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Deconfounding Serial Recall

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Immediate recall of nine-digit lists was examined with a method designed to disentangle three factors: input serial position, output position, and response set size (the number of items yet to be recalled). Recall began at Input Serial Position 1, 4, or 7 and included either three consecutive items (in partial recall) or all items from the cued point to the end of the list and then continuing from the beginning in a circular fashion (in whole recall). Lists were spoken or printed and were sometimes temporally grouped. Specially selected comparisons demonstrated that (1) the large primacy effect in serial recall occurs mostly because of output interference, without which larger recency effects are seen instead; (2) benefits of mnemonic grouping are dependent on stimulus grouping mainly for auditory stimuli; and (3) auditory superiority effects stem from a greater resistance of acoustic memory to output interference. We offer an integration of results from serial recall and other memory tasks and caution against modeling serial recall in isolation.

Key Words: serial recall; serial order memory; short-term memory; memory models; modality effects; grouping effects; memory load.

In immediate serial recall, a list of items is to be recalled just after the end of the list in the order in which the items were presented. Despite a rich history of research with this task, the results remain difficult to understand inasmuch as multiple factors are confounded with one another. It is this problem that we address, through a new combination of recall conditions and comparisons among them.

Nipher (1878) carried out the first known study of serial recall. He observed that "In writing logarithms which were read off to me, it was observed that it appeared to be much more difficult to remember the figures in the middle of the number than those at the extremes." Soon afterward, Ebbinghaus (1885) carried out a more extensive study. Around this time, also, the role of serial recall in daily life increased with the proliferation of telegraphs in the 1850s and the invention of the telephone in 1876. Serial recall became a popular topic of research among information processing psychologists (for comprehensive reviews see Harcum, 1975; Kausler, 1974; Murdock, 1974; Neath, 1998) and has remained so.

Many studies of serial recall with regular, ungrouped lists (e.g., Jahnke, 1963; Madigan, 1971) have shown, in the visual modality, a severe decline across serial positions and then a slight upturn at the end of the list (i.e., a large primacy effect and a small recency effect); in the auditory modality, a similar function at the beginning of the list but a much larger upturn at the end (i.e., large primacy and recency effects). Recently, there has been a proliferation of mathematical models attempting to explain the pattern of immediate serial recall (e.g., Anderson & Matessa, 1997; Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1999; Henson, 1998; Lewandowsky, 1999; Lewandowsky & Murdock, 1989; Nairne, Neath, Serra, & Byun, 1997; Page & Norris, 1998). We make no attempt to compare or assess these models in full but our findings speak to the viability of some of the fundamental assumptions underlying the models. Two assumptions that we discuss are nicely summarized by Lewandowsky (1999). One assumption (Lewandowsky, 1999, p. 444) is of the "decreasing strength with which successive list items are encoded," a *primacy gradient* assumption that is widespread; indeed,

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Lewandowsky termed it “virtually ubiquitous.” Serial recall typically shows a large primacy effect and a much smaller recency effect, at least in the visual modality (e.g., Jahnke, 1963; Madigan, 1971), and the primacy gradient is one popular explanation of that fact. In keeping with that notion, for example, the primacy model (Page & Norris, 1998) yields an activation value with a gradient favoring early list items. However, we report evidence questioning whether one should make a primacy gradient the basic mechanism behind serial position effects in serial recall.

Another mechanism discussed by Lewandowsky (1999) is response suppression (cf. Henson, 1998; Houghton, 1990), whereby items are temporarily suppressed once they are recalled in order to prevent them from being incorrectly recalled again, as they otherwise would be, for example, according to a primacy gradient. Lewandowsky (1999) also has accounted for the small recency effect in visual serial recall (i.e., serial recall of visually presented materials) as the result of the response suppression of prior list items, reducing the set of response choices available to be recalled. However, we report evidence on alternative mechanisms that theoretically could serve this function. These include an often-used mechanism, (1) the basic distinctiveness of recent items in memory at the time of recall and, to some extent, of items near either end of the list; and a less-used mechanism, (2) the memory load resulting from items in the list yet to be recalled, which must be retained in the correct serial order. We call this memory load the *response set size*.

Factors in Serial Recall

Although the task instructions in serial recall are quite simple, the requirement of recalling an arbitrarily ordered list in the presented order is a difficult one, involving many mental processes that still have not been sufficiently sorted out. We focus on three factors to be disentangled from one another: the input serial position, the output serial position, and the response set size. Input serial position, the location in which an item occurs within the input protocol provided by the experimenter, and output serial position, where the item occurs within the response protocol produced by the subject, are both well known. Although attempts have been made to disentangle them in the past (e.g., Tulving & Arbuckle, 1966), we suggest that they still have not been completely clarified.

Typical serial position functions occur for particular tasks, but the relative amounts of primacy versus recency effects differ considerably between immediate memory tasks (e.g., Murdock, 1976), making the role of input serial position still a mystery. The effect of output position may be to cause what is termed “output interference,” the degradation of memory representations as recall proceeds across output positions. That degradation could occur either because each item, as it is recalled, specifically interferes with the memory representations of other items not yet recalled or because forgetting stems from the delay imposed by responding. We cannot distinguish between these possibilities and refer to both of them collectively as output interference.

Response set size is a term that we have introduced to refer to the number of items that the subject must plan to recall, but has not yet recalled, in the current trial (i.e., the list length minus already-recalled items). The importance of response set size has, to our knowledge, never been examined directly but there are reasons to hypothesize that it could play a role in recall. The basic notion is that the response set size diminishes as recall proceeds, potentially making it easier to recall items toward the end of the recall period because competition is decreased. This will be true, however, only if most of the list items are held in a limited-capacity mechanism and this mechanism can exclude items that are not to be recalled or already have been recalled.

One motivation for suggesting a response set size mechanism is that it would seem to be a natural counterpart to the concept of response suppression (Lewandowsky, 1999). If items were removed by this mechanism from the pool of possible response candidates after being recalled, then fewer and fewer possibilities would remain as recall progressed, and the response set size consequently would decrease across output positions. More broadly, if there is any mechanism that produces a memory system that maximizes efficiency by concentrating resources on items that are yet to be recalled, response set size effects should result. Arguing against these effects, though, it may be necessary to retain the items already recalled in order to help remember which ones have not yet been recalled. Whereas response suppression theoretically could allow already-recalled items to be remembered without depleting a limited-capacity resource, it may be too weak or transient to serve such a function.

Input and output serial position effects. Various methods have been used to separate the effects of input and output serial positions. For example, studies of forward versus backward recall (Cowan et al., 1992; Li & Lewandowsky, 1995; Hulme et al., 1997; Madigan, 1971) presumably involve a reversal of the output position effect (and, actually, of the response set size effect also) without changing the input serial position effect. They show a marked reversal of the serial position function, underscoring the potential importance of output position, which could produce poorer recall of later-recalled items. (In contrast, response set size effects would have been expected to improve recall at the later output positions. If there was such an effect, it at least was obscured by a larger output-position effect).

Unfortunately, though, backward recall provides only limited, indirect evidence of output serial position effects, not a quantification of input and output position effects. Moreover, there is reason to believe that backward recall may be accomplished by a complex process in which repeated forward retrievals are carried out covertly so that successive items are "peeled off" for recall in a reiterative, covert forward recall process (Page & Norris, 1998). Probed recall experiments (e.g., Waugh & Norman, 1965; Woodward, 1970) and partial report experiments (e.g., Anderson, 1960; Brown, 1954; Healy, Fendrich, Cunningham, & Till, 1987) reduce or eliminate the possibility of output interference and response set size effects and reveal drastically altered serial position effects (specifically, small primacy effects and large recency effects in recall). Such experiments help us to observe the influence of multiple effects but cannot provide estimates of each effect.

Response set size. Studies that could be used to predict whether response set size effects should be found have yielded mixed results. One might consider the response set to be a memory load. We could find no fully appropriate study in which a memory load was imposed before serial recall and tested afterward (i.e., a memory preload with an embedded serial recall task) so as to impose a load on serial recall without causing output interference, which would be a confounding factor. Klapp, Marshburn, and Lester (1983, Experiment 8) found no effect of a preload on serial recall of embedded three-digit lists but there was a ceiling effect in recall. Baddeley and Hitch (1974) found rather modest effects of a six-digit preload on free recall. In studies of the serial recall of five-word lists, Johnson (1971) and Martin and Kelly (1974) tested pupillary dilation and secondary-task reaction times, two measures of effort. Effort appeared to increase monotonically as the list was presented and to decrease monotonically as the list was recalled, as one would expect if effort were related to the response set size.

Research on spoken response times for errorless trials in immediate, serial recall (Cowan et al., 1998; Hulme et al., 1999) is not as one would expect from the studies of effort in recall, though. Mean interword pauses in the responses increase linearly as a function of list length, as if a memory search across the list must occur during these periods. In contrast to expectations from the effort studies, though, mean response times stay fairly constant across serial positions (except for a speedup often found at the end of a list). If already-recalled items were habitually eliminated from the search set, a much more extended speedup across the list probably would be expected. [Scalloped inter-response-time functions were obtained by Kahana and Jacobs (2000) but these were for a rather different situation, keypress responses for repeated, learned lists of 11 through 13 consonants.]

