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Human Factors: The Journal of the Human Factors and Ergonomics Society 1988 30: 617
DOI: 10.1177/001872088803000506

HUMAN FACTORS, 1988, 30(5), 617–632

Multiple Resources for Processing and Storage in Short-Term Working Memory

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A frequent assumption in cognitive psychology is that performance in decision making and planning is severely restricted by the limited capacity of short-term working memory. Many predictions of this theory have not been supported, possibly because working memory may be composed of multiple resources rather than a single resource. The present experiments study two tasks, both involving memory for digits. Although these tasks can employ the same modality for input and for responding, they appear to differ in their demands for working memory resources. Specifically, the tasks appear to differ in resources required for processing at input, and they also differ in resources in the sense of storage capacity. The results support a version of multiple-resource theory applied to working memory in which resource composition depends on internal mediators even when stimulus and response modality are held constant.

INTRODUCTION

Recent cognitive models have included "a system for the temporary holding and manipulation of information during the performance of a range of cognitive tasks such as comprehension, learning, and reasoning" (Baddeley, 1986, p. 34). This system, often called "working memory," was described in introspective psychology. For example, Huey (1908, p. 148) held that in order for one to understand language, the individual words must "hang suspended" in immediate memory so that "the attention may wander backward and forward to get a fuller meaning." This suggests that any limit in working memory should be reflected in limits in comprehension, reasoning, decision making, and planning. For these reasons the study of working memory is beginning to appear in the field of human factors (e.g., Kantowitz and Sorkin, 1983, p. 170; Klapp, 1987; Wickens, 1984, p. 218).

Multiple-resource theory (e.g., see Navon and Gopher, 1979; Wickens, Sandry, and Vidulich, 1983) has been successful in describing performance in several dual-task situations. The present experiments extend aspects of this theory to handle dual tasks involving working memory. We emphasize one prediction of multiple-resource theory: that if two tasks use the same resource, they will interfere with each other, but if the two tasks use different resources, there will be little or no interference. The term "resources" is used here only in this very limited sense because other ways in which the term has been used will not be supported by our data.

When resource theory is applied to work-

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ing memory, two bases for resource distinction can be identified: memory tasks may use the same or different resources (1) for processing (e.g., input coding) and/or (2) for storage. A rough analogy to a parallel-configured computer may make this distinction clearer. Two tasks may use the same or different central processing units, and they may use the same or different memory locations for storage. Experiments 1 and 2 deal with the processing aspect of resource independence and involve interference between concurrent active processing for two tasks. By contrast, Experiments 3 and 4 involve interference between material passively stored in memory and concurrent tasks. Because Experiments 3 and 4 involved potential competition for memory storage space rather than for active energy-demanding processes, an energy metaphor for "resources" is not appropriate for understanding these experiments.

Although there may be several ways in which resources for processing and storage in working memory might be segregated (Klapp, 1987), the specific distinction considered in the present experiments is between auditory/verbal and visual/spatial resources. We are not the first to propose this distinction in short-term working memory (see Baddeley and Lieberman, 1980; Frick, 1984, 1985; Kroll, Kellicut, and Parks, 1975; Saltzberg, Parks, Kroll, and Parkinson, 1971). However, our study extends the previous research by considering both processing and storage aspects of this distinction and by attempting to manipulate resource composition without varying input or output modality.

The experiments reported here compared the amount of interference when two reference tasks, called probe digit (PD) and missing digit (MD), were carried out concurrently with several distracting tasks. Although PD and MD both involved presentation of eight digits in random sequence (in the same modality) and both involved a single-digit output response, there was reason to suppose that they might emphasize different resources (Klapp, Marshburn, and Lester, 1983). The MD task, originally known as "missing scan" (Buschke, 1963), requires that the subject identify which of the nine possible digits (from the population 1–9) had *not* been presented in the original eight-digit sequence. In contrast, the PD task was tested by presentation of one of the eight digits as a "probe" to which the subject responded with the digit that had followed the probe in the original sequence.

Whereas the PD task requires that subjects remember the digits in order, the MD task requires only that the items be retained (without reference to order). The strategy of our experiments is to determine the sensitivity of PD and MD to distraction from various concurrent tasks. One might suppose that MD (not requiring order information) would in general be less disrupted by any concurrent task than would PD (requiring order information). This turns out not to be the case (see especially Experiment 2). Rather than differing in global difficulty or sensitivity to interference, the two tasks appear to differ in terms of the underlying strategies and resources involved.

