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Testing visual short-term memory: Simultaneous versus sequential presentations

ROBERT W. FRICK
University of Washington, Seattle, Washington

Two experiments testing immediate ordered recall are presented; in these experiments, subjects engaged in repetitive speech ("articulatory suppression") during a visual presentation in order to prevent auditory recoding of the stimuli. In both experiments, a simultaneous presentation produced results that suggested the use of visual short-term memory, whereas a sequential presentation did not. In Experiment 1, visual confusion errors occurred more often than would be expected by chance for a simultaneous presentation but not for a sequential presentation. In Experiment 2, recall from visual short-term memory was expected to suffer more when subjects wrote a prefix than when they spoke a prefix; this effect occurred for a simultaneous presentation but not for a sequential presentation. These results suggest that existence of a visual short-term store that retains a simultaneous presentation but not a sequential presentation.

Tests of visual short-term memory for verbal stimuli often use a sequential presentation (i.e., presenting the to-be-remembered stimuli one at a time). Perhaps a sequential presentation is used because experiments studying visual short-term memory often compare it with auditory short-term memory, auditory presentations are usually sequential, and experimenters wish to hold as many factors constant as possible. However, Shulman (1971) suggested the need for comparing sequential and simultaneous visual presentations; Penney (1975) suggested that a sequential presentation may not optimize use of visual short-term memory and that simultaneous presentations should be tested; and Kahneman and Henik (1977) suggested that the relevant visual analog to a sequential auditory presentation might be a simultaneous visual presentation. Therefore, the experiments reported in this paper compared sequential and simultaneous visual presentations.

Experiment 1 concerned the problem of finding an immediate recall paradigm that tests visual short-term memory for verbal stimuli such as digits or letters. Such a paradigm would allow results obtained for visual short-term memory to be compared with a substantial body of results from research upon auditory short-term memory. The first step to eliciting use of visual short-term memory is to present the stimuli visually. However, a visual presentation is not sufficient: For a sequential visual presentation of letters, "confusion errors" (substituting an incorrect letter for a correct letter during recall) tend to be auditory (Conrad, 1964); that is, they tend to involve two letters that sound similar (or are spoken similarly; Wickelgren, 1969). These auditory confusion errors suggest that subjects recode a visual presentation auditorily and retain the items in an auditory short-term memory.

Use of a visual short-term store has been demonstrated for nonverbal stimuli, which cannot be recoded auditorily (e.g., Cermak, 1971). For verbal stimuli, use of a visual short-term store has been demonstrated by testing recognition latencies (e.g., Posner, Boies, Eichelman, & Taylor, 1969). Use of a visual store for immediate recall of verbal stimuli has been demonstrated by testing supraspan lists of consonants (Laughery, Welte, & Spector, 1973) and by testing Chinese speakers for recall of Chinese ideographs (Yik, 1978). In these latter two experiments, however, the evidence for use of an auditory store was stronger than the evidence for use of a visual store. Therefore, there is ample evidence for the existence of a visual short-term store, but no paradigm that predominantly tests visual short-term memory for recall of verbal stimuli has been found.

Auditory recoding of visually presented stimuli can be eliminated (or at least impaired) by engaging the auditory system in another task (e.g., Parkinson, Parks, & Kroll, 1971). The simplest method, first used by Murray (1967), is called "articulatory suppression," and involves having the subject speak a repetitive phrase during the presentation of the stimuli. Articulatory suppression requires no equipment and demands little of the subject's attention, as suggested by the finding that it does not impair performance on missing scan (Klapp, Marshburn, & Lester, 1983) or ordered recall of grouped auditory presentations (Klapp, Greim, & Marshburn, 1981). Articulatory suppression eliminates evidence of auditory recoding of visually presented stimuli (e.g., Baddeley, Lewis, & Vallar, 1984; Conrad, 1972; Healy, 1975a; Murray, 1967; L. R. Peterson & Johnson, 1971; Richardson, Greaves, & Smith, 1980; Salamé & Baddeley, 1982).

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It is "tempting" to assume that when auditory short-term memory is not being used, visual short-term memory is (Salamé & Baddeley, 1982, p. 161). However, there is no evidence for this assumption. If visual short-term memory is used during articulatory suppression, the confusion errors in immediate recall should tend to be visual, fusion errors in immediate recall should tend to be visual, that is, confusing two letters that are visually similar. A study using articulatory suppression and a sequential visual presentation found no more visual confusion errors than would be expected by chance (Conrad, 1972).

Therefore, the purpose of Experiment 1 was to reinvestigate the use of visual short-term memory with articulatory suppression, testing both sequential and simultaneous presentations. These presentations were tested with and without articulatory suppression. Confusion errors were collected using the consonants in the alphabet.

EXPERIMENT 1

Method

Subjects and Design. Students from introductory psychology classes at the University of Washington voluntarily participated in order to earn extra credit. English was their first language. There were four groups of 28 subjects, who received either a sequential or a simultaneous presentation and either engaging or not engaging in articulatory suppression.

Stimuli. The stimulus for each trial was a string of letters selected at random from the alphabet, excluding A, E, I, O, U, Y (to avoid presenting words or pronounceable nonwords). A letter could appear twice in a string, but repetitions were always separated by at least four other letters. The letters were presented using an Apple II+ computer with a Lazer chip and a green NEC monitor, Model JB-1201M.

In the sequential presentation, the letters were presented one at a time in the middle of the screen at the rate of two letters per second. In the simultaneous presentation, the letters were presented all at once centered in the middle of the screen, for .5 sec times the number of letters in the presentation.