Lewandowsky and Murdock (1989) have included mechanisms that essentially depend on the response set size to produce recency effects in their model of serial recall but those mechanisms have been questioned (Nairne & Neath, 1994). Overall, the literature offers no resolution as to whether the response set size plays a role in recall.

Moderating Factors

We studied these three factors to be disentangled (input serial position, output serial position, and response set size) along with two other, moderating factors: list modality and grouping. These have been shown many times to be critically important in serial recall, alone and in combination. Many studies have shown a pronounced advantage for the auditory modality over the visual modality toward the end of the list, the recency portion, in serial recall (e.g., Madigan, 1971; for a review, see Penney, 1989). There also is an advantage of recall for lists grouped into subsets of three or four items over ungrouped lists or other groupings (e.g., Severin & Rigby, 1963; Wickelgren, 1967; for a review see Cowan, in press-a). Modality and grouping also interact. Frankish (1989) showed that the auditory modality superiority effect is much larger for grouped lists than for ungrouped lists. Thus, ideally, any study of deconfounded factors should separately examine each combination of modality and grouping. We presented nine-digit, spoken or printed lists either ungrouped or grouped into three subsets of three items.

A Method to Deconfound Serial Recall

We used a task in which a randomly ordered series of the digits 1–9, with no within-list digit repetitions, was presented either visually or aurally on every trial by computer for immediate serial recall. The subject used a keypad to enter digits into boxes appearing on the computer screen, representing the nine serial positions. In such a task, there is no question about the identity of the items themselves; in principle at least, the task only involves determining the order of the nine available digits. First let us consider what (confounded) factors would come into play if the task always were to recall all items in the order presented, as is typical in serial recall tasks. When the first digit is to be recalled, the input serial position is 1, the output position is 1, and the response set size is 9; when the second digit is to be recalled, the serial position is 2, the output position is 2, and the response set size is down to 8; and so on through the ninth serial position, for which the input and output positions both are 9 and the response set size is 1. Thus, from such a study it would not be possible to determine the separate contributions of input position, output position, or response set size to the recall serial position function.

To distinguish between input serial position, output position, and response set size in the present study, a postlist cue indicated at which of three locations recall should begin: Input Serial Position 1, 4, or 7. It also indicated whether recall should include only three consecutive items (partial recall) or all nine (whole recall). In the latter case, if recall began somewhere other than Position 1, it proceeded to the end of the list and then cycled around to Serial Position 1, continuing forward from there until a response was made for each serial position. For example, if the cue were for whole recall beginning with Serial Position 4, it would cover Positions 4–9 and then Positions 1–3. (The responses nevertheless were spatially arranged according to the input serial positions, 1–9.) There are a number of previous recall studies of various types in which recall was partial (Anderson, 1960; Brown, 1954; Healy et al., Fendrich, Cunningham, & Till, 1987) or was to begin at one particular noninitial point and cycle around to complete recall (e.g., Butterfield, Belmont, & Peltzman, 1971; Keppel, 1964; Manning & Turner, 1984; Rellinger, Borkowski, Turner, & Hale, 1995; Woods & Epstein, 1969). However, none of these studies used partial and circular-whole recall in combination to obtain a deconfounding of three factors; nor did any of them examine effects of both modality and grouping.

The deconfounding occurs for various comparisons in which two of the factors are equated and only one differs between conditions. The way in which this situation can be helpful is illustrated in the three examples within Fig. 1. In each section of the figure, the stimulus list is shown and different conditions are shown on subsequent lines (marked by letters). The large, open circle in each row indicates the cued starting point of recall; the bold, solid line and arrow indicate the portion of recall that is used in the controlled comparison; and the bold, dashed line indicates the remaining portion of recall in the whole-report condition, not used in the comparison.

The first (top) example illustrates how deconfounded input serial position effects can be investigated. In the example, partial recall is compared for the three different cued starting locations. In each case, the output serial position goes from 1 to 3 as recall progresses, and the response set size goes from 3 to 1. Thus, there is a nonconfounded comparison of Input Serial Positions 1, 4, and 7 to one another (Output 1, Response Set Size 3 in all three cases); of Input Serial Positions 2, 5, and 8 (Output 2, Response Set Size 2 in all three cases); and of Input Serial Positions 3, 6, and 9 (Output 3, Response Set Size 1 in all three cases). Comparisons also could be made instead among the first three outputs in whole recall, in which case the Response Set Sizes would be 9, 8, and 7 but all else would be as in the comparisons made within partial report.

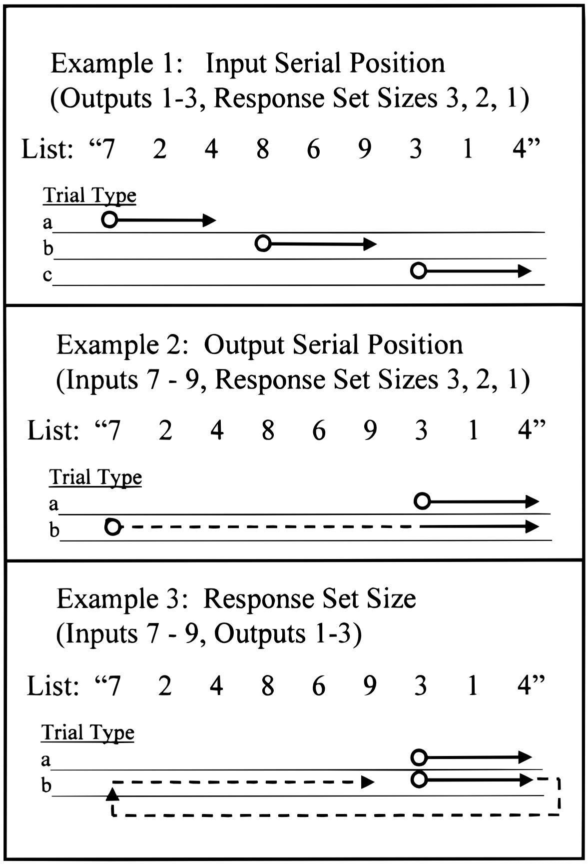

FIG. 1. Three examples of specific comparisons in which two theoretical factors of recall are controlled in order for a third factor to be examined in a deconfounded manner. The three panels of the figure show deconfounded functions for input serial position (top), output serial position (middle), and response set size (bottom). See Table 2 for a complete description of nonconfounded comparisons that can be extracted from the present data set.

The second (middle) example in Fig. 1 illustrates how output serial position effects can be investigated. Essentially, it is done by comparing the same three input serial positions when recalled *early in partial recall* versus *late in whole recall*. In the example, Input Serial Positions 7–9 are examined in each case. They are compared for trials with partial recall that began at Input Serial Position 7 and trials with whole recall that began at Input Serial Position 1 because, in both cases, for the critical Input Serial Positions 7–9, the response set sizes and the input serial positions were the same; the only thing that differentiated them is the output positions. Fair comparisons can be obtained for Output Positions 1 vs 7, 2 vs 8, and 3 vs 9. In each comparison, one mean comes from partial recall (Output Position 1, 2, or 3) and the other mean comes from whole recall (Output Position 7, 8, or 9).

Last, the third (bottom) example in Fig. 1 illustrates how response set size effects can be investigated. This can be done by comparing the first three outputs in partial vs whole recall. In the example, this is done for Input Serial Positions 7–9. For both partial and whole recall, the Output Positions are 1, 2, and 3. The only difference is that the Response Set Size is 3, 2, and 1 in partial recall vs 9, 8, and 7 in whole recall (inasmuch as six additional items remain to be recalled from earlier input serial positions, as shown by the dashed line).

Table 1 summarizes the different conditions tested in the experiment, with each condition represented in a separate row of the table. Table 2 summarizes the comparisons that can be made. There are four comparison types to examine input serial position effects, three types to examine output serial position effects, and three types to examine response set size effects (numbered in column 1 of the table). However, each type actually includes three specific comparisons, as the table shows. For example, for input serial position comparisons, the three comparisons included in a row are (1) Positions 1 - 4 - 7, (2) Positions 2 - 5 - 8, and (3) Positions 3 - 6 - 9. Notice that the only factor that differs between the types of condition being compared (adjacent rows of Table 2 within a numbered comparison) is the factor of interest, shown in bold in each case. In practice, similar conclusions emerged from all comparisons in a particular row, so the data are plotted in a simple manner that shows them all together. It also must be kept in mind, however, that each comparison is to be made separately for each combination of modality and stimulus grouping.

Even though empirical expectations based on the prior literature were completely born out in the experiment, there were some new findings that probably would come as a surprise from particular theoretical viewpoints and that have a bearing on which principles make sense within models of serial recall. These models often make assumptions about the input coding, output interference, and response set size. In this experiment, some of these assumptions can be assessed directly, by examining deconfounded factors.