The effects of two types of additional tasks on PD and MD will be investigated. For Experiments 1 and 2, these tasks were concurrent with the input of the memory digits, and inferences will be drawn concerning processing resources. By contrast, Experiments 3 and 4 did not involve concurrent processing demands. Rather, they used a memory-loading paradigm (Baddeley and Hitch, 1974; Klapp et al., 1983). In these experiments the PD and MD tasks were completed during the retention interval of another memory task such that one component of storage was loaded when the PD or MD task was undertaken. If PD uses auditory-verbal storage but

MD uses visual-spatial storage, then a verbal-auditory memory load should disrupt PD more than MD. Conversely, a visual-spatial memory load should disrupt MD more than PD.

EXPERIMENT 1

Previous research has shown that irrelevant vocalization (such as saying "la la") reduces performance on immediate ordered recall of verbal items such as digits (Crowder, 1978; Levy, 1971). While replicating this result Klapp et al. (1983) also showed that MD was not susceptible to this form of interference. From the perspective of multiple-resource theory, the vocalization of "la la" and the ordered recall task competed for the same limited resource, but irrelevant vocalization and MD did not. However, there are several alternative interpretations of these findings. For example, perhaps the difference is that ordered recall requires production of several digits at recall and is therefore more sensitive to any form of interference than MD, which requires only a single-digit response. That is the reason for comparing PD and MD—both of which require only a single-digit response —in the present experiments. In particular, Experiment 1 tested the effect of irrelevant vocalization on PD and MD.

Method

Subjects. The eight subjects were native speakers of English and students in introductory psychology at California State University, Hayward, who participated in this option of a course requirement. One subject was replaced because she did not say "la" fast enough to keep up with the digit display.

Overview. In all conditions subjects viewed a list of eight sequentially presented single digits and then immediately made a single key-press response. For each trial the digits were selected from the set 1–9, with one digit omitted. The remaining digits appeared in random order. Subjects were instructed to pronounce the digits aloud as they appeared in the *relevant vocalization* condition, or to pronounce the syllable "la" aloud as each digit appeared in the *irrelevant vocalization* condition.

Design. Each subject was tested in all four conditions (irrelevant and relevant vocalization crossed with PD and MD tasks) with the order of testing balanced across subjects. Testing occurred in two 50-minute sessions, each comprising one task under two conditions of vocalization. Each condition consisted of nine unscored practice trials followed by 36 scored trials presented as two sets of 18 trials with a rest interval between sets.

Each of the nine digits was omitted equally often in each set of nine trials. The order of the remaining digits was independently randomized for each trial. For the PD condition the digit that had appeared in each of the first seven serial positions was used as the probe once in every nine trials, and in addition the third and fifth positions were used a second time. (The last digit presented cannot be a probe because it has no successor.) The order in which the positions were used within a block of nine trials was random.

Apparatus. The subject and experimenter were in individual sound-isolation chambers (Industrial Acoustics 400 A). The experiment was controlled by a microcomputer, and all alphanumerical stimuli were displayed on a monitor at a visual angle of 0.6 deg. Subjects responded by pressing one of nine numbered switches placed just below the monitor in a horizontal array with 3.25 cm spacing.

Trial event sequence. Each trial began with the 1-s display "GET READY" followed by a 250-ms blank interval. The eight digits then appeared one at a time in the same display location. Each digit appeared for 150 ms, with a blank interval between digits of 50 ms, except that after the third and sixth digits this interval was increased to 350 ms. The longer pause produced temporal grouping, known to increase performance relative to ungrouped presentation (e.g., Klapp et al., 1983; Ryan, 1969).

Immediately after the last digit, the response prompt appeared and remained until the subject responded. For MD the prompt was the symbol "#?." For PD the prompt was the probe digit followed by a question mark. After the subject responded, the correct answer was displayed for 5 s. If no response occurred within 5 s, the prompt was replaced with "NO RESPONSE."

Results

The number of correct responses was determined for each subject in each of the four conditions. The proportion of correct responses averaged across subjects appears in Table 1. Overall performance was better on MD than on PD, $F(1,7) = 83.3, p < 0.001$, and irrelevant vocalization reduced performance compared with relevant vocalization, $F(1,7) = 20.0, p < 0.001$. Of critical importance for our analysis, vocalization interacted with task, $F(1,7) = 22.01, p < 0.005$, such that irrelevant vocalization depressed performance on PD more than on MD. Whereas irrelevant vocalization depressed performance significantly on PD, $F(1,7) = 27.6, p < 0.001$, an effect that held for all eight subjects, it had only a small and nonsignificant effect on MD, $F(1,7) = 3.1, p > 0.1$.

