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Core verbal working-memory capacity: The limit in words retained without covert articulation

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Abstract

Verbal working memory may combine phonological and conceptual units. We disentangle their contributions by extending a prior procedure (Chen & Cowan, 2005) in which items recalled from lists of previously seen word singletons and of previously learned word pairs depended on the list length in chunks. Here we show that a constant capacity of about 3 chunks holds across list lengths and list types, provided that covert phonological rehearsal is prevented. What remains is a core verbal working-memory capacity.

Keywords

Working memory; Articulatory suppression; Serial recall; Capacity limits; Verbal working memory

There has been an interesting progression in how researchers conceive of processes taking place in the immediate, serial recall of word lists. Miller (1956) observed that the limit was not in the amount of information, but in the number of meaningful units, or chunks. For example, words are drawn from a much larger pool than digits and therefore contain much more information per item; nevertheless, the lengths of word and digit lists that can be reproduced in immediate recall tasks are very similar. Words and numerals are examples of chunks, as are all of the words in an idiomatic expression if one knows it, or the letters within an acronym (e.g., IBM) if one knows it. Miller observed that people can immediately recall lists with about 7 chunks.

A subsequent well-known approach highlighted the role of a phonological loop in which verbal working-memory capacity was said to be determined by the duration of phonological working-memory activation and the speed of an articulation process to reactivate fading traces (Baddeley, 1986; Baddeley & Hitch, 1974). This approach successfully predicted some effects overlooked by Miller (1956). Lists of phonologically similar words such as *bat*, *cat*, and *mat* were not recalled as successfully as lists of dissimilar words if serial order was required, and lists of long words were not recalled as successfully as lists of short words. These effects based on the phono-logical forms of words disappeared with a concurrent task

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in which repetition of a word prevented covert articulation—that is, articulatory suppression (Baddeley, Lewis, & Vallar, 1984; Levy, 1971; Murray, 1968; Peterson & Johnson, 1971). However, the model as described by Baddeley (1986) provided no clear explanation for the residual capability to recall several words under articulatory suppression, a task that presumably would have blocked verbal information from entering the phonological store. That model had no storage device other than phonological and visuo-spatial stores, and it seems implausible that the words spared by articulatory suppression could be retained primarily in visuospatial form.

The seminal paper of Baddeley and Hitch (1974) did allow for a central form of working-memory storage, which was later omitted for the sake of parsimony by Baddeley (1986). The recently amended model of Baddeley (2000) reintroduced a similar device as an episodic buffer, said to store abstract information and the bindings between items. In an alternative approach (Cowan, 1988, 1999, 2001), the focus of attention was said to hold a limited number of meaningful, abstract units, or chunks (Miller, 1956), about 3 to 5 in adults, with other information briefly activated outside of the focus of attention. Baddeley (2001) subsequently endorsed that capacity estimate for his episodic buffer, which makes the recent Baddeley and Cowan models similar in many respects. Both of these approaches include both central, general, capacity-limited storage and code-specific, time-limited storage.

Given that these recent models include both general and code-specific storage mechanisms, it becomes difficult to disentangle them. For example, they both might contribute to the recall of about 7 items in immediate recall (Miller, 1956). Possibly, individuals use capacity-limited and time-limited mechanisms together in a complementary fashion. The smaller chunk estimate of about 3 to 5 items comes from situations in which the contribution of phonological rehearsal is presumably minimal because the items to be recalled are too long for the phonological loop (Glanzer & Razel, 1974), the information comes from long-term memory but illustrates the working-memory capacity limit through subjects' need to output the material in multiple bursts of limited size (Broadbent, 1975), or the items cannot be rehearsed because they are briefly presented or a suppression task is included (Cowan, 2001).

None of these sources of evidence is strong enough to reveal a capacity limit that is the same across lists of various lengths. Chen and Cowan (2005) made an attempt to find such a capacity limit in an experiment using word singletons and learned word pairs as chunks of two different sizes and found performance equivalence across lists of one- versus two-word chunks (for example, equivalent proportions correct in lists of 6 singletons and lists of 6 learned pairs). However, this equivalence was not obtained across lists that included different numbers of chunks. Possibly, the more general equivalence did not hold because the contribution of covert articulation depends on the list length. Therefore, we repeat the procedure of Chen and Cowan with articulatory suppression during reception of the list.

The immediate precursor (Chen & Cowan, 2005) to the present study was in turn based on a prior study by Cowan, Chen, and Rouder (2004). To investigate whether verbal memory is limited by a fixed number of chunks, Cowan et al. (2004) had participants recall in order a list of 8 common monosyllables, which were always presented in pairs. Prior to the test, participants had studied words 4 times but not all of them were in pairs. They occurred in consistent pairs 0, 1, 2, or 4 times out of 4, forming 0-pairing, 1-pairing, 2-pairing, or 4-pairing conditions, respectively. Various extents of pairing during study should result in different numbers of 1-word and 2-word chunks being formed in different conditions. The results (recall of intact pairs and singletons) suggested that the sum of 1-word and 2-word chunks in the response across all conditions was a constant of about 3.5, despite the fact that the sum of words recalled varies from 4.88 to 6.54. This finding appeared to support a simple chunk-based capacity in verbal working memory. However, that constant was obtained using only 8-word lists.