METHOD

Participants

The subjects in the final sample were 32 college students (17 male and 15 female) who were native speakers of English and participated as part of their work in introductory psychology courses. Eight additional subjects drawn from the same population were excluded from the analyses for various reasons: three were not native speakers of English, two spoke during the test session, one was too sleepy, one wished to leave because of a health problem, and during one subject's session the computer malfunctioned.

Design

Each trial included the digits 1–9 in random order, presented aurally or visually via the computer. They were presented either in groups of three or ungrouped. In partial recall, three of the digits were to be recalled in serial order (those in Serial Positions 1–3, 4–6, or 7–9), whereas, in whole recall, all nine digits were to be recalled. A printed cue indicated whether recall was to start at Serial Position 1, 4, or 7. In whole recall, it continued in order through Serial Position 9 and then, if it had begun at Serial Position 4 or

TABLE 1

Values of Output Position and Response Set Size for Each Combination of Input Serial Position and Starting Recall Position in the Present Study

First-recalled position	Factor	Input serial position 1	2	3	4	5	6	7	8	9
		Whole-list recall								
1	Output Position	**1**	2	3	4	5	6	7	8	9
	Response Set Size	9	8	7	6	5	4	3	2	1
4	Output Position	7	8	9	**1**	2	3	4	5	6
	Response Set Size	3	2	1	9	8	7	6	5	4
7	Output Position	4	5	6	7	8	9	**1**	2	3
	Response Set Size	6	5	4	3	2	1	9	8	7
		Partial recall								
1	Output Position	**1**	2	3	—	—	—	—	—	—
	Response Set Size	3	2	1	—	—	—	—	—	—
4	Output Position	—	—	—	**1**	2	3	—	—	—
	Response Set Size	—	—	—	3	2	1	—	—	—
7	Output Position	—	—	—	—	—	—	**1**	2	3
	Response Set Size	—	—	—	—	—	—	3	2	1

Note. Each adjacent pair of rows in the table depicts a single type of trial. The first-recalled item in each trial type (Output Position 1) is listed in bold. Each trial type shown in the table was used in both trials with visual and trials with auditory presentation and in both trials with ungrouped and trials with grouped stimuli (which were grouped into sets of three items).

7, it returned to Serial Position 1 and continued from there until answers were given for all 9 serial positions. The combination of presentation modality, presentation grouping condition, part vs whole recall, and the starting position of recall resulted in 24 (= 2 × 2 × 2 × 3) trial types. Each subject completed 5 blocks of trials, with a complete set of 24 trials presented in random order within each block for a total of 120 trials.

Apparatus, Stimuli, and Procedure

Subjects were tested individually in a sound-attenuated chamber equipped with a Power Macintosh computer and audiological headphones. Spoken digits were digitally stored and presented via computer at 56–58 dB(A) as measured with a sound level meter and earphone coupler. Each digit lasted less than 500 ms. Printed digits were 9.5 mm high and were presented individually at the center of the computer screen, each for 500 ms. For lists of both spoken and printed digits, the onset-to-onset time between digits in ungrouped lists was 1 s. In grouped lists, additional 1-s periods (blank and silent) were inserted after the third and sixth digits in the nine-digit list, dividing the list into three groups of three items. During the instructions the subjects became familiar with all of the types of displays that they were about to see in the experiment and got practice entering the digits using the keypad.

The subject initiated each trial with a button-press and 500 ms later a ready signal appeared: if a printed list was going to be presented, a yellow box in which the word “ready” was printed or, if a spoken list was going to be presented, an empty yellow box and the spoken word “ready.” After 1 s the yellow box was replaced by a red box and, 1 s later, the subject heard the first list item or saw it in the center of the red box.

Each list was followed by a response screen 1 s after the onset of the last digit in the list. The response screen contained a series of nine boxes extending horizontally across the screen. When the stimuli were grouped into three sets of three, spaces were introduced between sets of three boxes, also. In partial report, one group of three had a bar above it indicating that that group was to be recalled, with an arrow always pointing to the box corresponding to the current item to be

TABLE 2

Data Selection for Deconfounded Comparisons

Comparison Type	Report Condition	Cued Serial Position	Input Serial Positions	Output Positions	Response Set Size
		Examination of Input Serial Position Effects			
1	Partial	1	**1, 2, 3**	1, 2, 3	3, 2, 1
	Partial	4	**4, 5, 6**	1, 2, 3	3, 2, 1
	Partial	7	**7, 8, 9**	1, 2, 3	3, 2, 1
2	Whole	1	**1, 2, 3**	1, 2, 3	9, 8, 7
	Whole	4	**4, 5, 6**	1, 2, 3	9, 8, 7
	Whole	7	**7, 8, 9**	1, 2, 3	9, 8, 7
3	Whole	1	**4, 5, 6**	4, 5, 6	6, 5, 4
	Whole	4	**7, 8, 9**	4, 5, 6	6, 5, 4
	Whole	7	**1, 2, 3**	4, 5, 6	6, 5, 4
4	Whole	1	**7, 8, 9**	7, 8, 9	3, 2, 1
	Whole	4	**1, 2, 3**	7, 8, 9	3, 2, 1
	Whole	7	**4, 5, 6**	7, 8, 9	3, 2, 1
		Examination of Output Serial Position Effects			
1	Partial	1	1, 2, 3	**1, 2, 3**	3, 2, 1
	Whole	4	1, 2, 3	**7, 8, 9**	3, 2, 1
2	Partial	4	4, 5, 6	**1, 2, 3**	3, 2, 1
	Whole	7	4, 5, 6	**7, 8, 9**	3, 2, 1
3	Partial	7	7, 8, 9	**1, 2, 3**	3, 2, 1
	Whole	1	7, 8, 9	**7, 8, 9**	3, 2, 1
		Examination of Response Set Size Effects			
1	Partial	1	1, 2, 3	1, 2, 3	**3, 2, 1**
	Whole	1	1, 2, 3	1, 2, 3	**9, 8, 7**
2	Partial	4	4, 5, 6	1, 2, 3	**3, 2, 1**
	Whole	4	4, 5, 6	1, 2, 3	**9, 8, 7**
3	Partial	7	7, 8, 9	1, 2, 3	**3, 2, 1**
	Whole	7	7, 8, 9	1, 2, 3	**9, 8, 7**

Note. Each type of comparison (numbered at left) is based on responses represented in adjacent rows of this table. Values of the single factor that can vary are shown in bold.

recalled. In the whole report condition all three groups of boxes had bars above them and the arrow again indicated where recall should begin. As each digit was typed by the subject, it appeared in the corresponding box on the screen. The subject had the option of using the delete key to erase responses back to a desired output position, allowing reentry of the digits starting at that point. The average subject used this option, once or more, on 14.6% of all trials (SD = 6.1%). (The pattern of performance was not changed at all when such trials were omitted. The correlation between group means across 144 conditions calculated including versus excluding trials in which the delete key had been used was $r = .99$, with no important discrepancies in the means.) When the subject was satisfied with the responses, the "enter" key was to be pressed.

Subjects were encouraged to take breaks as needed between blocks of 24 trials. They were asked if they had questions about the procedure just after reading and hearing instructions and before the experiment began, and again after the first block of trials. They were allowed to respond to each trial at their own pace.

Statistical Analyses

Within-subject confidence intervals. Rather than carry out a large number of ANOVAs for inferential purposes, within-subject 95% confidence intervals for the proportions correct were calculated according to guidelines discussed by Loftus and Masson (1994). A within-subject confidence interval provides a powerful comparison of within-subject conditions by excluding between-subject variability from the confidence intervals. Confidence intervals for means were calculated separately for the visual ungrouped (± .075), visual grouped (± .073), auditory ungrouped (± .068), and auditory grouped (± .060) conditions. In each of these conditions we treated the nine serial positions in whole recall along with the three serial positions in partial recall, for each of the three first-recall-position conditions, as 36 [= (9 + 3) × 3] levels of a single factor in a one-way ANOVA. This ANOVA yielded the mean squared error value entering into the confidence interval calculation (see Loftus & Masson, 1994). Thus, each set of 36 means shared the same confidence interval range. For some of the graphs, separate confidence intervals would produce too much clutter so a single interval (± .075) is drawn as the "maximum 95% confidence interval" though the actual intervals were often a bit smaller (as indicated above).

Additionally, to allow a high-power view of small effects of response set size, we took data from the first three output positions and averaged the results across all input serial positions, separately for the auditory and visual modalities, grouped and ungrouped stimuli, and partial versus whole recall. These 8 (= 2 × 2 × 2) averages then served as levels of a single factor in a one-way ANOVA that yielded a mean squared error value used to calculate a confidence interval (± .033) that was applied to each of the 8 averages.

Conventional estimates of variability. It may be helpful to compare the within-subject estimates described above with more conventional estimates in order to allow an assessment of the degree to which the estimates are affected by the statistical method. The standard errors of the mean, calculated separately for the 144 conditions of the experiment and then averaged across these conditions, averaged .039 (*SD* of the *SEM* = .009). The 95% confidence intervals ranges, calculated in the conventional fashion that includes between-subject variability, averaged ± .08. Thus, the within-subject estimation procedure and the conventional procedure yielded roughly comparable estimates of variability, suggesting that between-subject variability was small compared to the within- subject variability between conditions.