TABLE 1

Proportion Correct for Experiment 1

Task	Vocalization Condition		Decrement
	Relevant	La La	
MD	0.82	0.75	0.07
PD	0.73	0.38	0.35

Discussion

This interaction corresponds to the previous reports (Klapp et al., 1983, Experiments 4 and 5). Throughout these experiments there is little or no effect on irrelevant vocalization on MD performance, but there is a larger and significant effect of the comparison task, ordered recall, or PD. The present experiment shows that this interaction is not attributable to a difference in the number of digits in the response.

These findings also tend to rule out one possible (but unlikely) strategy for the MD task. In principle subjects could avoid using memory by adding the digits and then subtracting the sum from 45. We have not encountered reports of this strategy; furthermore, the irrelevant vocalization should have interfered with MD performance if this strategy were used.

A plausible interpretation is that irrelevant vocalization interferes with PD processing because this requires the same resource that is used for vocalization. By contrast, processing for the MD task may use less or none of this resource. What resource is involved? Two possible interpretations of interference arising from irrelevant vocalization are that (1) articulatory processes are needed, so that irrelevant articulation is interfering (e.g., see Baddeley, 1978), or (2) auditory resources are needed, so that production of irrelevant sound is interfering.

Considerable recent evidence favors the auditory interpretation. First, the effect of irrelevant articulation can be eliminated if the articulation is unvoiced (e.g., the subject mouths "la la") and the memory items are presented in both auditory and visual form (Klapp, Greim, and Marshburn, 1981, Experiment 2). Second, recall is better with auditory input than with unvoiced articulation of the visually presented items, and no better with both auditory and articulatory input than with auditory presentation in the absence of articulation (Klapp et al., 1983, Experiment 1). Third, presentation of irrelevant auditory speech disrupts immediate memory (Colle and Welsh, 1976; Salame and Baddeley, 1982). And finally, the phonological similarity effect (Conrad and Hull, 1964) shows that sets of target items with phonemic features in common are less well recalled than sets with distinctive phonemic features. This effect occurs even with irrelevant unvoiced articulation accompanied by relevant auditory input (Baddeley, Lewis, and Vallar, 1984) and in patients who are unable to speak (Baddeley and Wilson, 1985).

We conclude that PD involves auditory resources but that MD may not. An alternative interpretation of the lack of disruption of MD by irrelevant vocalization would be that this task is not sensitive to disruption by any concurrent task. Experiment 2 tests that possibility by examining the effect of a different concurrent task on both MD and PD.

EXPERIMENT 2

Experiment 2 again compared the effect of concurrent distractors on PD and MD, but the distractor was spatial tracking rather than vocalization. Because of this shift in distractor, Experiment 2 was a "mirror image" of Experiment 1 in that the digits were presented in the auditory modality and the distraction in the visual modality. One possible interpretation of Experiment 1 is that PD involves an auditory representation and MD a visual-spatial representation. This predicts that the result of Experiment 2 should be an interaction in the opposite sense of that observed in Experiment 1. Whereas auditory distraction had more effect on PD than on MD in Experiment 1, spatial distraction should have more effect on MD than on PD in Experiment 2.

Method

Subjects. The 16 subjects were drawn from the same population as in Experiment 1, except that all were right-handed males.

Design. Alternate subjects were assigned to the MD and PD memory tasks as they reported for the experiment. Each subject was tested on the memory task with and without the spatial distractor task. Half of the subjects in each group received the dual-task condition first, followed by the control single-task condition. The remaining subjects were tested in the reverse order. Each of these conditions was presented as a 24-trial block, the first 6 trials of which were unscored practice trials. For the 18 scored trials in each block, each possible digit (1–9) was selected twice as the omitted digit.

Spatial distractor. This task was implemented on an Apple II microcomputer. Using his left hand, the subject was to move the handle of a switching joystick (Wico Model 15-9714) forward, back, right, or left through a distance of 2 cm. The handle was constrained to move only in these four directions by a cross-shaped template added to the commercial joystick assembly. One movement occurred as each of the eight digits was spoken by the experimenter.