Chen and Cowan (2005) used a similar paradigm of immediate recall as Cowan et al. (2004) did but varied the list length to include 4-word, 6-word, 8-word, and 12-word lists. In addition, Chen and Cowan adopted a training procedure to manipulate participants' familiarity with stimuli by including three types of lists: one consisting of word pairs never seen before the test (the no-study conditions), one consisting of word pairs for which the words had been seen individually but not in the pairing shown (the singleton conditions), and one consisting of word pairs that had been well learned (the pair conditions). In lists with a particular number of chunks, the proportion of words recalled, without respect to the serial order of recall, was quite similar no matter whether the list had 1-word chunks (nonstudied words or singletons) or 2-word chunks (learned pairs). Despite that regularity in the data, however, a reanalysis shows that the sum of 1-word and 2-word chunks recalled varied strikingly across conditions with different list lengths.

This variation in recall of chunks across list lengths in Chen and Cowan (2005) could have stemmed from characteristics of the phonological loop. For verbal lists about 4 chunks long, the event-based buffer is already large enough to hold the memory so that the holding capability of the phonological loop may be redundant. For verbal lists longer than what the event-based working-memory buffer can hold in chunks, but within the length of about 2 seconds in speech, it becomes possible and beneficial for the event-based buffer to outsource a portion of the memory load to the phonological loop. For verbal lists even longer, however, the phonological loop might get overwhelmed by too much speech material, so that relatively few word representations could be restored from it (Hulme et al., 1997). Any contribution from the phonological loop to verbal working memory would inflate the estimate of event-based working memory, which presumably has a constant chunk-based capacity. According to this reasoning, a more accurate estimate of a central capacity requires suspension of the phono-logical loop function to prevent its unwanted influence. We therefore report a replication of the serial recall experiment of Chen and Cowan (2005), but with covert articulation prevented by an articulatory suppression task.

The expectation is that, with covert rehearsal of the list suppressed, the number of chunks recalled will be constant across lists of various lengths in singleton conditions (which presumably contain 1-word chunks) and learned-pair conditions (which presumably contain learned 2-word chunks). The expectation is not perfectly clear for nonstudied words, as they might not be adequately encoded as single conceptual units in working memory. For example, a lapse of attention might result in the entry of a word into working memory as a string of phonemes but not as a unified lexical or semantic item. The no-study conditions were included in the serial recall phase as controls to assess the effect of word training on performance.

Method

This experiment is identical to Experiment 2 in Chen and Cowan (2005) except that, in the second phase, the immediate serial recall task in the current experiment was administered under articulatory suppression.

Participants

A total of 33 undergraduates from the University of Missouri participated in this experiment for course credit. They were native speakers of English with normal hearing and vision.

Apparatus and stimuli

From a set of 99 nouns, 80 were selected for each participant and were randomly assigned to the different list conditions, with just enough words in each condition to make the lists without repeating words. The word pool is described by Chen and Cowan (2005). Words were visually presented by computer.

Design

As in Chen and Cowan (2005), this experiment had 10 list conditions, denoted as 4n, 6n, 8n, 12n, 4s, 6s, 8s, 12s, 4p, and 6p. The letter in a condition name indicates the extent of familiarity participants had with the stimuli in that condition before the list-recall test: “n”, no-study conditions with stimuli not shown to participants before list recall; “s”, singleton conditions with stimuli studied individually; and “p”, pair conditions, with stimuli studied as consistent word pairs that were uniquely selected for each participant. The digit in a list condition name indicated the length of a to-be-remembered list in terms of chunks. For example, condition 6p refers to a list of six 2-word chunks, word pairs that had been well learned before the immediate serial recall test. We assumed that singletons (and possibly non-studied words) formed 1-word chunks whereas paired words formed 2-word chunks, assumptions justified on the basis of the training regimen and the final free-recall test results.

Procedure

The procedure of this experiment, including training, immediate serial recall under articulatory suppression, and final free-recall phases, differed from Experiment 2 of Chen and Cowan (2005) only in the use of articulatory suppression in the immediate serial recall phase.

Training—This phase started with initial presentations of singletons and word pairs in random order. It then proceeded to cued recall exercises, intended to familiarize participants with those stimuli. On each such trial, a word was presented, and the participant was to type in the word with which it was consistently paired or, if there was no such pairing, to indicate that the word had been presented as a singleton. Feedback was given. Training continued with the repeated presentation of the entire set of stimuli (except for the words to be reproduced as responses) until the participant was 100% correct on the set.

Immediate serial recall under articulatory suppression—After training, the participant became acquainted with the recall task through 4 practice trials, which had the identical format of the subsequent formal trials but with different words. Then the participant completed 10 trials, with 1 for each list condition, all under articulatory suppression, a concurrent task of repeating an irrelevant word aloud. For pair conditions (4p and 6p), words in the list were always presented in the same pairing as they were learned during training. For singleton and no-study conditions (4s, 6s, 8s, 12s, 4n, 6n, 8n, and 12n), words in the list were presented in a new pairing randomly generated by the computer program.