RESULTS

Appendix A presents the mean and standard deviation for each of the 144 condition/serial position combinations in the experiment to permit any comparison of interest at a later date.

Typicality of the Data Set

Before making specific comparisons it is important to check if the data are similar to what would be expected on the basis of previous research. Figure 2 shows that they are. This figure shows all of the data from trials in which the cued starting position was Input Position 1. As mentioned, previous studies of serial recall with regular, ungrouped lists have shown that visual presentation results in a severe decline across serial positions and a slight upturn at the end of the list (e.g., Jahnke, 1963; Madigan, 1971). Such a function is shown in the top panel of the figure. In contrast, aural presentation results in a more bow-shaped serial position function that includes a much larger recency effect than with visual presentation (e.g., Madigan, 1971). That sort of function was indeed obtained with ungrouped spoken lists, as shown in the bottom panel of the figure.

Another interesting aspect of the data has to do with grouping effects. Frankish (1989) showed that the grouping of stimuli is much more helpful for spoken lists than for printed lists, and a similar effect can be seen here. There was little difference between grouped and ungrouped lists in the visual modality (separate lines within the top panel of Fig. 2), whereas there was an enormous difference in the auditory modality (bottom panel).

This finding might appear to conflict with the intuitive notion that it is possible to carry out grouping in one's mind even with visually presented stimuli. However, the data offer a resolution of that paradox. It can be seen in the top panel of Fig. 2 that subjects most likely did, indeed, group the visual stimuli. Given that recall always began at Serial Position 1, 4, or 7, it

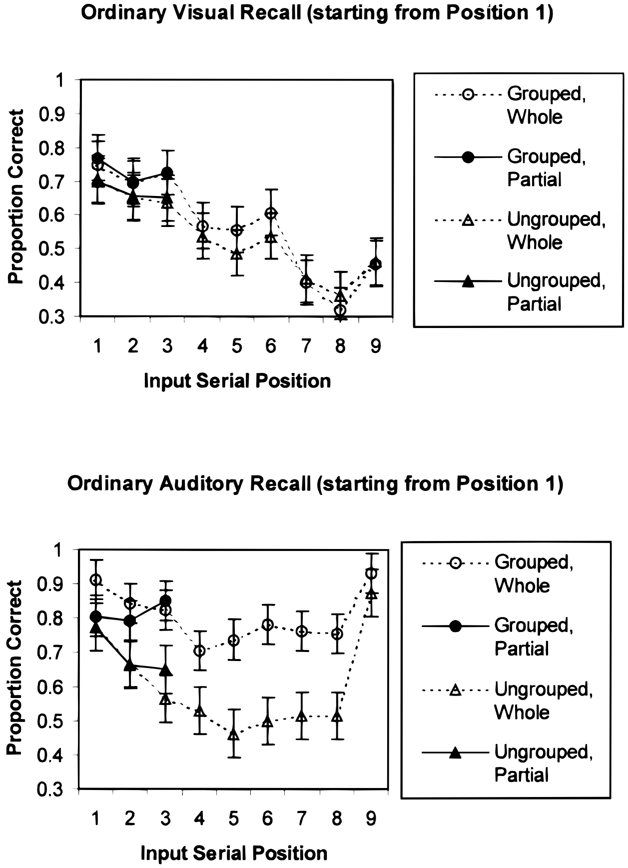

FIG. 2. The proportion correct as a function of input serial position for trials in which recall began at Input Serial Position 1, for trials with visual stimuli (top) and auditory stimuli (bottom). These data show that the results of the present experiment are consistent with other serial recall experiments. In visual serial recall, notice the scalloped effect suggesting a grouping strategy regardless of the actual stimulus grouping as opposed to auditory serial recall, which shows a large effect of stimulus grouping. Error bars show standard errors.

would have been efficient to think of the nine digits as grouped into three subsets of three digits, in which case the starting point for recall always would coincide with the beginning of a group. Accordingly, the figure (top panel) shows that responses to visual stimuli had an uneven pattern in which there was a separate serial-position scallop for each subset of three digits in the list, suggesting a separate local, bowed serial position function for each subset.

There was an important difference between this pattern and that observed with auditory stimuli (bottom panel of Fig. 2). For visual stimuli, the pattern of grouping and level of performance both were independent of the physical presentation of stimuli. In contrast, for auditory stimuli, the level of performance and grouping pattern apparently were heavily dependent on the presence versus absence of intergroup pauses in the stimuli.

For the grouped auditory lists, each group of three items revealed a local recency effect (bottom panel of Fig. 2) but not a local primacy effect as the visual stimuli did (top panel), further emphasizing modality differences in the effects of grouping. Although one could come up with reasonable post hoc explanations for this small, specific difference, it was unanticipated and we do not discuss it further for the sake of simplicity.

Another feature of Fig. 2 is that it illustrates, for the beginning of the list, the absence of an effect of response set size. In both panels of the figure, one can see that performance in partial recall (solid lines) was similar to performance in whole recall (dashed lines). Thus, in recalling Input Serial Positions 1–3, it did not much matter whether the subject also had to go on to recall Serial Positions 4–9 or not.

The data shown in Fig. 2 are typical of serial recall but do not deconfound the factors of input and output serial positions, which are perfectly correlated in that figure. In the following sections, data are plotted in such a manner that deconfounded comparisons can be made.

Effects of Input Serial Position

Bear in mind that the serial position effects shown in Fig. 2 are not pure indications of input serial position effects because later serial positions in that figure sustain more output interference and diminishing response-set sizes. We now examine the effect of input serial position with these other factors controlled. The left-hand panels of Fig. 3 provide a clean comparison by including only the first three items recalled. These data are shown for grouped lists in the top panel and ungrouped lists in the bottom panel. (The panels of Fig. 3 are organized in a different manner than those in Fig. 2 so that each figure can highlight the most noteworthy effects.) For whole recall, Output Positions 4–9 were excluded from the left-hand panels. The data thus included Input Serial Positions 1–3 from trials with recall starting at Position1, Input Serial Positions 4–6 from trials with recall starting at Position 4, and Input Serial Positions 7–9 from trials with recall starting at Position 7. For ease of presentation, these three segments are connected together with a common line (separately for each combination of grouping and modality conditions). For partial recall, the same description of what was included here applies; however, there were no Output Positions 4–9 to be excluded, so the plotted data include all of the partial-recall data.

It is clear from Fig. 3 (left-hand panels) that the effect of input serial position, examined with other factors controlled, looks more like ordinary probed recall (with large recency effects) than it does like ordinary serial recall (with large primacy effects). This shows that the ordinary serial recall effect is heavily influenced by output interference effects and/or response set size effects (which are more completely disentangled later on). Thus, with output serial position restricted to the first three items recalled, as in the left-hand panels of Fig. 3, there are only small primacy effects and larger recency effects in serial recall. This is true for both partial recall and whole recall.

Another interesting aspect of the left-hand panels of Fig. 3 is that relatively similar effects of serial position were found for grouped lists (top panel) and for ungrouped lists (bottom panel). Moreover, relatively similar effects were found for visual presentation (dashed lines) and auditory presentation (solid lines). Of course, in the recency portion of the curves, a ceiling effect limits the possibility for modality differences. As is shown below, grouping and modality effects increase substantially after there is more output interference. The implications of this finding are reviewed after additional data are presented.

It is possible that, when subjects are asked to begin recall at Position 4 or Position 7, they covertly rehearse the list beginning at Position 1 until arriving at the requested starting point. However, any such covert recall process apparently cannot cause the kind of output interference that overt recall does, considering the much larger recency effects in visual recall in the left-hand panels of Fig. 3 (depicting recall of three items beginning in any position) than in Fig. 2 (depicting recall of all nine items beginning in Position 1).

