fully sufficient to account for the entire set of latency data. In particular, we (Figures 2 and 3) and others (e.g., Hendrikx, 1984, 1987; Sanders & Willemsen, 1978) have observed a drop in latencies for the last several serial positions, particularly the final position. Sanders and Willemsen (1978) explained this pattern of data with their positional cueing theory, in which it is assumed that individuals can access the first and last few items on a list directly, whereas the remaining items must be accessed through forward scanning (see also Hendrikx, 1984); the latencies for the last few positions may reflect a mixture, across trials, of direct access and forward scanning (Sanders & Willemsen, 1978). This is broadly consistent with the assumption of an "end marker" in serial recall with respect to which items, particularly later list items, are anchored (Henson, 1998). Although modelling work by Farrell and Lelièvre (in press) questions the extensive use of end markers in serial recall, there may be a role for such representations in a paradigm in which arbitrary access to final items is required.

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Appendix

Stimuli used in the experiments

The short words used in the experiment appear in Table A1, and the long words appear in Table A2, along with phonetic transcriptions from the CELEX database (Baayen et al., 1995).

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Notes

[1] We thank Elisabet Service for pointing out the possible relevance of feature overwriting, and the role of different syllables, for explaining these results.

Table 1

Recall accuracy for short (1-syllable) and long (3-syllable) target words, and resulting word length effects, as a function of the total number of long words on the list. Asterices indicate significance at the .05 level.

Number of long words	Short	Long	WLE
1 (long isolate)	.82	.91	-.09*
2	.80	.82	-.02
3	.78	.77	.01
4 (short isolate)	.79	.74	.04
Pure (0 or 5)	.78	.68	.10*

Table A1

Short words (1-syllable)

sort	[sO:t]	win	[wIn]	hang	[h&N]	juice	[dZu:s]	ape	[eIp]
ground	[graUnd]	smoke	[sm@Uk]	grant	[grA:nt]	brush	[brVS]	blur	[bl3:r*]
bring	[brIN]	pale	[peIl]	kid	[kId]	tense	[tEns]	ant	[&nt]
doubt	[daUt]	search	[s3:tS]	cloud	[klaUd]	cliff	[klIf]	ace	[eIs]
break	[breIk]	plain	[pleIn]	league	[li:g]	tool	[tu:l]	crutch	[krVtS]
strange	[streIndZ]	hat	[h&t]	rod	[rOd]	fork	[fO:k]	boar	[bO:r*]
plan	[pl&n]	queen	[kwi:n]	damp	[d&mp]	mill	[mIl]	flea	[fli:]
shot	[SOt]	seek	[si:k]	crop	[krOp]	cease	[si:s]	waltz	[wO:ls]
desk	[dEsk]	route	[ru:t]	bull	[bUl]	dock	[dOk]	chance	[tSA:ns]
bright	[braIt]	proud	[praUd]	shore	[SO:r*]	beam	[bi:m]	lump	[lVmp]
meat	[mi:t]	calm	[kA:m]	gear	[gI@r*]	bolt	[b@Ult]	speech	[spi:tS]
risk	[rIsk]	skill	[skIl]	fence	[fEns]	spear	[spI@r*]	glad	[gl&d]
cross	[krOs]	egg	[Eg]	belt	[bElt]	badge	[b&dZ]	stock	[stOk]
noise	[nOIz]	guilt	[gIlt]	crude	[kru:d]	bluff	[blVf]	chose	[tS@Uz]

Table A2

Long words (3-syllable)