To initiate a trial, the participant pressed the ENTER key when ready and, concurrently, started to articulate the word “the” at the rate of two repetitions per second. Upon the key press, a fixation cross appeared at the centre of the screen, and a voice recording of “the” was also repeatedly played from loudspeakers on both sides of the computer screen, governing the participant's repetition pace. One second after the appearance of the fixation cross, it was replaced by a list of word pairs, with each pair replacing the previous one and remaining on screen for 2 seconds. At the end of the list of word pairs, the loudspeakers ceased, and the participant stopped articulating. The textual instruction “recall a word” was then shown, and a numbered column of response slots was displayed on the computer screen, guiding the participant to recall words in their presented order by typing them into the corresponding slots. The participant recalled for as long as he or she wished, with all responses staying on the screen throughout the recall period. If the participant forgot a word for a particular serial position on the list, the instruction was to leave the corresponding slot blank.

The results from serial recall were scored in two ways. Under lenient scoring, credit was given to any word from the to-be-remembered list that was recalled, regardless of the position of its recall. Under strict scoring, however, credit was given only to words recalled at the correct serial position.

Final free recall—As in Chen and Cowan (2005), an unexpected final free-recall test was administered. Participants were to recall whatever words they could remember from the experiment. They could take as much time as they wished to do so.

Results

Constant chunk-based capacity with immediate serial recall under lenient scoring

Lenient scoring is relevant to the mechanisms of working memory that retain items, regardless of whether the order is correctly retained. Using this scoring on the present data, almost all learned pairs in the response were recalled with two word members in their original order, with only 3.1% in reversed order for condition 6p. These intact learned pairs recalled were counted as 2-word chunks in the response. For a small number of cases (i.e., 6.6 % and 2.7% of the response in 6p and 4p, respectively) in which only one member of a learned word pair was retrieved or both were retrieved, but not in adjacent positions, we counted these stray words as independent 1-word chunks. Words recalled from singleton and no-study conditions were counted as 1-word chunks. In this analysis, therefore, the term “chunk” can refer to either a 1-word or a 2-word chunk.

The black bars in Figure 1 show the results. A one-way analysis of variance (ANOVA) revealed that there was no significant difference in the number of chunks recalled across various list lengths and extents of familiarity, $F(9, 288)$ 1.56, $p = .13$, partial eta squared $\eta_p^2 = .05$. One can see that encoding was slightly less efficient for nonstudied words, but that difference did not reach significance. For the remaining list conditions, the capacity limit was about 3 chunks, in good keeping with the estimate offered by Broadbent (1975) and the lower boundary of the estimate by Cowan (2001). For those conditions, $F(5, 160) = 0.68$, $p = .64$, $\eta_p^2 = .02$ (i.e., very small). In contrast, as shown by the white bars in Figure 1, a reanalysis of data from Chen and Cowan (2005, Exp. 2) showed that, with articulatory suppression absent from the immediate recall stage, there was an effect of list condition, $F(9, 279) = 4.17$, $p < .001$, $\eta_p^2 = .12$. Without the no-study conditions, $F(5, 155) = 5.56$, $p < .001$, $\eta_p^2 = .15$. Combining results for the two experiments, a 2 (without suppression vs. with suppression) × 10 (list conditions) ANOVA revealed all three significant effects: an articulatory suppression main effect, $F(1, 63) = 47.07$, $p < .001$, η_p^2 .43; a list condition main effect, $F(9, 567) = 1.96$, $p < .05$, $\eta_p^2 = .03$; and an interaction effect, $F(9, 567) = 4.00$, $p < .001$, $\eta_p^2 = .06$.

Information available in Figure 1 is also useful to test whether the contribution of covert verbal rehearsal to working memory was an inverted U-shaped function of list length as we suspected it would be. The index of this contribution was the difference between the suppression and no-suppression results for each list condition in terms of chunks recalled. Figure 2 shows the mean differences along with polynomial fits for the nonstudied and singleton conditions. The results show that, across all conditions, an inverted U-shaped function describes the contribution of covert rehearsal, with the largest contribution for 8-chunk lists. The finding that there was a larger contribution of rehearsal to the 6p condition (which includes 12 words) than to the 4p condition (which includes 8 words) suggests that it is chunks, rather than words, that governs this relationship. At first glance, this appears to contradict the prediction from the phonological loop mechanism (Baddeley, 1986) that it is the phono-logical length of a list that determines how well it can be rehearsed. However, participants might rehearse only the first word of each learned pair in the list and still succeed at recalling the list perfectly by regenerating each rehearsed word and its paired associate at test.

Variable performance with immediate serial recall under strict scoring

In stark contrast to the constant chunk-based capacity reported above under articulatory suppression, no constant amount of memory was found when performance was measured under strict scoring and evaluated in either chunks or words (see Figure 3). For chunks recalled, a 2 (with suppression vs. without suppression) × 10 (list conditions) ANOVA produced all three significant effects: an articulatory suppression main effect, $F(1, 63) = 42.92$, $p < .001$, $\eta_p^2 = .41$; a list condition main effect, $F(9, 567) = 13.40$, $p < .001$, $\eta_p^2 = .18$; and a two-way interaction, $F(9, 567) = 2.27$, $p = .017$, $\eta_p^2 = .04$. However, the list condition effect was significant here not only with suppression absent, $F(9, 279) = 7.88$, $p < .001$, $\eta_p^2 = .20$, but also with suppression present, $F(9, 288) = 7.60$, $p < .001$, $\eta_p^2 = .19$. The same was true for an analysis of words recalled except that the interaction between suppression and list condition was not significant. There is no apparent chunk-based constant capacity for strict serial recall.