Effects of Output Serial Position

The middle and right-hand panels of Fig. 3 show results that, together, allow a clear view of output position effects for grouped lists (top panel in each case) and ungrouped lists (bottom panel in each case). The middle panels include only data for the middle three items recalled. For partial report (circles), only three positions are recalled so these are the same data as in the previous figure, repeated here for the sake of comparison. However, for whole report (X's),

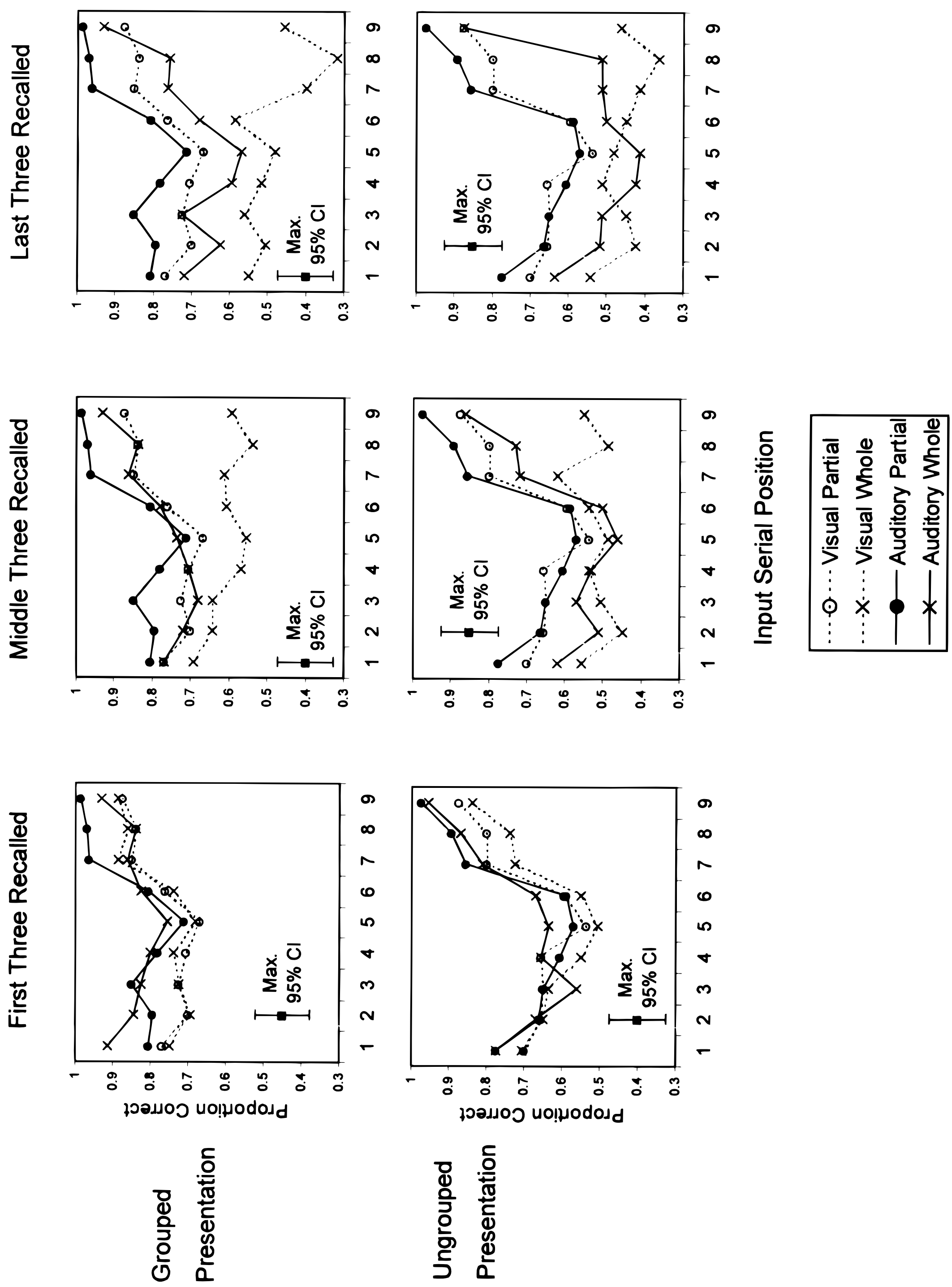

FIG. 3. Effects of input and output interference on serial recall in various conditions. Top: Grouped presentation; bottom: ungrouped presentation. Partial-report data are the same in the left-hand, middle, and right-hand panels, which differ only in the whole-report data that are included. Data points that are connected by lines in panels within this figure are drawn from three conditions with different starting points of recall (see Table 1).

this is a different subset of the data. It is the recall of Input Serial Positions 1–3 for trials with recall starting at Input Serial Position 7, recall of Input Serial Positions 4–6 for trials with recall starting at Input Serial Position 1, and recall of Input Serial Positions 7–9 for trials with recall starting at Input Serial Position 4. One cannot obtain a deconfounded view of output position effects from these panels because the data shown from whole report not only follow more recalled items than the data from partial report, but also are followed by more items to be recalled than partial report; so response set sizes are uncontrolled. However, the panels are still instructive because the results are rather similar to the right-hand panels, which do portray deconfounded comparisons.

The right-hand panels of Fig. 3 include only data for the last three items recalled. For partial report (circles) it is again the same data, whereas for whole report (Xs) it is different: It is the recall of Input Serial Positions 1–3 for trials with recall starting at Input Serial Position 4, recall of Input Serial Positions 4–6 for trials with recall starting at Input Serial Position 7, and recall of Input Serial Positions 7–9 for trials with recall starting at Input Serial Position 1. This is again shown for grouped lists (top panel) and ungrouped lists (bottom panel).

The results for both grouped and ungrouped list recall show very different output interference effects for auditory and visual presentations. Auditory presentations resulted in a modest effect of output interference across most serial positions (points versus Xs on solid lines in the middle and right-hand panels of Fig. 3). Visual presentations, on the other hand, resulted in a much more extreme loss of information at the end of the list as a function of output position (circles versus Xs on dashed lines in the middle and right-hand panels).

In ungrouped lists (bottom panels of Fig. 3), for auditory lists only, it appears as if the final serial position was completely spared the effects of output interference. In grouped lists (top panels of the figure), however, it appears as if the final *group of three* serial positions was spared for the auditory lists. Thus, grouping may have changed the size of the unit for which the auditory recency advantage applied. This small difference is not discussed further.

Effects of Response Set Size

The effects of response set size can be examined in the left-hand panels of Fig. 3 by comparing results for partial report (circles) to that for whole report (Xs). That is because, in both cases, although the output positions were the same (given that the first three recalled positions are plotted), the response set sizes were much smaller in partial recall (Response Set Sizes 3–1) than in whole recall (Response Set Sizes 9–7), as indicated in Table 2. Although fairly similar functions were obtained for partial and whole recall, a slight but consistent advantage for partial recall can be seen at the end of the list in certain conditions. For visual stimuli in ungrouped lists, one can see a small difference across the last 6 input serial positions. For auditory stimuli in grouped lists, a moderate-sized difference can be seen for the last three input serial positions.

Left: The proportion correct as a function of input serial position for data points obtained from Output Positions 1, 2, and 3. In both panels, notice that the effects of presentation modality (solid lines for auditory and dashed lines for visual presentation) are small and that the overall serial position function resembles that typically obtained in probed rather than serial recall. The greater primacy effect typically seen in serial recall thus must result from greater output interference. The slight advantage for partial recall (circles) over whole recall (Xs) at the end of the list suggests that there may be a small role of response set size in producing the small recency effect typically seen in serial recall. Middle: The proportion correct as a function of input serial position for data points obtained from the middle three items. Whole report data are from Output Positions 4, 5, and 6. (These panels do not yield deconfounded comparisons but are useful for a complete view of the data set.) Right: The proportion correct as a function of input serial position for data points obtained from the last three items. Whole report data are from Output Positions 7, 8, and 9. The difference between partial and whole report is in the output serial position. Notice the large effect of output interference toward the end of the list (in a comparison with the left panels' results) for visual lists only.

It thus seems possible that the reduction of response set size produces the upturn in performance for the last-recalled position(s). It is unclear exactly why, as one can see in the left-hand panel of Fig. 3, no effect occurred for recall beginning in Serial Position 1; only, at best, for recall beginning in Serial Positions 4 (slightly, for ungrouped visual stimuli) and 7 (for ungrouped visual and grouped auditory stimuli). However, it is quite possible that the type of memory load that has an effect is not just any need to recall additional items but, more specifically, the need to recall items in an order different from the presentation order. It is only in that particular situation that one cannot accomplish recall simply by reading from some episodic record in memory. If this is the case then the response set size factor would be of no consequence for ordinary serial recall, though it would be for circular recall starting midlist.

It is noteworthy, in any case, that any such effect of response set size was small at best. In order to assess the overall effect of response set size, we averaged the data shown in the left-hand panels of Fig. 3 across serial positions to obtain highly stable means. The results are shown in Fig. 4. This figure suggests that, overall, there may be a very small (4%) effect of response set size for visual ungrouped lists only, as can be seen by comparing the vertically striped bars in partial report (left) versus whole report (right). No overall effect can be seen at all for visually presented, grouped lists or for either ungrouped or grouped spoken lists.

DISCUSSION

The purpose of the present experiment was to distinguish between the effects of input serial position, output serial position, and response set size in the serial recall of nine-digit lists. This was examined separately for grouped and ungrouped (regularly timed) lists and for lists presented in the auditory and visual modalities. A manipulation of partial versus whole recall and of the starting point of recall allowed comparisons in which only one factor varied. Several conclusions can be drawn on the basis of the evidence regarding (1) the typicality of the data set, (2) effects of stimulus grouping and modality, (3) effects of input serial position, (4) effects of output position and modality, and (5) effects of response set size. What follows is a description and theoretical interpretation for findings under each of these topics. Finally, serial recall is related to evidence from other procedures.

The Typicality of the Data Set

Given that some of the serial position functions that were shown seem unusual for serial recall, it is important to emphasize that these functions are unusual because they portray deconfounded factors, not because the manipulations evoked unusual response strategies. Reassuringly, recall from the beginning of the list showed that the data set was not unusual. The typical pattern of serial-recall results was obtained, as shown in Fig. 2. We replicated findings from many studies of large primacy effects in serial recall as well as findings indicating that recency effects are much larger for auditory than for visual stimuli (e.g., Madigan, 1971) and that effects of stimulus grouping are much greater in the auditory modality (e.g., Frankish, 1989).