Procedure. Before being tested, the subjects read aloud two unordered strings of letters that contained all the letters of the alphabet, to verify that the letters were being perceived correctly. Any errors in reading were corrected.

There were 4 practice trials and 36 experimental trials, divided into three blocks of 12 trials. Each block of trials covered a range of three string lengths, with 4 trials at each length, beginning with the shortest length. The length of letter strings encompassed by this range depended upon the condition and the subject's ability, so that the difficulty of recall was approximately the same across subjects and conditions: The sequential presentation with articulatory suppression began with four-letter strings, the simultaneous presentation without articulatory suppression began with six-letter strings, and the other two conditions began with five-letter strings. The range was adjusted between blocks when a subject had recalled correctly more than 6 trials or fewer than 2 trials in a block.

Whenever the string length changed, the trial began with a message that informed the subjects of the new string length. For each trial, the subjects received a visual message "ready" and then a visual message "begin repetition," upon which the subjects engaging in articulatory suppression began repeating aloud "one, two, three, four." This repetition continued until the presentation of letters was finished. When the presentation was finished, the subjects attempted to recall the stimuli orally. They were given no feedback.

Defining auditory and visual errors. It may seem at first that visual (or auditory) errors could be defined simply by the errors that occur in visual (or auditory) perception. However, under optimum conditions, few errors in perception occur. To create errors, the perceptual image of the stimuli must somehow be degraded. There are a number of dimensions upon which letters are similar or different, and a procedure for degrading the perceptual image of a letter cannot uniformly degrade all of these dimensions. If two letters differ on Dimension 1 and share Dimension 2, when Dimension 1 is degraded the letters will tend to be confused and when Dimension 2 is degraded the letters will tend not to be confused. Therefore, there is no one "correct" set of visual (or auditory) errors. Merely changing the duration of presentation changes the pattern of visual perceptual errors (Fisher, Monty, & Glucksburg, 1969); larger differences in procedure, such as whether or not the location of the test letter is varied, could be expected to produce even larger differences in the pattern of errors.

Presenting too many digits for short-term memory to retain and allowing decay of information in short-term memory are also methods of degrading an image of the stimuli, and there is no reason to expect the pattern of errors produced in a short-term memory experiment to be exactly the same as the pattern of errors produced in any given perceptual experiment. The ultimate question is whether the confusion errors produced in a short-term memory experiment can be explained in terms of the perceptual features of the letters. Because constructing a theory of errors for visual short-term memory was beyond the scope of this experiment, somewhat arbitrary choices were needed in order to define visual and auditory confusion errors for the purpose of data analysis.

In auditory short-term memory, it is well-accepted that vowels are retained better than consonants, such that (BCDGPTVZ) forms a confusable set and (KQZ) does not, despite the fact that the letters in the second set share a common consonant sound. Therefore, letters with the same vowel sound in the same position were defined as auditorily confusable, forming the sets (BCDGPTVZ), (FMNSX), and (JK). The "ell" sound seemed to be too much like a vowel to include it in the set (FMNSX). In retrospect, the nasal consonants (M and N) were not often confused with F, S, or X (in the condition that otherwise produced auditory confusion errors).

There was no similar consensus about the relevant dimensions of visual confusion errors in visual short-term memory. Therefore, the set of visual errors described by Laughery et al. (1973) [(CDGQ), (FL), (BDP), (BPR), (KR), (MNVWX), (JT), (HK), (HN), and (VXZ)] was adopted. This set is discrete and well-defined, and using it eliminated any post hoc decisions about what was a visual confusion error. Also, this set already had been used to detect visual errors in short-term memory. In retrospect, some of the pairs (in particular, MX, NW, and VZ) were not often confused (in the condition that otherwise produced visual errors). However, it would have been statistically inappropriate to use the results of this experiment to refine the definition of visual errors.

Defining confusion errors. A confusion between two letters was said to occur when at a serial position one letter was reported instead of another. The direction of the confusion error (e.g., whether P was reported for a Q or Q was reported for a P) was ignored. This procedure might have overrepresented a reversal of two letters; for example, reporting QP instead of PQ would have counted as two PQ confusions. On the other hand, counting a reversal as two errors might be appropriate: Having reported a Q for a P, it may be a sign of further visual confusion to report a P instead of a Q. If the reversal of two letters had been treated as one visual confusion, how to analyze a reversal of three letters (e.g., reporting RPQ instead of PQR) or a reversal of nonadjacent letters (e.g., reporting RQP instead of PQR) would not have been obvious. Another problem arose when PQ was reported as QR. Should this be treated as two confusions (PQ and QR) or as a reversal and a confusion (between P and R)? Of course, a post hoc analysis might have revealed which method of defining confusions produced the highest proportion of visual errors, but a post hoc decision on how to analyze the data would have compromised the interpretation of the statistical tests. Therefore, confusion errors were defined as simply as possible.

Confusion errors were not taken from trials in which the number of letters in the response did not equal the number of letters in the presentation, because on such trials the serial position of the letters in the response was ambiguous. Errors that occurred when subjects responded with a vowel were ignored, because a chance rate for their occurrence could not be calculated.

Results

Initially, 39 letter pairs were defined as auditorily confusable, and 28 letter pairs were defined as visually confusable (see Method section). The letter pairs common to both sets (e.g., CG and MN) were subtracted from each set, to form a third set of both auditorily-and-visually confusable letters. Thus, of the 190 possible letter pairs, there were 29 auditorily confusable pairs, 18 visually confusable pairs, and 10 auditorily-and-visually confusable pairs. For each subject, the percentage of a type of error was calculated by dividing the total number of confusion errors of that type by the subject's total number of confusion errors. The average of these percentages for each type of error and each condition is presented in Table 1.