The symbol guiding the movement moved up, down, right, or left through a distance of 2 cm on a CRT display located approximately 50 cm from the subject's eye (angle of movement was approximately 2 deg). On half of the trials the subject was to move in the direction 90 deg clockwise from that displayed. Thus when the symbol moved up, the subject moved to the right, and when the symbol moved left, the subject moved back. On the remaining trials the rotation was counterclockwise. Each rotation condition appeared as a block of six trials. These blocks alternated between rotation directions, with the order balanced across subjects. The program evaluated the joystick position approximately 400 ms after the movement and provided auditory feedback tones for correct and incorrect responses. After each trial (set of eight movements), the number of correct and incorrect movements was displayed.

Before the memory task was introduced, subjects practiced the distractor task alone. They had to reach a criterion of six out of eight correct movements on three consecutive trials. Practice ended when the criterion was met or after 36 trials, whichever occurred first. Separate practice procedures were given for clockwise and counterclockwise tasks, and the subject had to meet the criterion on each. All subjects qualified. A strategy of imagining a counterclockwise or clockwise continuous rotation was suggested as a way to assist in determining the correct response.

The distractor display served to time the spoken presentation of the memory digits by the experimenter. Thus the digits and the spatial stimuli appeared at a rate of 1.5 s per item, except that an additional 1.5-s pause occurred after the third and sixth items in order to provide grouping. The tones for the distractor appeared (at random) in the control (no distractor) condition so as to equate the conditions regarding nonmemory auditory input. However, the subject did not see or respond to the distractor display in the control condition.

TABLE 2

Proportion Correct for Experiment 2

Task	Spatial Distraction: Control	Spatial Distraction: Distracted	Decrement
MD	0.87	0.42	0.45
PD	0.71	0.39	0.32

Results

Performance on the memory task appears in Table 2. Note first that performance in the control conditions was comparable to performance in the control conditions of Experiment 1. This is expected because there were no substantive changes in the procedure for those conditions. The decrement—control performance minus distracted performance —was greater for MD than for PD, as confirmed by the significant Task × Distraction interaction, $F(1,14) = 5.81, p < 0.05$. This interaction is opposite in sense to the corresponding interaction of Experiment 1. Whereas auditory distraction had a greater effect on PD than on MD (Experiment 1), the visual-spatial distractor had a greater effect on MD than on PD (Experiment 2). However, in Experiment 2, the decrement resulting from distraction was significant for both the MD task, $F(1,7) = 112.45, p < 0.001$, and the PD task, $F(1,7) = 86.1, p < 0.001$. For each task, all eight subjects performed worse in the distracted condition.

Performance on the distractor task was 73% when the distractor was accompanied by MD and 80% when accompanied by PD. Although this difference was nonsignificant, $F(1,14) = 2.1, p = 0.16$, the trend corresponded to the significant interaction in the memory data. Thus the finding that the distractor disrupted MD more than PD (Table 2) cannot be attributed to more emphasis being placed on the distractor when the memory task was MD rather than PD.

Discussion

One model that would account for the results of Experiment 1 may be rejected by these findings. The rejected model assumes that PD involves retention of both order and item information but that MD requires only item information. Although the item-order distinction has been useful in understanding other data (Healy, 1982), it does not handle the present data. The assumption that PD requires more information (order plus item) than MD (item only) predicts that any distractor should disrupt PD as much as or more than it disrupts MD. Contrary to this prediction, Experiment 2 indicated that the spatial task disrupted MD more than PD.

Another potential interpretation of the disruption of MD by the spatial distractor is that subjects keep track of the digits as they appear by representing each digit as the movement of one finger—an external motor strategy that would be disrupted by the distractor because of the motor action required. This possibility seems remote because seven of the eight subjects in the MD group specifically denied use of the finger strategy and only one vaguely indicated attempting it.

A model that is consistent with the results of both Experiments 1 and 2 holds that PD is primarily auditory and MD is primarily spatial. The concurrent auditory distractor (Experiment 1) disrupted the auditory input processing for PD, and the concurrent spatial distractor (Experiment 2) disrupted spatial input processing for MD. The spatial interpretation of MD corresponds to the introspective reports of some subjects that, for MD, digits were checked off in a visually imaged array during input. If PD involves an auditory strategy and MD a spatial strategy, then the results of Experiments 1 and 2 could mean either that (1) these strategies are fixed, leading to interference between corresponding tasks (both auditory or both spatial), or (2) subjects change the strategy for the digit task to a less optimum modality when confronted with a concurrent task in the preferred modality.