Further analyses suggested that the difference between lenient and strict scoring is that the capacity-limited store does not include complete serial order or position information. If one knows only the serial order of items within chunks, or only that plus the order of items in memory that were adjacent in the list, long lists are at a disadvantage in strict scoring. This holds under the assumption that the n chunks in working memory are distributed across the list and so, for longer lists, are more likely to be separated by unrecalled items that could disrupt correct serial recall. We investigated this in two analyses across experiments, corresponding to the means in Figure 4. The analyses produced comparable results for the experiments with and without suppression and thus were combined across experiments in the analyses to be reported. These analyses resulted in no effects involving articulatory suppression as a factor but did produce list condition effects.

Supporting our assumption that chunks in memory were distributed across the list, the proportion of trials with the recalled items coming from adjacent list positions (e.g., Items 5, 6, 3, 4 but not 7, 8, 3, 4) differed across list conditions, $F(9, 441) = 11.52$, $p < .001$, $\eta_p^2 = .19$. Further analyses of subsets of the data were conducted to separate list length and training effects. An analysis of the 4n, 6n, 8n, 12n, 4s, 6s, 8s, and 12s conditions (2 training conditions × 4 list lengths) produced only a main effect of list length, $F(3, 156) = 20.29$, $p < .001$, $\eta_p^2 = .28$. The recalled chunks were more often nonadjacent for longer lists. An analysis of the 4s, 6s, 4p, and 6p conditions (2 chunk sizes × 2 numbers of chunks) produced effects of both chunk size, $F(1, 61) = 20.65$, $p < .001$, $\eta_p^2 = .25$, and number of chunks, $F(1, 61) = 24.20$, $p < .001$, $\eta_p^2 = .28$. Lists with bigger chunks (paired conditions) or more chunks (longer lists) were less likely to be recalled from adjacent list positions.

Next, we asked whether the order of recalled chunks was nevertheless preserved equally across list lengths. Theoretically, that could occur even though the strict serial position scores were superior for shorter lists. Thus we examined the proportion of trials in which the items that were recalled were in the presented order, even if incomplete (e.g., Items 1, 2, 7, 8 but not 1, 2, 8, 7 or 7, 8, 1, 2), which produced only a main effect of list condition, $F(9, 441)$

= 8.10, $p < .001$, $\eta_p^2 = .14$. Exactly as was found for adjacent-item recall, a further analysis of the 4n, 6n, 8n, 12n, 4s, 6s, 8s, and 12s conditions produced only a main effect of list length, $F(3, 156) = 8.44$, $p < .001$, $\eta_p^2 = .14$, and an analysis of the 4s, 6s, 4p, and 6p conditions produced effects of both chunk size, $F(1, 61) = 38.90$, $p < .001$,$\eta_p^2 = .39$, and number chunks, $F(1, 61) = 9.89$, $p < .001$, $\eta_p^2 = .14$. Lists with bigger chunks or more chunks were less likely to be recalled in order. Notice that Figure 4 shows very similar patterns for recall of adjacent items and recall of items in order.

The poorer serial position scores for longer lists could have been a direct consequence of omitting more items from the middle of longer lists, making the recall positions of subsequent items too early. This, however, cannot explain why the chunks remembered from longer lists were less likely to be recalled in the correct order. Therefore, we suggest that the capacity-limited representation that does not depend on rehearsal may not include the order of nonadjacent chunks (found more often in longer lists)—at least, not as often as it includes the order of adjacent chunks (found more often in shorter lists).

Final free recall

To check assumptions regarding chunks, we examined the proportion of response words from each list condition produced in final free recall. If two words were recalled intact or in reversed order compared to the immediate recall presentation, they were counted as a 2-word chunk; otherwise, each word counted as a 1-word chunk. As shown in Figure 5, for pair conditions, over 60% of stimuli were recovered from long-term memory as 2-word chunks; for singleton conditions, no more than 10% were recalled as 2-word chunks. In contrast, the pattern for 1-word chunks was reversed, with less than 10% for pair conditions but ~20% for singleton conditions. No-study conditions, except for 4n, showed very low performance. A 2 (2-word chunks vs. 1-word chunks) × 10 (list conditions) ANOVA confirmed a significant interaction, $F(9, 288) = 49.90$, $p < .001$, $\eta_p^2 = .61$, which remained significant when nonstudied conditions were excluded, $F(5, 160) = 60.62$, $p < .001$, $\eta_p^2 = .66$.

Our assumption that 2-word chunks resulted primarily from learned associations is salient in the proportion of 2-word chunks in final free recall. For 6p and 4p conditions, respectively, 86.2% and 89.5% of words retrieved were preserved as 2-word chunks, whereas the proportions were very small for singleton conditions (2.7% for 4s, 7.6% for 6s, 19.9% for 8s, and 9.3% for 12s).