Analyses of each condition. First, each condition was analyzed separately. The percentage of each type of error was compared with the percentage that would be expected by chance if all confusions were equally likely.

In the simultaneous presentation with articulatory suppression, visual errors occurred 2.1 times more often than would be expected by chance [$t(27) = 3.11$, $p < .01$]. The proportion of visual errors was above chance levels at all portions of the serial position curve. There was a marginally significant trend for the auditory errors to occur less often than would be expected by chance, [$t(27) = 1.97$, $p < .10$]; however, this was an artifact of the increased percentage of visual errors—as a percentage of the remaining nonvisual errors, the auditory errors did not occur less often than would be expected by chance [$t(27) = 0.88$]. The auditory-and-visual errors did not occur more often than would be expected by chance [$t(27) = .95$].

In the sequential presentation with articulatory suppression, one subject did not make any countable errors and was discarded from the analysis. No type of error occurred reliably more often than would be expected by chance. The percentage of combined visual errors (combining both visual and auditory-and-visual errors) was not above chance [$t(26) = 0.87$], and the percentage of all three types of errors combined was not above chance [$t(26) = 0.43$]. Traditionally, the total number of each type of error is divided by the total number of errors, and this proportion is compared with chance expectations (e.g., Conrad, 1964, 1972). This procedure is not statistically appropriate for demonstrating an increase in visual errors, because it assumes that errors made by the same subject are independent. However, given its increased power, it should be considered before accepting the null hypothesis of no increase in visual errors. Of the 822 errors collected in this condition, 99 (12%) were classified as visual, which is more than the 9% that would be expected by chance ($p < .05$). The proportion of visual errors in the first serial position (ignoring whether or not the subject reported the correct number of letters) was especially high (25 of 113, or 22.7%, $p < .05$). Therefore, a conclusion of no increase in visual errors would be incautious. Nonetheless, this evidence for visual errors is statistically unacceptable. An appropriate conclusion seems to be that if there was an increase in visual errors, the increase was small.

For the sequential presentation without articulatory suppression, auditory errors occurred 2.0 times more often than would be expected by chance [$t(27) = 3.17$, $p < .01$], and auditory-and-visual errors occurred 2.7 times more often than would be expected by chance [$t(27) = 5.45$, $p < .001$]. Visual errors occurred less often than would be expected by chance, but this reduction was an artifact of the increased proportion of auditory and auditory-and-visual errors; the percentage of visual errors in the pool of nonauditory errors was about what would be expected by chance [$t(26) = 0.82$].

For the simultaneous presentation without articulatory suppression, the auditory-and-visual errors occurred 1.6 times more often than would be expected by chance [$t(27) = 2.21$, $p < .05$]. The increase in auditory errors over chance was statistically nonsignificant, but the percentage of combined auditory errors (combining the auditory errors and the auditory-and-visual errors) was greater than would be expected by chance [$t(27) = 2.48$, $p < .05$]. Similarly, the increase in visual errors over chance was statistically nonsignificant, but the percentage of combined visual errors (combining the visual and auditory-and-visual errors) was greater than would be expected by chance, [$t(27) = 2.58$, $p < .05$]. Therefore, the statistics suggest that in this condition at least one type of error (visual or auditory) occurred more often than would be expected by chance, without indicating which type of error was occurring.

ANOVAs. A second method of analyzing the data is by 2 × 2 analyses of variance, with one independent variable of articulatory suppression (compared with no articulatory suppression) and a second independent variable of type of presentation (sequential versus simultaneous). Auditory errors were reduced 11% by articulatory sup-

Table 1
Average Percentage of Each Type of Confusion Error, for Simultaneous and Sequential Presentation, With or Without Articulatory Suppression (AS)

	Type of Error		
	Auditory	Visual	Both
Chance Expectation	15	9	5
Sequential Presentation			
no AS	30	7	14
with AS	14	10	6
Simultaneous Presentation			
no AS	18	12	9
with AS	11	20	6

pression [$F(1,107) = 14.02$, $p < .001$], and increased 7% by sequential presentation (as opposed to simultaneous presentation) [$F(1,107) = 6.43$, $p < .05$], with no interaction between these two factors [$F(1,107) = 2.22$]. Visual errors were increased 6% by articulatory suppression [$F(1,107) = 7.34$, $p < .01$], and decreased 8% by the sequential presentation [$F(1,107) = 11.27$, $p < .01$], with no interaction [$F(1,107) = 1.65$]. Auditory-and-visual errors were reduced 5% by articulatory suppression [$F(1,107) = 12.16$, $p < .001$], and increased 2% by the sequential presentation [$F(1,107) = 4.02$, $p < .05$]. There was a marginally significant interaction [$F(1,107) = 3.91$, $p < .10$], such that most auditory-and-visual errors occurred in the sequential presentation without articulatory suppression. The explanation of the pattern of auditory-and-visual errors seems to be that the auditory-and-visual set was more auditorily confusable than visually confusable.

A measure of capacity is the number of letters in a string that a subject correctly recalled 50% of the time. (When no string length was correctly recalled exactly 50% of the time, capacity was calculated by interpolating between the two string lengths that were recalled just more often and just less often than 50% of the time.) The average capacity for each condition is presented in Table 2.

The articulatory suppression impaired capacity 1 letter [$F(1,108) = 67.11$, $p < .001$], and the sequential presentation impaired capacity 1.5 letters [$F(1,108) = 137.86$, $p < .001$]. There was an interaction [$F(1,108)=5.33$, $p < .05$], such that the impairment from articulatory suppression and sequential presentation together was larger than the sum of their individual effects.