EXPERIMENT 3

Experiments 1 and 2 involved performing the PD and MD tasks during concurrent active processing of the auditory or spatial distractor. By contrast, Experiments 3 and 4 represented a variation of the memory-loading paradigm developed by Baddeley and Hitch (1974). Passive retention of a memory "load," rather than active processing of another task, was required concurrently with the PD and MD tasks. For Experiment 3 the memory load was a set of visually presented letters to be recalled in order. The MD or PD task occurred while the load was retained. Thus the entire digit task occurred during the retention interval for the letter task. For these memory-loading experiments, independent groups of subjects were assigned to the PD and MD tasks in order to prevent possible problems with differential transfer that can occur when subjects are required to transfer between tasks.

Because ordered recall is easily disrupted by auditory interference (Klapp et al., 1983, Experiments 4 and 5), we assume that the letter load task uses the auditory system. If the MD task involves a storage system that is independent from the auditory system, then the concurrent load should not interfere with MD, and the MD task should not interfere with the concurrent load. In contrast, mutual interference is predicted between the concurrent load and the PD task, as both are assumed to use the same auditory storage system.

A critical feature of this experiment was a delay provided between input of the load letters and presentation of the embedded digit task. This delay was used because subjects tend to rehearse early, but not later, in a retention interval (Dillon and Reid, 1969; Kroll et al., 1975; Stanners, Meunier, and Headley, 1969). If the embedded task was presented immediately after the letters, interference could occur between letter rehearsal and the digit task. This is undesirable because we want to test interference between passive retention of the letters and the digit task rather than between concurrent active processing of the two tasks (which was investigated in Experiments 1 and 2). The role of a delay in eliminating interference arising from active rehearsal was previously demonstrated (Klapp et al., 1983), and a classification of memory-loading research based on whether such a delay was employed appears in a recent review (Klapp, 1987).

Method

Subjects. The 24 subjects were selected from the same population as in the other experiments. Six subjects were rejected for failing to meet the performance criterion on the practice day and one was rejected who was unable or unwilling to perform a concurrent memory task.

Design. The apparatus was the same as in Experiment 1. Letter recall for the memory load was tested with PD, MD, and control digit tasks in the retention interval. For the control digit task, the same digit was presented eight times and the subject responded by pressing the corresponding switch. Performance on MD or PD was tested with the letter memory load and with a control letter load task involving memory for one letter.

Independent groups of 12 subjects each were tested with MD or PD tasks. Within each group half of the subjects were instructed to give emphasis and priority to the letter load task and half to the embedded digit task. (One subject was misinstructed.) Subjects were alternated through these groups as they reported for the experiment.

Each subject was tested in three conditions: (1) both tasks present, (2) load letter task with control digit task, and (3) digit task with control load task. The order of these conditions was balanced across subjects. Each subject participated in four sessions on separate days, with one session for practice and subject selection and three sessions for the three test conditions. Each scored session involved 18 unscored warm-up trials and 36 scored trials. Rest intervals occurred after each set of 18 trials.

On the practice day subjects first practiced the task to be emphasized for nine trials, ignoring the other task. Then the other task was practiced alone. When the load task was practiced, a set of nine trials was repeated until the criterion of at least six out of nine correct recalls was achieved. If this had not occurred by the third set of trials, the subject was dismissed.

Loading task. For each trial the six letters to be presented were selected randomly without replacement and then randomly ordered from the following seven possibilities: G, M, F, H, K, L, and R. The letters each appeared for 150 ms followed by a 100-ms blank interstimulus interval, except that after the third letter this interval was increased to 350 ms so as to group the letters into two sets of three.

Subjects were to pronounce the letters aloud as they appeared and then to rehearse by overt pronunciation during a 5-s interval. At the signal "STOP REHEARSAL" they were to complete the current rehearsal and then remain silent. This rehearsal interval, followed by a delay, was provided because we wanted to allow subjects to finish their overt rehearsals before introducing the digit task.

After completion of the digit task, the display "LETTERS (?)" signaled the subject to recall the letters aloud in order. Scoring was dichotomous—the recall was either correct (all letters in correct order) or incorrect. The correct string of letters was displayed at the end of each trial.

For the control letter load task the events were similar to those just described for the "real" load task, except that a single letter was repeated six times (rather than six different letters). Subjects were to pronounce the letter as it appeared, "rehearse" it during the rehearsal interval as in the "real" task, and pronounce it six times at the recall command.