Discussion

A constant chunk capacity in verbal working memory was identified through a new procedure with articulatory suppression and a chunking manipulation, supporting an important but rarely tested cognitive hypothesis. We have extended the conclusion that there is a constant capacity in chunks. Cowan et al. (2004) found such constancy for 8-word lists, but a constant capacity did not hold across varied list lengths (Chen & Cowan, 2005). Here we show that there is an approximately constant capacity of about 3 chunks, regardless of list length, provided that covert verbal rehearsal is suppressed, and participants are not held responsible for serial order information (cf. Figures 1 versus 3). The finding highlights the importance of a chunk-capacity-limited system (Baddeley, 2001; Cowan, 2001) and disentangles it from phonological storage and processing (Baddeley, 1986).

The observed inverted U-shaped function between the effect of articulatory suppression and list length in chunks (Figure 2) elucidates the relationship between phonological storage and chunk-based storage. These two holding mechanisms for verbal working memory probably collaborate in a parallel manner to handle specific verbal-memory tasks, such as immediate serial recall and free recall, and are subject to length limits and chunk limits, respectively (Chen & Cowan, 2005). However, we cannot specify the exact nature of this collaboration between multiple storage mechanisms in working memory.

An advantage of acquiring multiword chunks is that it is then unnecessary to keep each word in capacity-limited working memory, but just some index to each chunk, perhaps the chunk's first word. The capacity-limited store appears not to include complete information about the serial order of chunks that were nonadjacent in the list, resulting in order coding that was most deficient for longer lists, with or without articulatory suppression (Figure 4).

The final free-recall data not only justify our assumption about the chunking status of stimuli in the immediate recall, but also shed light on the interplay between long-term and working memory. For no-study and singleton conditions, temporary pairings of stimuli were seen only once prior to final free recall. Nevertheless, a few of these temporary pairings were restored from long-term memory in all list conditions (See Figure 5). This suggests that attentional processing sometimes survived articulatory suppression to form multiword chunks in the event-based buffer.

Figure 5 also highlights the outstanding performance of the pair conditions over other conditions in final free recall. The memory advantage of learned pairs is not fully explained by assuming that they include twice as many retrieval cues as do singletons. The pair conditions, in which 72.9% of the words were recovered from long-term memory, in fact showed more than double the performance of the singleton conditions, in which only 26.0% of the words were recovered from long-term memory. If new semantic connections were formed between arbitrarily paired words during training, the long-term representation of learned word pairs may have benefited from deep processing (Craik & Tulving, 1975).

We hope our evidence for a 3-or-so-chunk capacity in working memory will provoke further study. The findings address a capacity-limitation concept that has varied through the years, including estimates of 7, 4, 3, and 2 chunks (respectively, Miller, 1956; Cowan, 2001; Broadbent, 1975; Gobet & Clarkson, 2004), and a 1-chunk focus of attention within a 4-chunk region (Oberauer, 2002). What has been most difficult is ruling out the sceptic's hypothesis that there is no fixed-capacity mechanism (see Cowan, 2001), and our data clearly strengthen the case for fixed capacity.

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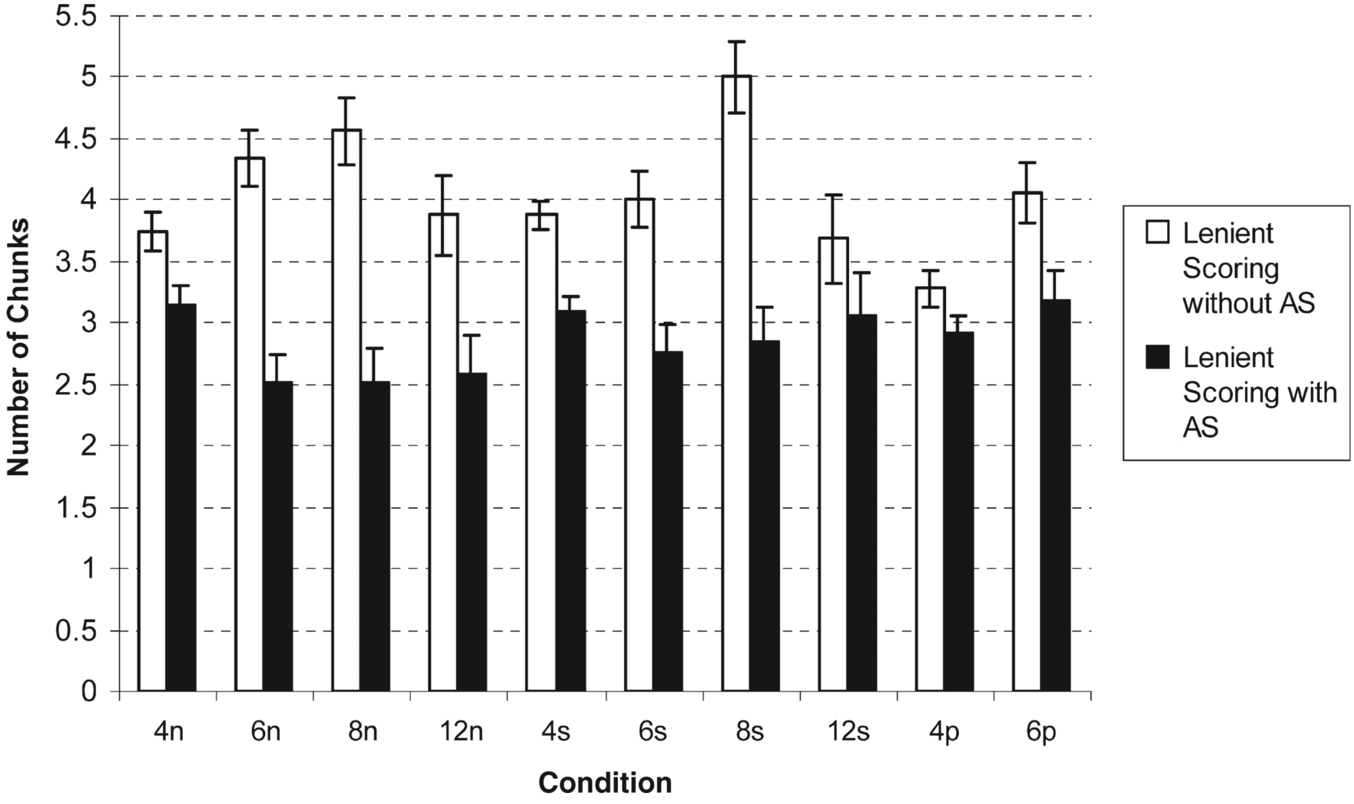