Effects of Stimulus Grouping and Modality

It can be seen (Fig. 2, top panel) that subjects were able to group visually presented lists in a manner consistent with the groupings that were presented on half of the trials (three subsets of three), even on trials in which the stimuli were ungrouped. Specifically, the scalloped functions in this panel are nearly identical for grouped and ungrouped lists. In contrast, a benefit from grouping in the auditory modality was much more dependent on actual stimulus grouping, as shown by the large grouping effect in the bottom panel of Fig. 2.

This pattern of auditory and visual grouping effects suggests that subjects not only make use of auditory sensory memory (Cowan, 1984, 1988; Crowder, 1976; Massaro, 1975; Massaro & Loftus, 1996; Nairne, 1990; Penney, 1989), they actually are dependent on that type of memory and cannot ignore or disregard it. This matches previous views, based on irrelevant-speech effects, suggesting that access to the au-

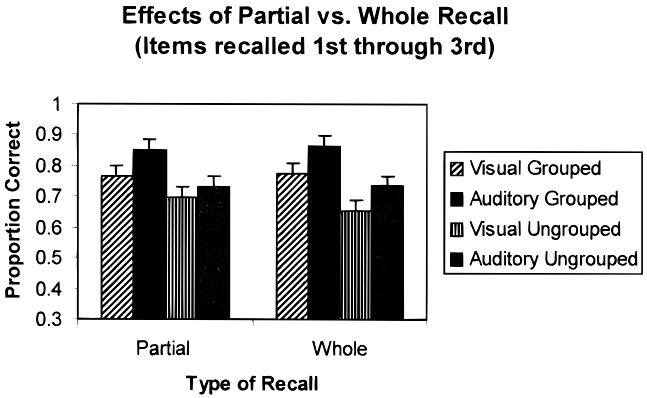

FIG. 4. Mean proportion correct for partial recall (left) versus whole recall (right) of the first three items recalled, averaged across all nine serial positions from the relevant conditions, for visual grouped, auditory grouped, visual ungrouped, and auditory ungrouped lists (successive adjacent bars). This figure shows that the *overall* effect of response set size was nil, with the exception of visual ungrouped lists. Error bars reflect the maximal 95% within-subject confidence interval.

ditory trace is obligatory (e.g., Salamé & Baddeley, 1982).

Effects of Input Serial Position

For the first few output positions, the input serial position functions resembled what is usually obtained in probed recall (e.g., Woodward, 1970), as shown in Fig. 3 (left-hand panels). Specifically, unlike typical serial recall functions, there were only small primacy effects and larger recency effects within these functions that include only the first few output positions. This was true in both presentation modalities similarly. The deconfounded effects of input serial position may pose a theoretical problem for models of visual serial recall in which the large primacy effect and the much smaller recency effect occur for reasons other than output interference. It would appear to be consistent with the feature model of Nairne (1990), in which the primacy advantage in serial recall is produced entirely by output interference.

The pattern shown in the left-hand panels of Fig. 3 would appear to pose a problem for models in which the serial position function in serial recall is accounted for by a primacy gradient that is present at the time that recall is to begin (e.g., Burgess & Hitch, 1999; Lewandowsky, 1999; Page & Norris, 1998). Theoretically, a primacy gradient, regardless of the mechanism creating it, should not disappear when output interference is minimized. In practice, rebuttal of a full model is not that easy to accomplish. For example, Page and Norris (1998, p. 763) included output interference in the form of the decay of the primacy gradient. What can be accomplished by evidence such as the present data set is to force such models to rely more on one type of mechanism (in this case, output interference of some type) and less on another type of mechanism (in this case, a primacy gradient of some type).

For convenience, we introduce here the term "encoding salience" to refer to the retrievability of an item after a list has been presented but before any output interference has occurred. The term is not meant to establish a clear division between encoding and retrieval processes other than to exclude the process of output interference. The present data are compatible with models in which the underlying encoding salience of an item is greater for the most recent items than for the first few items, with the least salience for the middle items, but with profound subsequent effects of output interference, which selectively degrade performance at earlier serial positions.

It is likely that several extant models could be amended to account for the present findings comfortably. In principle, the underlying input serial position function could be produced by a situation in which the distinctiveness of items at the time of recall is based partly on the reduced confusability of items at both ends of the list (e.g., Brown et al., 2000; Henson, 1998; Lee & Estes, 1981; Nairne et al., 1997) and partly on the enhanced temporal distinctiveness in the recency portion of the list (e.g., Baddeley & Hitch, 1993; Brown et al., 2000; Bjork & Whitten, 1974). To that, one must add output interference of some sort, whether from specific overwriting of features in the stimulus by features in the response (Nairne, 1990) or from the loss of distinctiveness of stimulus items with the passage of time (Brown et al., 2000).

It is also worth considering possible effects of guessing factors that theoretically could contribute to recency effects. If subjects mentally run through the list in order, and if they correctly think of the items that should go in the early serial positions (whether the assignment to specific positions is correct or not), then by default there would be few incorrect choices left to place in the later serial positions. However, any such guessing factor is, at least, not strong enough to overcome overt output interference.

Effects of Output Position and Modality

The modality effect was small for the first few output positions, as shown in the left-hand panels of Fig. 3. For later output positions, visual list performance became much worse toward the end of the list, whereas auditory list performance was mostly spared, as shown in the middle and right-hand panels of Fig. 3. Thus, modality effects in serial recall occur largely because the auditory stimuli are more resistant to output interference.

These results are consistent with what is found using forward versus backward recall. For example, Madigan (1971) obtained a very interesting pattern of effects in which spoken lists showed a large advantage over printed lists in the recency portion of ordinary serial recall, whereas the modality difference all but disappeared in backward recall. In backward recall, there were much smaller primacy effects and there were recency effects larger than in either modality within forward recall. The pattern seems to suggest that the recency portion of forward serial recall for visual materials suffers greatly from output interference, whereas that is not true for auditory recency. However, for the early input serial positions, both modalities seem to suffer similarly from output interference. Thus, overall, *auditory presentation seems to protect the end of the list from output interference*, a conclusion that has been reached before on the basis of earlier studies (Frankish, 1975).

However, there are limitations in the evidence from backward recall. First, backward recall changes not only the output serial positions, but also the response set sizes. Second, given other differences in the factors influencing forward versus backward recall, it has been suggested that backward recall does not use the same strategies as forward recall, relying instead on lexical, semantic, or visual information (Hulme et al., 1997; Li & Lewandowsky, 1995) or operating as a reiterative process of partial forward recall in which successive items are “peeled off” from the representation (Page & Norris, 1998). Thus, our results further clarify the role of output interference.

The presence of a huge output position effect for the visual modality only (for items toward the end of the list) and the greater benefit of grouping in the auditory modality both can be accounted for on the basis of an auditory memory trace that is rather long-lasting (Cowan, 1984) and resistant to interference. Several previous studies (Broadbent, Cooper, Frankish, & Broadbent, 1980; Hitch, Burgess, Towse, & Culpin, 1996; Manning & Turner, 1984) have suggested that auditory memory lasts longer than one would suspect from the extent of the auditory modality advantage in recall, which is limited to the end of the list; but that there rarely are cues that would allow subjects to use the less-recent portion of the auditory memory representation. (Grouping is such a cue, as the present Fig. 2 suggests.) The model of Nairne (1990) appears consistent with this finding in that modality-specific features are not subject to temporal decay and therefore can last a long time (e.g., throughout the recall period) if they are not overwritten.

Broadbent et al. (1980) commented on the larger grouping effect in the auditory modality.

They based these comments on a comparison made across different studies, and Frankish (1989) subsequently observed this interesting modality difference within a single experiment. In a way anticipating Nairne (1990), Broadbent et al. suggested that auditory memory of each sound is ordinarily overwritten by subsequent ones, limiting the available auditory memory to the most recent portion of the list. They suggested, however, that grouping cues can prevent that overwriting. Manning and Turner (1984) used a circular recall procedure in which subjects recalled the last three items of the list first. With it, they obtained further evidence in favor of Broadbent's hypothesis using a "suffix" item that followed the list and did not need to be recalled. A suffix item typically interferes with recall of the final few items in serial recall. Manning and Turner found that the last three items were much more susceptible to interference from the suffix in forward recall than in circular recall. However, circular recall increased the interference in the earlier input serial positions. Thus, it seemed as if the suffix effect was largest for whatever items had to be recalled *last*. This result can be understood if one assumes that the suffix interferes with acoustic memory but that the effects of this interference are observable only after there has been substantial output interference, making it more important to use the relatively long-lasting acoustic trace. Finally, Hitch et al. (1996) found that grouping effects survived an articulatory suppression task much better if the stimuli were spoken rather than printed, another indication that the grouping effect is more stimulus-linked for sounds.

In sum, the nature of the modality effect was difficult to understand from much previous work because the role of output interference was not taken into account. In the present study, output interference was manipulated with other factors held constant and the conception of modality effects in terms of resistance to output interference became clear.