Correlations with other confusion matrices. A third method of analyzing the visual errors is by correlating the confusion matrices gathered in this experiment with other perceptual confusion matrices [Fisher et al., 1969; Gilmore, Hersh, Caramazza, & Griffin, 1979; Hodges (as cited in Fisher et al.); Pew & Gardner (as cited in Fisher et al.); Townsend, 1971; Van der Heijden, Malhas, & Van den Roovaart, 1984]. To compare those experiments with this experiment, asymmetries and errors involving vowels were ignored. Visual perceptual errors were also collected in this laboratory by presenting letters briefly at random locations on the computer screen. One advantage of a correlational analysis is that it is not based upon just one definition of visual errors. The correlations are presented in Table 3. Split-half reliabilities (odd-even subject) are presented (as diagonal entries) where available.

Table 2
Average Estimated Capacity in Experiment 1

	Presentation	
	Sequential	Simultaneous
No articulatory suppression	5.6	6.8
With articulatory suppression	4.3	6.0

The confusion errors produced by the simultaneous presentation with articulatory suppression correlated reliably with all sets of visual confusion errors, confirming that subjects were making visual errors in this condition. The correlations involving the sequential presentation without articulatory suppression are not easily interpreted. In general, the correlations are positive but not statistically significant, but in two cases the correlation is significant. However, these statistically significant correlations are larger than the split-half reliability for this condition. The sequential presentation without articulatory suppression and the simultaneous presentation without articulatory suppression have the same pattern of results: nonnegative correlations that are occasionally statistically significant.

DISCUSSION

Simultaneous presentation with articulatory suppression. This condition was characterized by visual errors. All that visual confusion errors necessarily show is that visual processing occurred, and of course visual processing in the form of perception was already known to occur in all four conditions. However, a high rate of visual confusion errors did not occur in the other conditions. Given the duration of the presentation, there is no reason to expect perceptual errors. The only perceptual error subjects commonly made in reading the letters before testing was reported a U instead of a V, and this error was not considered in the data collection because U is a vowel. Only two errors that did not involve vowels were made in reading, and all errors in reading were corrected before testing.

It seems reasonable to suppose that for the simultaneous presentation with articulatory suppression, the subjects

Table 3
Correlations Between Confusion Matrices

	2	3	4	5	6	7	8	9	10	11
1. Hodges	.57*	.45*	.48*	.47*	.62*	.55*	.36*	.09	.04	.04
2. Gilmore et al.		.52*	.44*	.51*	.69*	.82*	.38*	.12	.14	.14*
3. Pew and Gardner			.49*	.49*	.53*	.62*	.38*	.13	.18*	.18*
4. Fisher et al. set 1				.81*	.60*	.48*	.27*	.07	.11	.04
5. Fisher et al. set 2					.66*	.53*	.29*	.04	.09	.07
6. Van der Heijden et al.						.66*	.42*	.20*	.00	.14
7. Perceptual, same equipment						.89*	.43*	.16*	.16*	.21*
8. Simultaneous with suppression							.47*	.13	.20*	.33*
9. Sequential with suppression								.09	.03	.15
10. Sequential, no suppression									.51*	.28*
11. Simultaneous, no suppression										.12

*$p < .05$.

remembered the letters in a visual store. When the representation of a letter was not degraded, the letter was reported correctly, and when the representation was completely degraded, no letter was reported or the subjects guessed a letter at random. However, when the representation was partially degraded, the subjects based their report on this degraded image and reported either the correct letter or a visually similar letter.

There was no increased proportion of auditory-and-visual confusion errors. There seemed to be no reason for this null result, except to suggest that this set might have contained a few items that in practice were not visually confusable, such as MX and VZ.

Sequential presentation with articulatory suppression. This condition was characterized by no more (or not many more) visual or auditory errors than would be expected by chance. This replicates Conrad's (1972) finding.

Whether there was any pattern to the confusion errors is not clear. A chi-square test of the pattern of errors suggested that they were not distributed randomly [$\chi^2(189) = 272.23$, $p < .001$, $N = 822$], and the confusion errors had reliable correlations with some other confusion matrices. However, the split-half reliability was near zero. If there is a pattern to the errors, this pattern is not easy to characterize. The most common errors were: LP (which occurred 16 times); BP, MP, MR, and RS (11 times); VW (10 times); and BD, KL, and NV (9 times). The confusion errors for this condition and for the simultaneous presentation with articulatory suppression are presented in Table 4.

There are several possible reasons for correlations between the errors in this condition and visual perceptual errors collected in this laboratory and by Van der Heijden et al. (1984). One possibility is that a visual short-term store is used for the sequential presentation with articulatory suppression, but too many random errors occur for use of the visual store to be observed. Another possibility is that visual short-term memory is only sometimes used, either by some subjects or in some serial positions. A third possibility is that the perceptual experiments may include confusion errors based upon use of a nonvisual store. More than visual information can be perceived under difficult viewing conditions (e.g., Marcel, 1983).