Figure 1.
Memory of chunks in immediate serial recall as a function of list conditions under lenient scoring. AS = articulatory suppression. The error bars indicate standard errors of the mean.

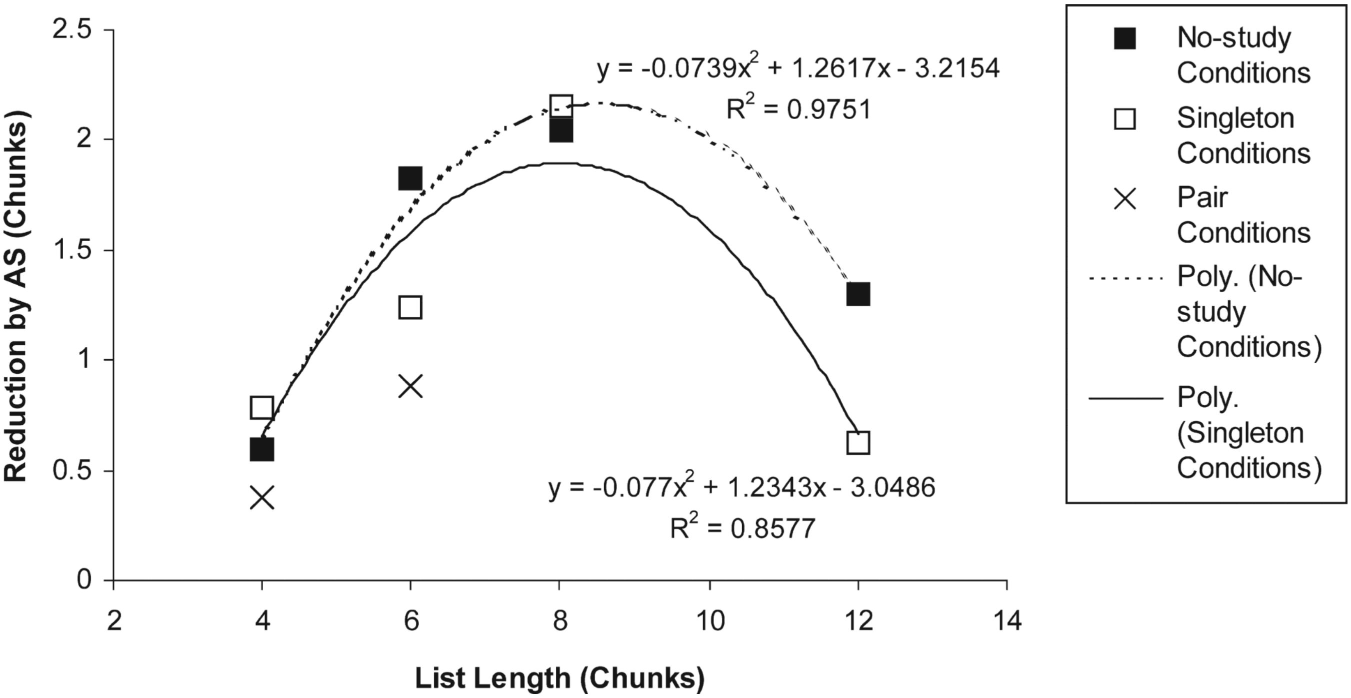

Figure 2.

Polynomial regressions of the mean performance reduction in chunks caused by articulatory suppression (AS), across the number of chunks in the list, separately for no-study and singleton conditions. Paired conditions also are shown.