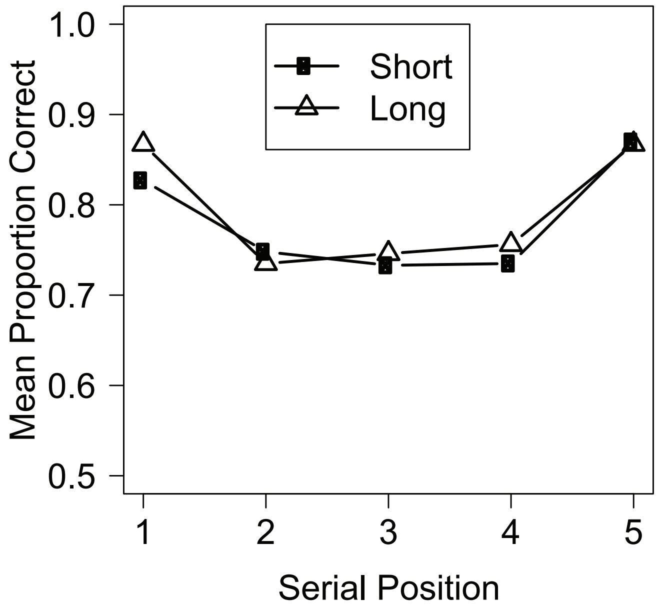
family	[f&] [m@] [lI]	newspaper	[nju:s][peI][p@r*]	principal	[prIn][s@][p]
history	[hI][st@][rI]	wonderful	[wVn][d@][fUl]	criminal	[krI][mI][n]
century	[sEn][tSU][rI]	poverty	[pO][v@][tI]	restaurant	[rE][st@][rO :N]
evidence	[E][vI][d@ns]	insurance	[In][SO:][r@ns]	pollution	[p@][lu:][S]
hospital	[hOs][pI][t]	employment	[Im][plOI][m@nt]	delicate	[dE][lI][k@t]
telephone	[tE][lI][f@Un]	atmosphere	[&t] [m@] [sfI@r*]	corridor	[kO][rI][dO:r*]
average	[&] [v@] [rIdZ]	enemy	[E][n@][mI]	gallery	[g&] [l@] [rI]
character	[k&] [r@k] [t@r*]	relative	[rE][l@][tIv]	creative	[kri:][eI][tIv]
attitude	[&] [tI] [tju:d]	chemical	[kE][mI][k]	nursery	[n3:][s@][rI]
professor	[pr@][fE][s@r*]	magazine	[m&] [g@] [zi:n]	camera	[k&] [m@] [r@]
election	[I][lEk][S]	furniture	[f3:][nI][tS@r*]	festival	[fE][st@][v]
advantage	[@d][vA:n][tIdZ]	manager	[m&] [nI] [dZ@r*]	document	[dO][kjU][mEnt]
yesterday	[jE][st@][dI]	survival	[s@][vaI][v]	instrument	[In][strU][m@nt]
memory	[mE][m@][rI]	interview	[In][t@][vju:]	sacrifice	[s&] [krI] [faIs]
luxury	[lVk][S@][rI]	musician	[mju:][zI][S]	disaster	[dI][zA:][st@r*]
bicycle	[baI][sI][k]	canopy	[k&] [n@] [pI]	bungalow	[bVN][g@][l@U]
battery	[b&] [t@] [rI]	crocodile	[krO][k@][daIl]	motorway	[m@U][t@][weI]
prisoner	[prI][z][@r*]	casino	[k@][si:][n@U]	computer	[k@m][pju:][t@r*]
passenger	[p&] [sIn] [dZ@r*]	strawberry	[strO:][b@][rI]	habitat	[h&] [bI] [t&t]
orchestra	[O:][kIs][tr@]	clarinet	[kl&] [r@] [nEt]	investment	[In][vEst][m@nt]
elephant	[E][lI][f@nt]	lottery	[lO][t@][rI]	triangle	[traI] [&N] [g]
potato	[p@][teI][t@U]	peppermint	[pE][p@][mInt]	enormous	[I][nO:][m@s]
umbrella	[Vm][brE][l@]	industry	[In][d@s][trI]	satellite	[s&] [t@] [laIt]
architect	[A:][kI][tEkt]				

Figure Captions

Figure 1. Mean proportion correct (left panel) and mean latency for correct responses (right panel) for Experiment 1, according to the probed position and the word length of the item presented at the probed position.

Figure 2. Mean latency of correct recalls according to serial position of the probe, and the number of long words preceding (left panel) or following (right panel) the target item.

Figure 3. Serial position functions for Experiment 2. Left panel: Mean proportion correct by serial position, for short and long word length conditions; Right panel: Mean recall latencies by serial position.