Effects of Response Set Size

Last, there was little effect of response set size overall (see Fig. 4). The small effect was at the later serial positions, as shown in the left-hand panels of Fig. 3 by the comparison of partial report (always Response Set Sizes 3, 2, and 1) to whole report (in this figure, Response Set Sizes 9, 8, and 7).

There are several implications of this finding for models of working memory. First, at least one model has accounted for the small upturn at the end of the visual serial recall function as the result of response suppression of already-recalled items, severely limiting the response set by the time the end of the list is reached (Lewandowsky, 1999). Our result shows that, even if the response set size is the reason for the upturn, it need not result from response suppression. Our design allows a deconfounded measure of response set size effects only for the first three recalled items, by which no response suppression of other items could have taken place. Yet, a small response set size effect emerged, presumably because of the memory load effect resulting from the need to keep in mind the remaining items to be recalled and their order or serial positions.

The implications of this effect, however, must be tempered by the fact that the memory load that produced a response set size effect (at the end of the list) was not ordinary, but rather one in which the subject was to cycle around to the beginning of the list after recalling the end of the list. Most other models of serial recall account for the small upturn at the end of the list in visual serial recall as an edge effect, the notion that confusion of nearby list items in memory is less for end-of-list items because they have only one neighbor (e.g., Brown et al., 2000; Henson, 1998; Lee & Estes, 1981; Murdock, 1960; Nairne et al., 1997). The present finding of a small response set size effect nevertheless reintroduces the possibility that this effect plays a role, given that the upturn itself is small in the visual modality.

A second implication is as follows. The absence of a more pervasive response set size effect seems, on the surface at least, at odds with the view that items are held by a limited-capacity mechanism. If they were, items would be expected to interfere with one another considerably, making performance poorer when the response set is larger. This was, at best, not the general rule; effects of response set size were small. One could ask how the data would be explained by Cowan (in press-a), who proposed that the focus of attention can hold about three or four independent chunks of information at a time. According to that theoretical review, serial recall is to be explained with a mechanism in which a list is chunked into multi-item groups and all groups are held in a capacity-limited form.

One simple account (though certainly not the only possible one; see Cowan, in press-b) is that there is a phase in the recall task, just before recall starts, in which a limited-capacity store (the focus of attention?) is filled to capacity with list items. Recall then would rely on the contents of the store in that phase. Some items may have been chunked together in the mental representation previously during the input of the list. Capacity is limited to about four such chunks and, if there are more chunks than that in the mental representation, some of them will not be recalled. The fact that the response set size decreases during recall itself will not be of any consequence because it is too late in the trial for the freed-up capacity to be refilled with additional items from the list. A lingering question for this view is how capacity mechanisms would be integrated with input and output mechanisms to form a comprehensive model of recall.

Relation to Other Memory Tasks

A general concept of immediate serial recall emerging from the present work is that it results from several basic mechanisms in combination. The first is an encoding salience that favors primacy items somewhat and favors recency items more, producing the functions seen in the left-hand panels of Fig. 3. The second is output interference, which is more potent for ungrouped lists than for grouped lists and more potent for visual lists than for auditory lists, resulting in an altered, postinterference gradient, as shown in the middle and right-hand panels of Fig. 3. The question then arises as to whether these same concepts may apply not only to serial recall, but also to other memory tasks. One question is the extent to which the differences between the results of different tasks depend on how much output interference each task imposes. Below, we assess the possible relation of these concepts to other tasks in the hopes of working toward a general, cross-task understanding of immediate memory of verbal lists. We briefly consider, in turn, probed recall, free recall, and recognition tasks (this last leading to a supplementary principle).

Probed recall. Many models of serial recall have been developed basically to account for the pattern of serial position effects similar to what is shown for the visually presented lists in Fig. 2. An important limitation of many of these models (e.g., Burgess & Hitch, 1992, 1999; Lewandowsky, 1999; Page & Norris, 1998), however, is that they cannot, without violating their basic principles, account for the results of probed recall procedures in which the subject is to produce only one item from the stimulus list. In contrast to the marked primacy effects found in serial recall, probed recall results in small primacy effects and much larger recency effects (Woodward, 1970; Woodward & Murdock, 1968). There are two ways to account for these differences between procedures. One way is to assume that serial and probed recall result from fundamentally different processes, in which case the models of serial recall should not apply to probed recall. Alternatively, though, it could be assumed that the same factors apply to both kinds of recall and that the function of ordinary serial recall is heavily influenced by output interference and/or response set size effects. Both output serial position and response set size effects are much reduced in probed recall in comparison to serial recall.

Above, we have shown that reducing output interference in serial recall results in a serial position function similar to what is usually obtained in probed recall: a small primacy effect and a large recency effect (see Fig. 3, left-hand panels). If this is the case then, contrary to one common practice among modelers, it does not seem to be a good idea to model probed and serial recall separately. Instead, it appears that tasks differ at least partly because of the amount of output interference and that an adequate model should be able to account for results from various tasks by including this as a factor.

Free recall. There is a link between the output order in free recall and the success of recall (noted by Deese & Kaufman, 1957), with earlier output positions recalled better than later ones. However, free recall poses problems for theoretical analysis because of the low degree of experimenter control. The usual pattern of free recall includes large primacy effects and even larger recency effects (e.g., Murdock, 1962) but it is difficult to separate cause and effect. For example, is the recency effect so large because recent items are most often recalled first, and therefore suffer the least output interference; or are recent items recalled first because they are easiest to recall?

A study by Craik (1969) helps to distinguish between these possibilities by exerting a limited amount of control over output order. Subjects were to recall as many items as possible either from the beginning of the list or from the end, depending on the trial condition; but beyond that restriction, the order of recall was up to the subject. The results support the general notion that output interference plays a very important role, and they nicely correspond to the present results with serial recall. Craik found a large end-of-list auditory modality superiority effect when recall started at the beginning of the list, but he found a much smaller auditory modality superiority effect, with large recency effects in either modality, when recall started at the end of the list. The beginning-of-list recall thus yields recency effects similar to the middle and right-hand panels of the present Fig. 3, depicting the case of high output interference in serial recall; whereas the end-of-list recall yields recency effects similar to the left-hand panel of the present Fig. 3, depicting the case of low output interference in serial recall. In both procedures, when recall starts at the end of the list, recall from short-term storage presumably can occur without the output interference that selectively impairs memory for recent visual stimuli.

Recognition. The results of recognition procedures constitute a little more of a puzzle than do those of probed and free recall. They include little or no output interference. If memory performance in any task were based solely on input salience and output interference, then recognition procedures should reflect the results of encoding salience and should produce results resembling the left-hand panels of Fig. 3, which shows small primacy effects and larger recency effects.

Some studies do show the desired effect. For example, Corballis (1967) presented five-digit lists and measured reaction times to a probe digit that was or was not in the list. With a relatively slow presentation rate (.6 s/p digit) the mean response times for subjects to indicate that the probe was in the list produced a serial position function that did include a small primacy effect and a large recency effect. With a fast presentation rate (.3 s/digit) only recency effects emerged but this could indicate insufficient perceptual encoding of the earlier digits in each list. Using a .5 s/p digit rate with word stimuli in a probe recognition procedure, McElree and Dosher (1989) showed some similar functions, with small primacy effects and larger recency effects, for both response times and memory strength (d').

The view that different immediate memory tasks operate through common principles leads to the prediction that it should be possible to make recognition look more like serial recall by adding interference; if not from output, then from some other source. At least one study confirms this prediction. Jahnke, Davis, and Bower (1989) carried out a probed recognition task in which several intervening interference items were presented before the recognition probe. They found a performance function more closely resembling the typical visual serial recall function, with a large primacy effect and a smaller recency effect (Jahnke et al., 1989, Table 5).

Duncan and Murdock (2000) present a more challenging result. They altered the expectations of receiving a recognition versus a serial recall task by either precuing the subject to the nature of the task on each trial or withholding that information until a postlist cue. When the cue was postlist, the proportions of tasks could vary; in some sessions serial recall was the task half of the time and in other sessions it was the task only rarely, leading to a general expectation of a recognition task. When a recognition task was expected, the response times showed a large recency effect (and perhaps a very small primacy effect). However, when subjects prepared for recall, the recognition response time function was slower and flat across serial positions. Thus, the mechanisms of input salience and output interference must be supplemented by some notion of strategy or attentional allocation during input of the list (e.g., attention to item versus order information: see Hockley & Cristi, 1996; Murdock, 1999).

One possible account of the Duncan and Murdock result is that an encoding salience function similar to the left-hand panels of the present Fig. 3 always holds, but that the time needed for the subject to switch mental set from a recall orientation to a recognition orientation, following the task cue, delays overt responding. This mental-set switching process (whatever it entails, which is not known) potentially could delay responding enough so that, during this delay, retrieval of the probe item is concurrently completed. That kind of parallel processing could obscure any serial position effects in recognition response time. Another possible account is that an ordinary, forward serial recall orientation emphasizes attention to the early serial positions, to some extent canceling out the recency effect, whereas an orientation to either recognition or recall with varying starting points (as in the present study) emphasizes attention to the list more evenly.