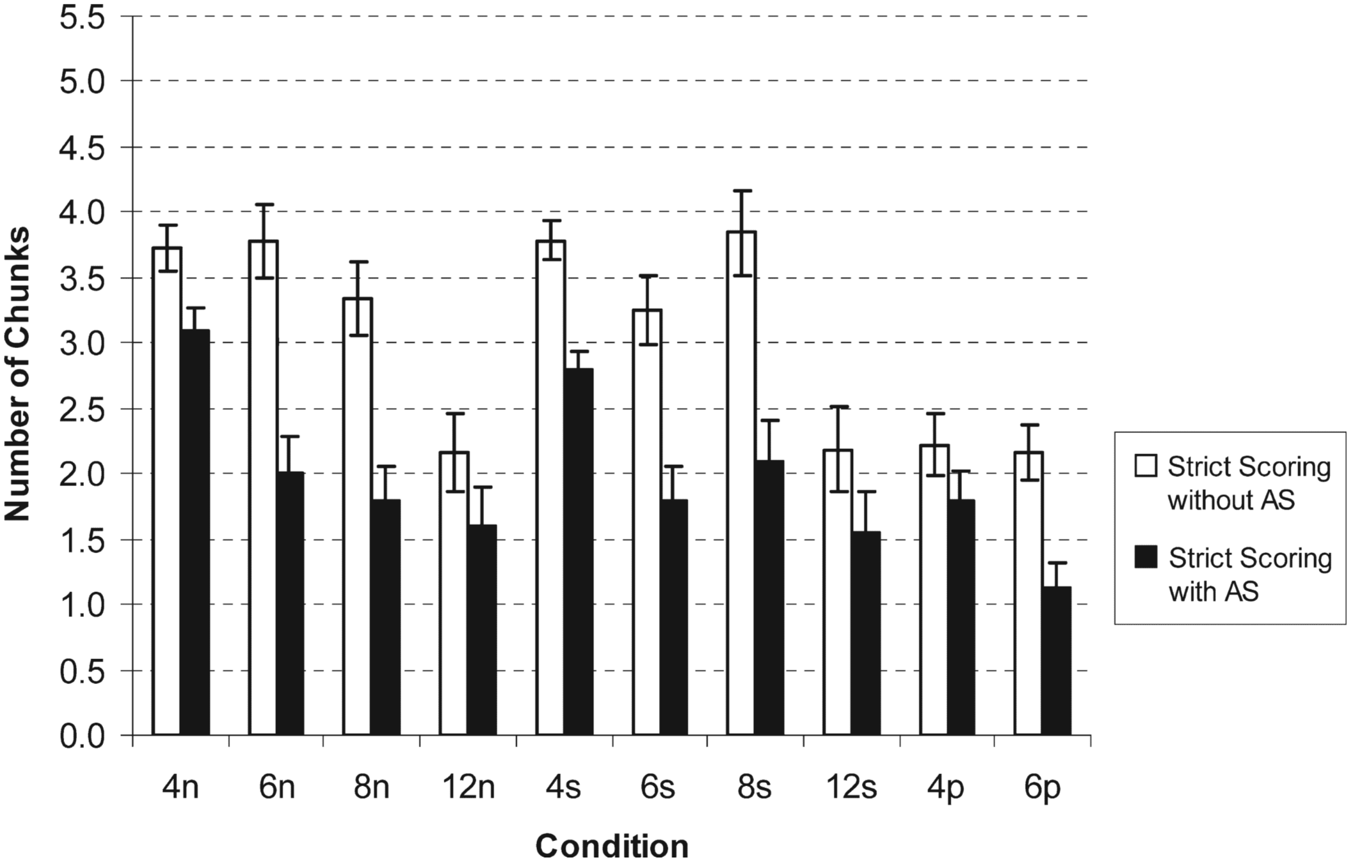

Figure 3.

Memory of chunks in immediate serial recall as a function of list conditions under strict scoring. AS = articulatory suppression. The error bars indicate standard errors of the mean.