Table 4
Confusion Matrices for Simultaneous (Top Right) and Sequential (Bottom Left) Presentations with Articulatory Suppression

Simultaneous

	B	C	D	F	G	H	J	K	L	M	N	P	Q	R	S	T	V	W	X	Z
B		1	3	5	2	2	4	1	0	7	3	7	2	4	5	1	3	3	0	1
C	1		6	3	7	2	4	5	0	0	2	0	5	1	3	2	8	1	3	4
D	9	1		2	3	1	4	4	2	1	7	3	6	3	2	3	6	2	4	2
F	3	4	2		5	6	9	8	5	6	1	6	3	8	9	5	4	2	0	3
G	6	1	1	4		5	3	1	0	2	2	3	10	4	5	1	1	6	3	3
H	3	7	2	2	6		7	4	4	5	10	3	3	5	3	1	1	4	7	3
J	3	4	5	4	4	7		5	1	4	2	1	2	1	0	6	2	0	2	6
K	2	5	1	2	1	3	4		4	5	6	4	7	5	3	1	1	4	7	3
L	6	8	5	4	1	3	3	9		8	4	2	1	5	0	7	2	2	2	3
M	3	5	7	6	4	9	4	2	5		15	6	3	6	1	2	6	18	1	1
N	4	3	5	8	2	6	4	3	8	6		4	1	3	1	0	6	2	4	1
P	11	3	3	2	3	4	4	1	16	11	7		1	8	4	6	1	0	0	3
Q	2	5	2	3	8	3	1	4	2	3	2	3		4	5	1	4	2	3	1
R	6	4	3	7	2	5	1	2	3	11	3	5	4		0	0	1	2	1	1
S	5	6	6	7	2	1	5	4	6	3	4	6	5	11		1	2	0	2	3
T	8	4	2	4	4	6	4	3	2	3	3	2	5	3	6		0	5	0	2
V	5	5	4	4	1	2	7	5	3	3	9	4	1	7	5	3		4	7	1
W	4	1	3	4	1	3	2	8	6	7	6	3	4	5	7	1	10		7	2
X	6	2	1	2	4	7	8	7	5	4	5	4	9	4	1	5	6	7		3
Z	2	3	0	5	3	8	2	2	4	2	7	4	2	3	2	8	7	3	6	

Sequential

It seems inappropriate to conclude that there is absolutely no increase in visual confusion errors in this condition, and hence it seems inappropriate to conclude that no use of visual short-term memory occurs in this condition. It is plausible that some subjects use visual short-term memory, and it is plausible that visual short-term memory is used for some of the serial positions (such as the first).

The question is, what is the predominant method of storing the items in this condition? It is possible that auditory short-term memory, visual short-term memory, or some combination was used in this condition, and for some reason their use could not be detected. However, the most straightforward interpretation of these results is that some nonvisual and nonauditory store retains the items. Further research would be necessary to identify the nature of this store; the pattern of errors found in this experiment gives little clue to its nature.

Sequential presentation with no articulatory suppression. The findings in this condition replicate previous findings (Conrad, 1964; Wickelgren, 1965) of increased auditory confusion errors, suggesting predominant use of auditory short-term memory in this condition.

Simultaneous presentation with no articulatory suppression. This condition was characterized by auditory-and-visual errors. Plausibly, some subjects used auditory short-term memory, some used visual short-term memory, and perhaps some used a combination. Assuming that a sequential presentation without articulatory suppression measures the capacity of auditory short-term memory and a visual simultaneous presentation with articulatory suppression measures the capacity of visual short-term memory, then auditory short-term memory and visual short-term memory have approximately the same averaged capacity (see Table 2). Therefore, there would be no reason for subjects as a group to prefer use of one store over the other. Experiment 1 was sensitive enough only to detect the increase in auditory-and-visual confusion errors (which would tend to occur no matter which of the preceding strategies the subject was using). Evidence indicating use of an auditory store is sometimes found in this paradigm (Shankweiler, Liberman, Mark, Fowler, & Fisher, 1979) and sometimes not (Adams, Thorsheim, & McIntyre, 1969).

Sequential presentation. First, note the pattern of effects for the articulatory suppression, which is usually agreed to eliminate evidence of auditory processing:

(1) An ANOVA showed that articulatory suppression reduced auditory confusion errors. (2) The articulatory suppression also increased visual errors, presumably because of a shift to using visual short-term memory and also because of the reduced percentage of auditory errors. (3) The two conditions with articulatory suppression showed no evidence of increased auditory confusion errors. (4) Articulatory suppression reduced the number of letters that could be recalled.

The sequential presentation had analogous effects: (1) An ANOVA showed that the sequential presentation reduced visual errors (2) The sequential presentation also increased auditory errors, presumably because of a shift to using auditory short-term memory and the reduced percentage of visual errors. (3) Neither condition with a sequential presentation showed any predominance of visual errors. (4) The sequential presentation reduced capacity. These results suggest that a sequential presentation may be as effective or almost as effective in preventing use of visual short-term memory as articulatory suppression is in preventing use of auditory short-term memory.

Simultaneous presentation. It has been noted several times that immediate ordered recall is better for a simultaneous visual presentation than for a sequential visual presentation (Crowder, 1966; Mackworth, 1962; Marcer, 1967). Two reasons for this have been suggested: (1) Having all the stimuli available at the same time provides more opportunity for organizing the stimuli into meaningful chunks (Adams et al., 1969; Marcer, 1967); and (2) the subject can allot attention to the stimuli in the most advantageous fashion (Crowder, 1966). These two factors probably play a role in increasing recall of a simultaneous presentation, but neither would explain why a simultaneous presentation produces more visual confusion errors and fewer auditory confusion errors than a sequential presentation. Apparently, a third factor is involved in improving recall of simultaneous presentations, the use of a visual short-term memory.

EXPERIMENT 2

Experiment 2 compared simultaneous and sequential presentations in a second situation, one for which visual short-term memory might be expected to have a particular effect. The "prefix effect" (discovered by Conrad, 1958) is an impairment in immediate recall produced by emission of a redundant digit immediately before the to-be-recalled items are reported. The impairment is not caused by the delay the prefix creates (Conrad, 1960) and is not caused by the act of retrieval from memory or by the added load on memory (Jahnke & Nowaczyk, 1977). The prefix effect is similar to the stimulus suffix effect, which is an impairment in immediate recall produced by hearing a digit after presentation of the to-be-recalled items. However, the influence of the prefix on the serial position curve is different from the influence of the suffix (Crowder, 1967), suggesting that the prefix effect and the suffix effect have different underlying causes.