Digit tasks. Eight digits were presented in random order, as in Experiment 1. After presentation of the final digit, the probe stimulus (digit followed by question mark) or the missing digit inquiry ("#" followed by question mark) appeared and a reaction-time (RT) clock was started. The subject responded by pressing one of the nine switches, stopping the RT clock. Subjects were not permitted to vocalize during the digit task, in contrast to the required vocalization during presentation of the load letters. This eliminated overt auditory interference between the digits and the memory representation of the letters. At the end of the trial (after the letters were recalled), the correct digit was displayed.

Results

Load task. As expected, performance on initial rehearsal of the letters was both high (93%) and independent of the nature of the digit task that followed, with all F ratios less than unity. The measure of performance on the letter task in Table 3 is the percentage of trials with correct initial rehearsal for which the final recall was also totally correct. This reflects loss of the letters during the digit task. The two groups of subjects (MD and PD) achieved nearly identical performance on the letters with the control digit task in the retention interval, showing that they were reasonably well equated. However, the groups differed markedly on letter retention with noncontrol digit tasks in the retention interval, with far worse performance on the letters with the concurrent PD task than with the concurrent MD task, $F(1,22) = 10.6$, $p < 0.005$.

These data may also be analyzed in terms of the dual-task decrement in letter retention. Letter retention was degraded for real compared with control PD tasks for 11 out of 12 subjects ($p < 0.003$, sign test). In contrast, for the MD embedded task, letter performance was degraded by the presence of a real rather than a control digit task for only 4 out of the 12 subjects (4 showed worse performance on the single-task control and 4 showed equal performance). The difference in these dual-task decrements can be verified as a significant Dual versus Single × Task Type interaction, $F(1,22) = 10.8$, $p < 0.005$.

We conclude that whereas the PD task interfered with letter recall, the MD task did not. An alternative interpretation is that subjects shift emphasis from the letter task to the concurrent PD tasks but not to the MD task. This alternative can be evaluated by examination of digit performance.

Digit task performance. Table 4 displays proportion correct and reaction time (RT) for the two digit tasks when accompanied by actual and control letter tasks. Proportion cor-

TABLE 3

Proportion Correct on Load Letter Recall as a Function of Embedded Task in Experiment 3

Type of Task	Embedded Task Control	Embedded Task Actual	Decrement
MD	0.92	0.89	0.03
PD	0.93	0.65	0.28

TABLE 4

Proportion Correct and RT (ms) for Embedded Digit Task in Experiment 3

Embedded Task	Load Task Control	Load Task Actual	Decrement
MD	0.88 (1077)	0.79 (1146)	0.09 (69)
PD	0.86 (2004)	0.60 (2090)	0.26 (86)

rect for MD and PD was nearly identical when tested with the control letter task. In contrast, for the real letter load, digit performance was better on MD than on PD, $F(1,22) = 7.5$, $p < 0.025$. Whereas PD performance was degraded by the presence of the letter task for all 12 subjects ($p < 0.001$, sign test), MD performance was degraded for only 6 of the 12 subjects. The difference in dual-task decrement produces a significant Task Type × Dual versus Single interaction, $F(1,22) = 9.4$, $p < 0.01$. This result complements that found for letter task performance.

As is also apparent in Table 4, RT was longer for PD than for MD, $F(1,22) = 41.0$, $p < 0.001$. There were no other significant main effects or interactions for RT, with all values of $F < 1.0$. However, the trends for RT correspond to the significant effects in the data for proportion correct, indicating that the latter cannot be attributed to speed/accuracy trade-off.

Emphasis instruction. Performance tended to be better for the emphasized task, although none of the trends approached statistical significance. We thus cannot determine unambiguously whether performance tradeoff occurred between the loading and embedded tasks. The major pattern of results—that is, more dual-task interference for PD than for MD—appeared in both conditions of emphasis, and this is the feature of the data that we stress.

Discussion

The letter and PD tasks interfered with each other. Thus the presence of the letter load disrupted performance on PD, and the presence of PD disrupted letter recall. By contrast, little or no mutual interference was observed between the letter load and MD tasks. This result is consistent with the premise that the letter load and PD tasks use the same limited storage system but that MD uses an independent system for storage.

Note that the independence of the MD and load tasks may not be attributed simply to the assumption that long-term and short-term memory are independent and that the load letters entered long-term memory as a result of rehearsal. This interpretation is not consistent with the result that the load and PD tasks exhibit mutual interference. If the memory load had entered long-term memory whereas the digit tasks involve short-term memory, this interference would not have occurred.