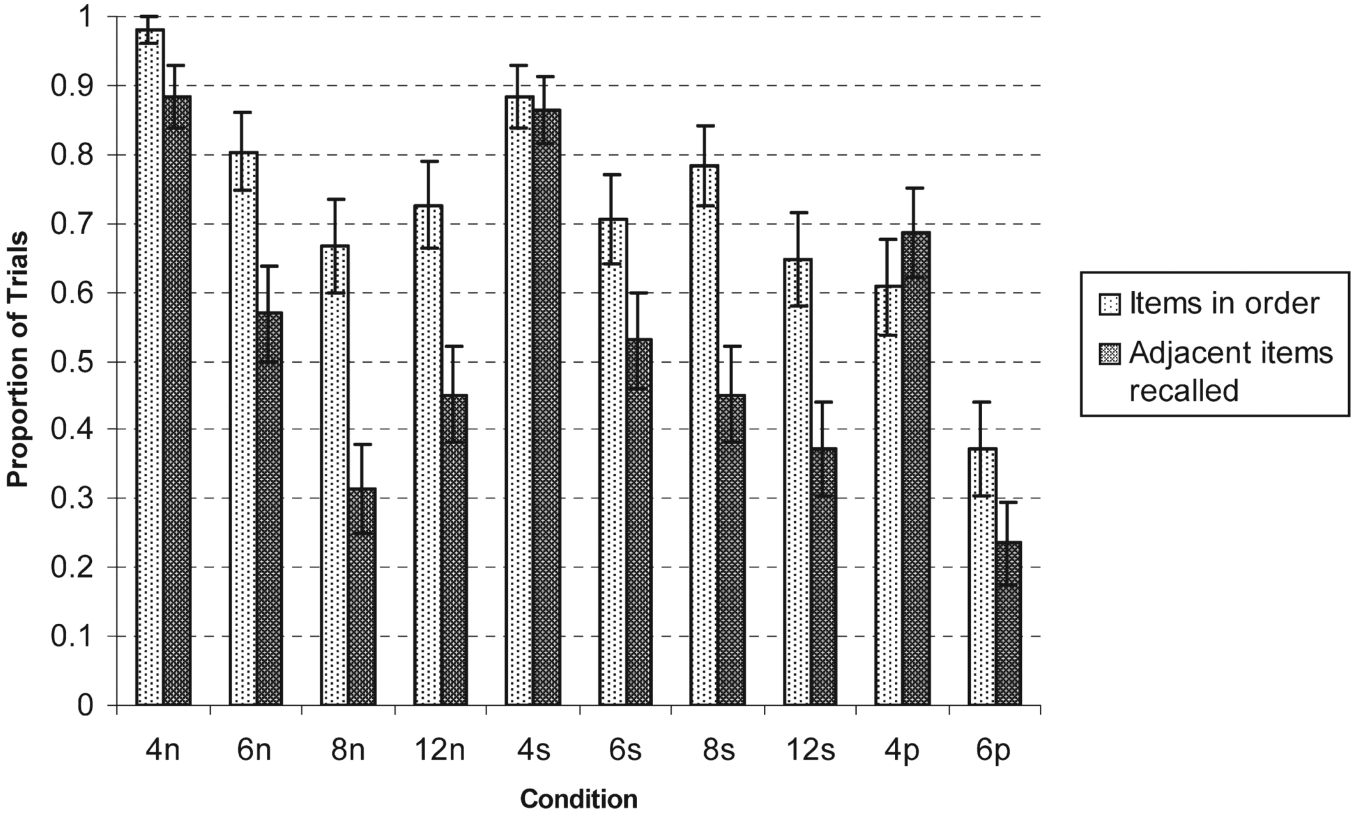

Figure 4.

Proportion of trials in which the recalled items were in the correct order (regardless of whether all items were recalled) and proportion of trials in which the recalled items were from adjacent positions on the input list, collapsed across the two experiments. The error bars indicate standard errors of the mean.

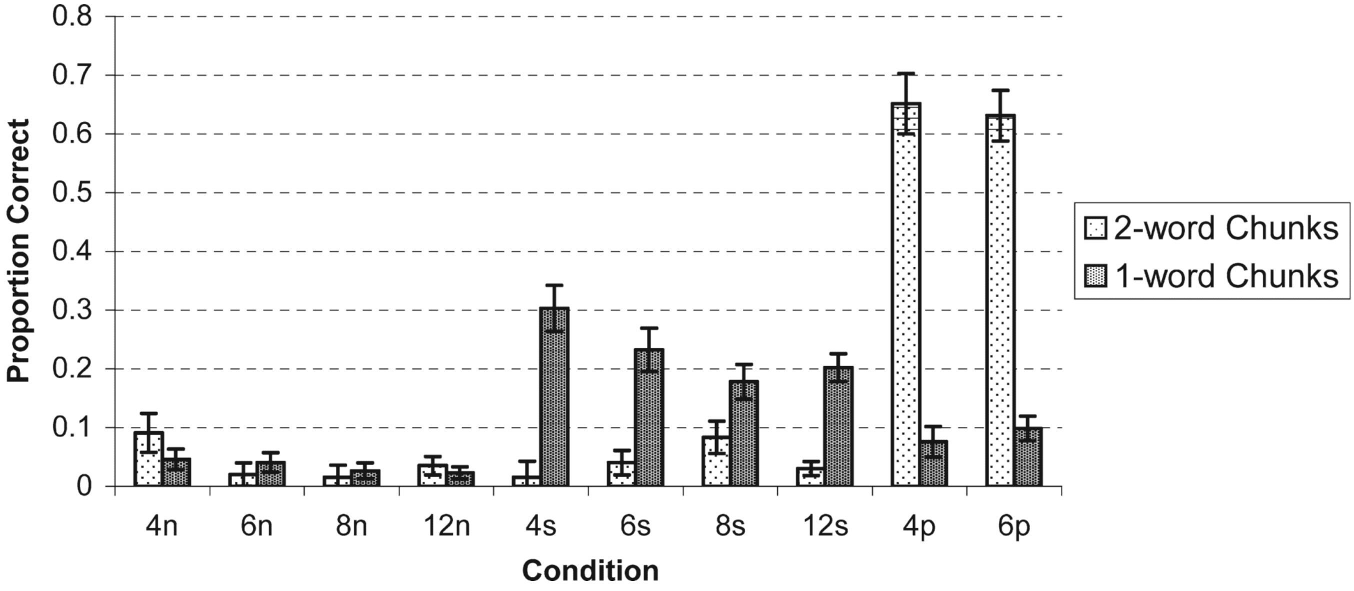

Figure 5.
Proportion of chunks recalled in final free recall as a function of list conditions. The error bars indicate standard errors of the mean.