It has been suggested that in order to emit a response, a sensory image of that response must be formed (Greenwald, 1970b; James, 1890); in particular, an auditory image must be created for speaking and a visual image must be created for writing (Greenwald, 1970a). Two auditory tasks or two visual tasks tend to interfere with each other more than an auditory task and a visual task would (e.g., Baddeley & Lieberman, 1980; Brooks, 1968, 1970; Proctor, 1978; Rollins & Hendricks, 1980; Segal & Fusella, 1970). Therefore, it is reasonable to suppose that when the to-be-recalled items are stored in auditory short-term memory, speaking the prefix would impair recall more than writing the prefix, whereas when the items are stored in visual short-term memory, writing the prefix would impair recall more than speaking the prefix.

It has already been shown that for presentations that elicit the use of auditory short-term memory, a spoken prefix impairs performance more than a written prefix (Lowe & Merikle, 1970); in fact, a written prefix sometimes creates no detectable impairment (Morton & Holloway, 1970). The question is whether the opposite effect occurs in visual short-term memory, and if so, which type of presentation (simultaneous or sequential) might produce the effect.

Therefore, in Experiment 2 the effects of written and spoken prefixes were tested for simultaneous and sequential visual presentations (of digits), both with articulatory suppression. A presentation rate of 550 msec per digit seemed optimal (subjectively) for eliciting use of visual short-term memory in the sequential presentation; the same rate (per digit) was used for the simultaneous presentation. An auditory presentation was also tested. The auditory presentation of digits was as fast as the stimuli would permit, 450 msec per digit, because a fast auditory presentation tends to elicit passive use of auditory short-term memory (Hockey, 1973). When subjects spoke the prefix, they also spoke the digits to be recalled, and when they wrote the prefix, they also wrote the digits to be recalled. The method suggested by Woodworth and Schlosberg (1954, p. 697) was used to measure digit capacity.

Method

Subjects. Eighty-four students from introductory psychology classes at the University of Washington voluntarily participated in order to earn extra credit. English was their first language.

Design. Thirty-two subjects received auditory presentations, 24 subjects received sequential visual presentations, and 28 subjects received simultaneous visual presentations.

Each subject was tested twice with a prefix, once with a spoken response, and once with a written response. In addition, the subjects were first tested without a prefix, in order to provide familiarity with the testing procedures and to determine the number of digits with which to begin subsequent testing. The response for this initial test was either spoken or written, counterbalanced for order across subjects.

Stimuli. The digits 0 to 9 were presented by computer. The auditory digits had been previously recorded and stored in the computer by an analog-to-digital conversion, and were presented by a digital-to-analog conversion that was amplified and played through a speaker. The actual spoken duration of the individual auditory digits ranged from 210 to 440 msec. A pause was inserted between digits during presentation so that the time from the middle of one digit to the middle of the next was 450 msec.

The visual stimuli were presented on a cathode ray tube. For the simultaneous presentation all digits were presented horizontally in the center of the screen for 550 msec times the number of digits in the string. For the sequential presentation, each digit was presented on the screen for 550 msec. Each digit was presented in the same location it would have been in had the presentation been simultaneous.

The digits in a string were generated randomly, with several constraints: (1) If the first digit was less than 5, the second digit was greater than or equal to 5, and vice versa; (2) although digits could recur within a string, the recurrences were separated by at least two other digits; (3) a digit could not differ from the preceding digit by 1; and (4) two adjacent differences between digits could not be equal, that is, such sequences as 579 or 852 never occurred.

The prefix 2 was chosen because saying "two" and writing "2" seemed to create approximately the same delay.

Measuring digit capacity. Testing without a prefix began at a level of five digits (per trial) in the auditory condition, four digits in the visual simultaneous condition, and three digits in the visual sequential condition. For the two experimental conditions, testing began at the highest level of the initial test on which the subject (1) had made no errors and (2) had not previously made more than one error. If this new level was greater than the subject's baseline digit capacity minus ⅔, 1 was subtracted from it.

Subjects were tested three times at each level, except when the first two trials were correct the third trial was presumed correct and not tested. After three trials, the length of the string was incremented by one digit. Testing was stopped when the subject missed all three trials at a level or when the subject recalled only one of three trials at a level for two successive levels.

A response was correct when all the digits were recalled in the correct order. Digit capacity was defined as the number of trials correct plus the trials presumed to be correct (the third trial when the first two were correct and trials at string lengths shorter than the initial starting level), divided by 3.

Procedure. The subjects were tested individually. The general procedure was explained to each subject at the start of the experiment, and each condition was described before that condition was begun.

A trial began with a 5-sec message on the screen indicating how many digits would be presented. Then the word "ready" appeared on the screen for 3 sec. This was followed by a dot that appeared half-way down on the left side of the screen for 1 sec and then the digit presentation. In the auditory condition, the subjects sat quietly during presentation. In the visual conditions, the subjects began repeating "A, B, C, D" when the message indicating the length of the string appeared. The subject continued with this repetition until the presentation was finished. When the presentation was over, the subject either wrote or spoke the response.