An alternative interpretation that cannot be ruled out by the data of Experiment 3 is that the MD task makes so little demand on any storage resource that it could not be interfered with by any memory load. One reason to doubt this interpretation is that MD is subject to interference by spatial tracking (Experiment 2) and hence clearly uses resources for input processing. However, it is possible that it may not use resources for storage. This possibility is tested in Experiment 4, in which a spatial rather than auditory memory load is held concurrently with the PD and MD embedded tasks.

EXPERIMENT 4

Experiment 4 was similar to Experiment 3 except that the memory load was spatial rather than verbal. The predicted result was an interaction opposite in sense to that in Experiment 3. Whereas the verbal memory load of Experiment 3 interfered with PD more than with MD, the spatial memory load of Experiment 4 was predicted to interfere more with MD than with PD.

Method

Overview. As in Experiment 3, either the MD or PD task occurred during the retention interval of a memory load. However, the memory load involved sets of four randomly generated spatial patterns presented in a horizontal array. Each pattern consisted of a 3 × 3 matrix, with five of the nine cells filled with the symbol "*" and the other cells vacant. These patterns were labeled with the letters A, B, C, and D. Subjects were required to pronounce "la la la" during presentation of the patterns in order to minimize verbal encoding. After the retention interval (filled with the PD, MD, or control digit tasks), one of the four patterns was presented. The subject was to identify whether this test pattern had been A, B, C, or D by pressing the corresponding key on a standard keyboard. Performance on this matrix task was emphasized for all subjects.

Subjects. The 30 subjects were from the same population as in the previous experiments, except that it was necessary to replace 10 subjects who did not reach the pretest criterion of six out of ten correct responses on pattern recognition by the second attempt. One additional subject was replaced because of an electrical power failure.

Design. Alternate subjects were assigned to the PD and MD tasks as they qualified for the experiment. Testing occurred over two 45-minute sessions. Each subject received 24 trials in each of three conditions, with the order balanced across subjects in each of the PD and MD groups. These conditions were (1) dual task, (2) spatial memory load paired with the control digit task used in Experiment 3, and (3) digit task paired with a control spatial memory load involving presentation of the same matrix in all four positions, with any response accepted as correct.

Each block of 24 trials (one condition) consisted of six trials with each correct answer (A, B, C, or D) to the matrix problem. Within each block of 24 trials, the following serial positions were used four times each for the PD task: 2, 3, 4, 5, 6, and 7. The 24 trials were independently randomized for each block.

Apparatus. An Apple II microcomputer was used with alphanumerical stimuli subtending a visual angle of 0.6 deg. The matrices were 3 deg square, and the array of four patterns was 22 deg wide.

Events on each trial. Each 32-s trial was initiated by the 1-s display of "la la la," indicating that the subject was to begin irrelevant vocalization. After a 1-s blank interval, the load patterns were displayed. Painting the patterns required 1.5 s, and then the display remained visible for 4 s. After a 1-s blank interval, the command "Stop la la" appeared for 1 s, followed by an additional 1-s interval. Then the embedded task was presented. The eight digits appeared sequentially, grouped as in the other experiments. This required 6 s, followed by a 1-s blank interval. Then the probe or "#?" prompt was presented and the subjects responded by pressing the appropriate number key. The pattern test then occurred. One of the previously presented matrices appeared, with the message "A, B, C, or D?" just below; subjects were to press the appropriate letter key. Feedback regarding the correctness of both pattern and number tasks was then displayed for 1.5 s. The intertrial interval was 6 s.

Results

Spatial load task. The proportion of trials in which the pattern task was correct appears in Table 5, for which the chance level was 25%. Performance was significantly worse when actual rather than control digit tasks were present, $F(1,28) = 12.8$, $p < 0.001$. There were no other significant effects or interactions. We had expected that the MD task would be more disruptive than the PD task in

TABLE 5

Proportion Correct on the Spatial Loading Task as a Function of Type of Digit Task in the Retention Interval of the Spatial Task in Experiment 4

Task Type	Digit Task Condition Control	Actual Task	Decrement
MD	0.71	0.63	0.08
PD	0.74	0.63	0.11

its effect on the spatial memory load. This did not occur.