Duncan and Murdock (2000) also found that when recognition was expected, unexpected serial recall trials produced a function that began at a much lower proportion correct than for expected serial recall but ended at the same level (approaching 0% at the final, seventh serial position). Thus, the function for unexpected serial recall was flatter across serial positions but it may be the result of a floor effect at later serial positions. The result does indicate that a strategic or attentional component must be present for optimal encoding in serial recall, as in recognition. This strategic component can be seen also in the fact that memory for ignored lists is much poorer than memory for attended lists (Cowan et al., 1999; Cowan, Nugent, Elliott, & Saults, 2000). Specifically, Cowan et al. (1999, 2000) found that memory for lists of spoken digits that were to be ignored during their presentation (while a visual task was carried out) and occasionally were postcued for immediate serial recall was much poorer than for attended lists, though recall of the ignored lists still showed a pronounced, bow-shaped serial position function.

The proposed underlying encoding salience function, involving small primacy effects and large recency effects, may or may not hold for the recognition of serial order. This has been studied in tasks in which a list is followed by two probe items and the subject must indicate whether these two items appear in the same order as in the list. The typical finding in this area is that performance depends on the recency of the second probe but very little on the serial position of the first probe (Hacker, 1980; Hockley, 1984; Muter, 1979). Occasionally, though, a small primacy effect can be seen also. McElree and Dosher (1993) tested four subjects extensively and the mean accuracy (d') for adjacent target pairs, averaged across subjects from their Table 1 are, for Serial Position Pairs 1–2, 2–3, 3–4, 4–5, and 5–6, respectively: 0.64, 0.56, 1.44, 1.05, and 1.75. For response times, from their Table 2, the means are, respectively, 1107, 1164, 906, 832, and 490 ms. For both measures, notice that a very small primacy effect (not necessarily significant) can be seen along with a large recency effect.

Whether there truly is a small primacy effect in order recognition, it is clear that the primacy effect is larger in item recognition, though never very large. The recency effect, in contrast, is large for both item and order recognition. This description may be related to what is found for item vs order *recall*, which shows only primacy effects for item information vs a bowed response function for order information (Healy, 1974). It appears that one can transform the recognition results to resemble Healy's recall results fairly well by adding more primacy and taking away some recency, as output interference in recall would do.

It is not at all clear why the recognition of order produces little, if any, primacy effect. If order of a probe pair is usually judged on the basis of relative recency, as various investigators have proposed (for a review see McElree & Dosher, 1993), then perhaps the subject fails to use information available in memory, indicating that an item occurred near the beginning of a list.

In sum, the comparison of memory tasks suggests that it might be possible to account for the various findings on the basis of a common set of principles. These would include (1) a distinctiveness-based encoding salience that typically includes a moderate primacy effect and a larger recency effect, (2) output interference effects that degrade performance more for later output positions, and (3) an attentional or strategic component that can alter the type of information available at the time of the memory test. The least resolved area according to this scheme is probably recognition, though it too may fit the scheme. One major impediment to such a unified view has been that large primacy and small recency effects are obtained in serial recall of visual lists. In this article, however, serial recall has been decomposed to reveal an underlying encoding salience more similar to what is seen in the other procedures, with smaller primacy effects and larger recency effects, when output interference is minimized.

Summary Remarks

The simplicity of presentation found in serial recall should not be mistaken for a theoretical simplicity inasmuch as several possible basic factors are confounded. We have shown that they can be deconfounded through a comparison of specially selected conditions and comparisons. The data from conditions with recall beginning at Input Serial Position 1 replicate what is found in ordinary serial recall (Fig. 2). However, comparisons that can reveal input serial position effects independent of other effects (Fig. 3, left-hand panels) show a large recency effect and smaller primacy effect. When output interference was high (Fig. 3, middle and right-hand panels), performance was severely impaired toward the end of the list in the case of visual presentation only and much less impaired under other circumstances. Thus, the auditory modality superiority effect is seen to be especially large under circumstances of high output interference. We have suggested that these effects also may be closely related to what is found in probed recall, free recall, and recognition procedures.

Finally, we have shown that there may be a very small role of response set size and have suggested that it logically could be a substitute for the response suppression mechanism proposed by Lewandowsky (1999) to produce the small visual recency effect. However, it is not clear if this principle is necessary to account for serial recall when one does not assume that there is a primacy gradient; temporal distinctiveness principles might well be enough to account for it (e.g., Brown et al., 2000). Although there very likely are important factors that could not be duly considered in this study (e.g., output modality and nature of the materials), extensions of the present methods hopefully can be useful in future research to carry out more incisive theoretical analyses of various factors within serial recall than in the past.

APPENDIX A

Means (and Standard Deviations) for Every Condition in the Experiment

Condition[a]	First recall position	Input serial position 1	2	3	4	5	6	7	8	9
VGP	1, 4, or 7	0.77 (0.18)	0.70 (0.23)	0.73 (0.23)	0.71 (0.23)	0.67 (0.19)	0.76 (0.22)	0.85 (0.14)	0.84 (0.18)	0.88 (0.15)
VGW	1	0.75 (0.25)	0.69 (0.25)	0.73 (0.22)	0.57 (0.25)	0.56 (0.25)	0.61 (0.25)	0.40 (0.29)	0.32 (0.27)	0.46 (0.27)
VGW	4	0.55	0.51	0.56	0.74	0.68	0.74	0.61	0.54	0.59

APPENDIX A—*Continued*

Condition[a]	First recall position	1	2	3	4	5	6	7	8	9
		(0.31)	(0.27)	(0.31)	(0.21)	(0.25)	(0.22)	(0.26)	(0.27)	(0.31)
VGW	7	0.69	0.64	0.64	0.52	0.48	0.59	0.89	0.86	0.89
		(0.22)	(0.27)	(0.26)	(0.27)	(0.29)	(0.30)	(0.15)	(0.18)	(0.12)
VUP	1, 4, or 7	0.70	0.66	0.65	0.66	0.54	0.59	0.80	0.80	0.88
		(0.27)	(0.22)	(0.23)	(0.27)	(0.26)	(0.29)	(0.22)	(0.21)	(0.20)
VUW	1	0.71	0.65	0.64	0.54	0.49	0.54	0.41	0.36	0.46
		(0.18)	(0.23)	(0.25)	(0.27)	(0.27)	(0.23)	(0.23)	(0.28)	(0.25)
VUW	4	0.54	0.43	0.45	0.55	0.51	0.55	0.62	0.49	0.55
		(0.26)	(0.23)	(0.26)	(0.27)	(0.29)	(0.25)	(0.24)	(0.23)	(0.20)
VUW	7	0.56	0.45	0.51	0.51	0.48	0.45	0.73	0.74	0.84
		(0.29)	(0.30)	(0.29)	(0.24)	(0.24)	(0.25)	(0.25)	(0.22)	(0.22)
AGP	1, 4, or 7	0.81	0.79	0.85	0.78	0.71	0.81	0.96	0.97	0.99
		(0.20)	(0.16)	(0.17)	(0.22)	(0.25)	(0.22)	(0.09)	(0.07)	(0.04)
AGW	1	0.91	0.84	0.83	0.71	0.74	0.78	0.76	0.76	0.93
		(0.11)	(0.15)	(0.18)	(0.22)	(0.22)	(0.24)	(0.24)	(0.24)	(0.16)
AGW	4	0.72	0.63	0.73	0.80	0.76	0.83	0.86	0.84	0.93
		(0.25)	(0.26)	(0.20)	(0.19)	(0.20)	(0.19)	(0.17)	(0.18)	(0.09)
AGW	7	0.77	0.72	0.68	0.59	0.57	0.68	0.94	0.94	0.95
		(0.21)	(0.20)	(0.23)	(0.21)	(0.25)	(0.27)	(0.11)	(0.11)	(0.11)
AUP	1, 4, or 7	0.78	0.66	0.65	0.61	0.57	0.59	0.86	0.89	0.98
		(0.21)	(0.24)	(0.26)	(0.26)	(0.25)	(0.24)	(0.21)	(0.16)	(0.06)
AUW	1	0.78	0.67	0.56	0.53	0.46	0.50	0.51	0.51	0.88
		(0.21)	(0.22)	(0.20)	(0.21)	(0.19)	(0.25)	(0.31)	(0.30)	(0.17)
AUW	4	0.64	0.52	0.51	0.66	0.64	0.67	0.72	0.73	0.86
		(0.19)	(0.27)	(0.21)	(0.19)	(0.20)	(0.21)	(0.20)	(0.21)	(0.15)
AUW	7	0.62	0.51	0.57	0.43	0.41	0.50	0.81	0.87	0.96
		(0.22)	(0.22)	(0.20)	(0.27)	(0.25)	(0.26)	(0.19)	(0.18)	(0.12)

Note. For partial recall, first recall positions 1, 4, and 7 refer to different trials inasmuch as only three digits were to be recalled in each partial recall trial. In whole recall, all nine items were to be recalled.

[a] V = visual; A = auditory; G = grouped stimuli; U = ungrouped; P = partial report; and W = whole report.

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