In the prefix conditions, the subject either said "two" before saying the answer or wrote "2" before writing the answer. The subject had to emit the prefix immediately after the digits were presented. A spoken response could not be reported in groups, that is, the subject could not say "fifteen" instead of "one, five." After writing the response, the subject reported it to the experimenter, and the experimenter recorded whether or not the subject was correct. Then there was an approximately 10-sec pause before a new trial was begun. If there were any irregularities in the trial, the trial was repeated.

The subjects were encouraged to report if they forgot to write the prefix during the experiment, in which case the trial was repeated. After the experiment, the subjects were asked if they had ever failed to write the prefix before the answer; also the answer sheet was checked to verify that a "2" had been written. The results from seven subjects were discarded after testing because the prefix had not been written before the answer.

Table 5
Average Digit Capacity in Experiment 2

	Initial	Prefix	
	Test	Written	Spoken
Auditory presentation	6.3	6.2	5.7
Visual, sequential presentation	4.1	3.9	4.0
Visual, simultaneous presentation	6.6	5.8	6.3

Results and Discussion

Analyses of the prefix conditions. Table 5 presents the average scores for the written and spoken response with prefixes in each condition. For the auditory presentation, the spoken prefix impaired recall .57 digits more than the written prefix [$t(31)=4.02$, $p < .001$], confirming previous findings (Lowe & Merikle, 1970). For the visual simultaneous presentation, the written prefix impaired recall .55 digits more than the spoken prefix [$t(27) = 4.71$, $p < .001$], suggesting modality-specific interference in the prefix effect. For the sequential visual presentation, the difference between the spoken prefix and the written prefix (.09 digit) was not significant [$t(23) = .64$].

Therefore, a result that might be expected for visual short-term memory (modality-specific interference in the prefix effect) was demonstrated for a simultaneous presentation with articulatory suppression but not for a sequential presentation with articulatory suppression.

Analyses of the initial test of capacity. The initial test of digit capacity in this experiment replicated three of the conditions in Experiment 1. (An auditory presentation, like a sequential presentation without articulatory suppression, presumably elicits use of auditory short-term memory.) Digits were tested instead of letters, and many details were varied, such as the procedure for varying string length. The initial test had either a written or a spoken response. Because there was no main effect for type of response [$F(1,78) = 2.45$, $p > .10$] and no interaction between type of response and condition ($F < 1$), results from the two different types of responses were combined.

The average capacities, included in Table 5, follow the same pattern found in Experiment 1: The average capacity for the simultaneous presentation suppression and the average capacity for the auditory presentation without articulatory suppression did not differ statistically [$t(58) = 1.11$]; with articulatory suppression, the capacity for the sequential visual presentation (4.1) was 2.5 digits less than the capacity for the simultaneous visual presentation [$t(50) = 10.32$, $p < .001$].

The most common confusion errors for the auditory presentation were 59 (23 times), 08 (13 times), and 04, 17, and 68 (12 times). The 0 was spoken as "oh.") The most common errors for the visual simultaneous presentation were 69 (14 times), 49 (13 times), 28 (11 times), and 24, 79, and 25 (10 times). The most common errors for the visual sequential presentation were 24 (15 times), 36 (12 times), and 23, 26, 38, and 46 (11 times).

GENERAL DISCUSSION

To summarize, Experiment 1 tested the immediate recall of letters. When subjects engaged in articulatory suppression and the letters were presented simultaneously, more visual confusion errors occurred in recall than would be expected by chance. For a sequential presentation with articulatory suppression, the proportion of visual errors was not significantly greater than would be expected by chance. Experiment 2 again tested visual presentations with articulatory suppression and immediate ordered recall. For the simultaneous presentation, recall was lower in the written prefix condition than in the spoken condition, a result that might be expected if visual short-term memory was being used. In the sequential presentation, there was no difference between the written prefix condition and the spoken prefix condition.

Thus, in two different experiments, the results suggested that a simultaneous presentation (with articulatory suppression) elicited use of visual short-term memory, but that a sequential presentation (even with articulatory suppression) did not.

Previous Research

There are several examples of previous studies in which, comparing across experiments, the results of a sequential presentation did not indicate the use of visual short-term memory, whereas the results of a simultaneous presentation did.

(1) For immediate recall of spatial information using a sequential presentation, there is either no evidence of direct spatial recall (Murdock, 1969; Healy, 1975b) or there is evidence of spatial recall which involves temporal factors (Healy, 1975a, 1977). Using a simultaneous presentation, Snodgrass and Antone (1974) found better recognition for spatial order than for temporal order.

(2) For a spatial array of numbers, the stimuli on the edges might be expected to be recalled more accurately than the other stimuli, analogous to better recall of the temporal boundaries of an auditory presentation (primacy and recency). Using a sequential presentation, this effect did not occur (Healy, 1975b), or it was small or only marginally significant (Healy, 1975a). For a simultaneous presentation, this effect did occur (M. J. Peterson, 1975).

(3) Immediate recall could presumably be increased by storing some digits in auditory short-term memory and some in visual short-term memory. Using a sequential presentation, no large increases in recall have been found (Murdock & Carey, 1972; Murdock & Walker, 1969); the small increases that are found could be attributed to the fact that presenting stimuli in two modalities groups the stimuli, which improves recall (Ryan, 1969). Using a simultaneous presentation, recall can be increased (Frick, 1984). In a pilot experiment to that study, I tested both sequential and simultaneous visual presentations (of the to-be-remembered visual stimuli). Compared with a control group in which the items were also grouped, recall was higher for the simultaneous presentation but not for the sequential presentation.