Mean Proportion Correct
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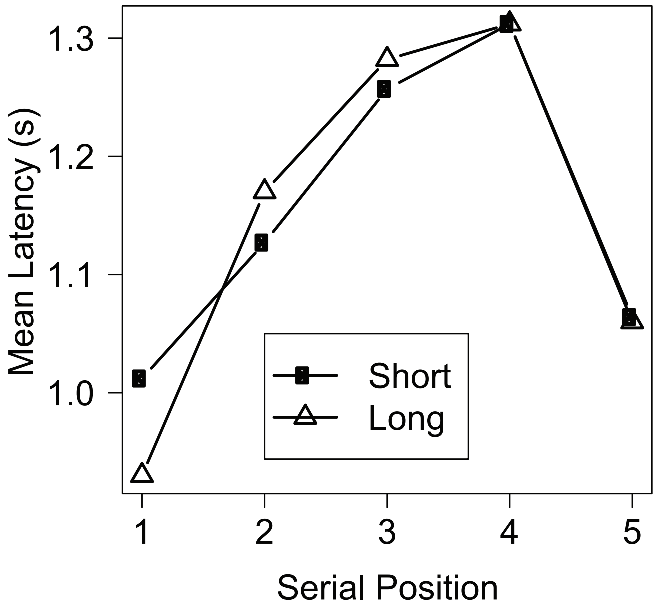
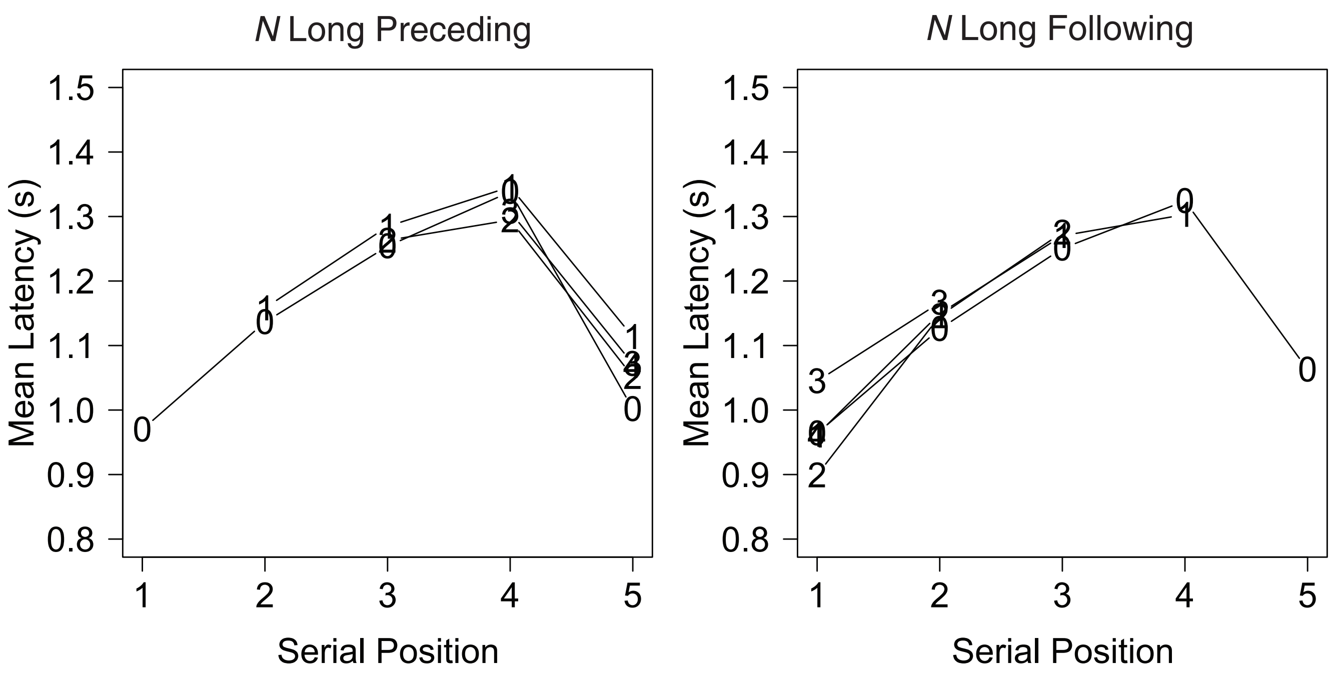
0.9
0.8
0.7
0.6
0.5
Short
Long
1
2
3
4
5
Serial Position


Mean Latency (s)
1.3
1.2
1.1
1.0
Short
Long
1
2
3
4
5
Serial Position


N Long Preceding
N Long Following
Mean Latency (s)
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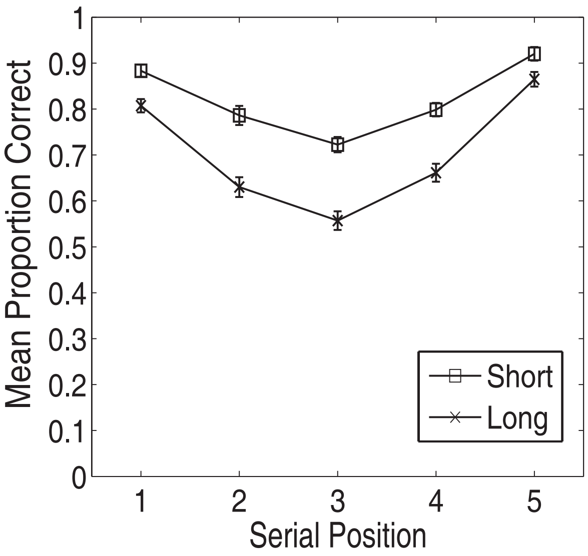
1.4
1.3
1.2
1.1
1.0
0.9
0.8
Serial Position
1
2
3
4
5


Mean Proportion Correct
1
0.9
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0.7
0.6
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0.3
0.2
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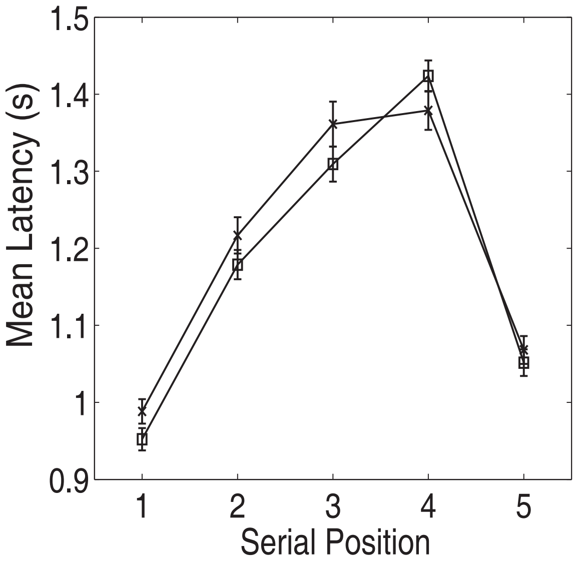
3
4
5
Serial Position
Short
Long


Mean Latency (s)
1.5
1.4
1.3
1.2
1.1
1
0.9
1
2
3
4
5
Serial Position