Style of presentation does not completely determine whether or not visual short-term memory is used: Some experiments using sequential presentations have shown evidence of visual processing (e.g., O'Conner & Hermelin, 1972). However, a simultaneous presentation appears to be important for eliciting use of visual short-term memory. A sequential presentation may not always elicit use of visual short-term memory; when it does, it might not allow for the full use of visual short-term memory. Other conclusions about visual processing based upon a sequential presentation deserve to be reconsidered [e.g., the conclusion that presenting pictorial forms does not lead to superior recall of spatial relationships (Anderson, 1976), and the conclusion that concurrent visual and auditory presentations cannot be retained (Dornbush, 1968)].

Sequential Presentation with Articulatory Suppression

It is possible that the failure to find an increase in visual errors in the sequential presentation with articulatory suppression was the result of a lack of statistical power, an inappropriate definition of visual errors, or some methodological error. Similarly, the lack of a difference between the written prefix condition and the spoken prefix condition in Experiment 2 might have resulted from a lack of statistical power, methodological errors, or errors in the assumptions that predicted a difference between writing and speaking. However, both of these effects were fairly robust for the simultaneous presentation with articulatory suppression, suggesting that the assumptions were correct and the procedures powerful enough to reveal use of visual short-term memory. These two experiments and previous research converge upon the explanation that sequential presentation is not very successful in eliciting use of a visual short-term store.

It is possible that sequential presentation is stored visually and that this visual store, unlike the visual store elicited by simultaneous presentations, does not produce visual confusion errors. The results of Experiment 2 suggest that this store also is not impaired by writing. If studies using a sequential presentation of only three items (Kroll, Kellicut, & Parks, 1975; O'Conner & Hermelin, 1972) are ignored, it appears that this store does not retain spatial information (e.g., Healy, 1975b; Murdock, 1969). The only existing reason for calling this store visual is that it is elicited by a visual presentation.

In Experiment 1, the items were all presented in the same location. There is a slight advantage for the presentation of each item of a sequential presentation in a different location (Parkinson, Kroll, & Parks, 1973), suggesting the possibility of some sort of visual interference (analogous to masking iconic memory) when the items are presented in the same location. However, in the sequential presentation of Experiment 2, the items were presented in various locations, and a large impairment in capacity occurred nonetheless. Therefore, presenting the items in the same location does not seem to be the primary reason that visual short-term memory is not used to remember sequential presentations.

If subjects could not remember a sequential presentation as such, why didn't they integrate the sequential presentation into a visual image equivalent to a simultaneous presentation (as in L. R. Peterson, Rawlings, & Cohen, 1977, or M. J. Peterson, 1975)? One possibility is that the strategy did not occur to the subjects. Because type of presentation was manipulated between subjects, subjects viewing a sequential presentation never viewed a simultaneous presentation. In an experiment that manipulated sequential and simultaneous presentation within subjects (Kroll et al., 1975), there was little difference between the two types of presentation, suggesting that the subjects might have formed an integrated image of the sequential presentation. However, in that experiment, because only three digits were presented, subjects did not have a difficult visual image to construct. Two other possible reasons for why subjects did not construct a visual image equivalent to that elicited by simultaneous presentation are that constructing an image might be too effortful or that the task of perceiving each new item might interfere with a visual image of the previous items. Providing some evidence for the latter possibility is Fisher and Karsh's (1971) finding that an auditory presentation was better than a visual sequential presentation in performing a task involving spatial processing of the stimuli.

Visual Short-Term Memory

Research by Phillips and his associates (Avons & Phillips, 1980; Christie & Phillips, 1979; Phillips, 1974; Phillips & Christie, 1977a, 1977b), using complex visual displays, has suggested the existence of a visual short-term memory that is distinguished from iconic memory by lasting longer, being less complete, not being maskable, and not being tied to a specific spatial location. In a sequence of displays, this visual short-term memory is restricted to the last display presented. Similarly, amnesics are not impaired on the immediate recognition of a single complex visual display (Warrington & Baddeley, 1974), but are impaired on immediate recognition of all but the last of several complex visual displays (Warrington & Taylor, 1973). One explanation of these results is that two or more displays contain too much information to be retained in visual short-term memory, and hence, only the last display is retained. However, in the present experiment, although the sequential presentation did not hold any more information than the simultaneous presentation, the sequential presentation apparently was not retained in visual short-term memory. Therefore, several lines of research point to the existence of a visual short-term memory that stores only one picture. In very brief simultaneous presentations, the limit to whole report also appears to be a limited-capacity visual store (cf. Bongartz & Scheerer, 1976), which plausibly is the same store as that elicited by simultaneous presentation with articulatory suppression or by a complex visual display.

A plausible reason for why visual short-term memory would not be used for immediate recall of a sequential presentation involves the basic nature of visual short-term memory. A sequential presentation represents the order of the items temporally, whereas a simultaneous presentation represents the order of the items spatially. One advantage to postulating separate auditory and visual short-term memories is that they can have different properties—in this case, that auditory short-term memory retains temporal order and visual short-term memory retains spatial order. Numerous theories have associated visual and spatial processing (e.g., Baddeley, 1981; L. R. Peterson et al., 1977; Paivio & Csapo, 1969). Baddeley (1981) incorporates this notion by calling visual short-term memory a "scratch pad" upon which information can be written: A scratch pad contains spatial information but no temporal information.

Conclusion

The most straightforward interpretation of these results is that there is a visual short-term memory that naturally retains simultaneous presentations but does not naturally retain sequential presentations. This is consistent with the hypothesis of a visual short-term memory that represents spatial order and has a capacity of one "picture." Methodologically, a simultaneous presentation with articulatory suppression can be used to test visual short-term memory for recallable verbal stimuli. On the other hand, a sequential presentation does not necessarily elicit use of visual short-term memory and, in any case, probably does not lead to optimal use of visual short-term memory.

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