Digit tasks. The proportion of trials on which the digit task was correct appears in Table 6. For the MD task, the presence of an actual rather than control pattern memory load reduced digit performance for 10 of the 15 subjects, with two subjects showing equivalent performance in the two conditions and three reversals ($p = 0.046$, sign test). However, this dual-task decrement was not quite significant when tested by analysis of variance, $F(1,14) = 4.35, p = 0.053$. In contrast, for the PD task, performance was nonsignificantly better for the dual-task compared with the control condition. However, this trend toward interaction of Type of Task × Single- versus Dual-Task was not quite significant, $F(1,28) = 3.66, p = 0.063$.

Discussion

Although there are statistical ambiguities in Experiment 4, the trends are consistent with the assumption that the spatial pattern load interfered with MD more than with PD. In contrast, the letter recall loading task of Experiment 3 interfered more with PD than with MD. A reversal of the pattern of results between Experiments 3 and 4 was predicted by the assumption that the letter load task of Experiment 3 involves auditory memory but that the pattern load task of Experiment 4 involves spatial memory.

Another aspect of these data is that in general, the spatial load in Experiment 4 had less effect on the digit tasks (and the digit tasks had less effect on the spatial load) than was the case for letter memory load in Experiment 3. This finding can be interpreted in several ways. First, whereas MD uses spatial resources for processing (Experiment 2), it may make minimal demands on spatial resources for storage, so that MD is affected only slightly by spatial loading. (We also assume that the reason spatial loading has no effect on PD is that PD makes even less use of spatial resources.) A second possibility is that spatial load in general may have less effect on any task during the retention interval as compared with the stronger effect of sequential letter loads. Finally, our particular spatial load tasks may have been much less effective than others would have been.

Potential problems with our spatial task include the fact that it may have been too easy. This is not likely, however, because 10 subjects had to be rejected before 30 subjects were found who could meet the criterion on this task. Another concern is that subjects may develop a strategy for the spatial load (especially with an embedded digit task) that conserves memory space. For example, they might elect to remember only one or two of the four input matrices. If the test matrix is one of these, the subject could respond correctly; otherwise, guessing between the remaining alternatives would be necessary. A

TABLE 6

Proportion Correct on Digit Task as a Function of the Presence or Absence of Spatial Memory Loading in Experiment 4

Digit Task	Spatial Task Condition Control	Actual Load	Decrement
MD	0.79	0.73	0.06
PD	0.73	0.76	(−0.03)

simple strategy of remembering only one matrix should lead to 50% performance, which approximates the observed performance in the dual-task conditions. Such a strategy would impose little memory loading. It would be desirable to try other spatial loading tasks to resolve these issues.

GENERAL DISCUSSION

Results from the concurrent active task paradigm (Experiments 1 and 2) suggest that the PD task emphasizes auditory-verbal resources and the MD task emphasizes visual–spatial resources. Vocalization interfered with PD more than with MD (Experiment 1), but tracking interfered with MD more than with PD (Experiment 2). The finding that MD and PD are differentially sensitive to interference from auditory and spatial concurrent tasks implies that they use different resources for processing but does not necessarily mean that they also involve different storage resources. For example, it is possible that these tasks use different codes for storage in the same memory region (Phillips and Christie, 1977).

One prediction of independent resources for storage is differential effects, when information of various forms is stored concurrently with the PD and MD tasks. This issue was addressed in Experiments 3 and 4 by requiring passive retention of a memory "load" concurrently with the PD and MD tasks. Time was allowed for active processing and initial rehearsal of the memory load prior to introduction of the PD or MD tasks (Klapp, 1987; Klapp et al., 1983). The verbal memory load interfered with PD more than with MD (Experiment 3), but the spatial memory load tended to interfere only with MD and not with PD (Experiment 4). These results support the view that PD involves a verbal storage system and MD, a spatial system.

Taken together, the results from the two paradigms are consistent with the conclusion that MD and PD differ in resources used for both processing and storage. How can we characterize this difference in resources? The possibility that the critical difference is that PD requires both order and item information whereas MD requires only item information predicts that PD must always be at least as sensitive to concurrent distractors as MD. However, Experiments 2 and 4 indicate greater disruption for MD than for PD.

A more promising model holds that MD involves primarily spatial (visual) resources and PD involves primarily verbal (auditory) resources. This model specifically addresses the finding that MD is sensitive to concurrent spatial processing and memory load and PD is sensitive to verbal processing and memory load. The distinction between spatial and verbal resources has played a major role within multiple-resource theory (e.g., Friedman and Polson, 1981) and may also be useful in interpreting the present data. However, the PD and MD tasks involved the same modality for input and for response within each experiment. Thus unlike most research involving multiple resources, these experiments dealt with resource composition determined by internal mediating processing and storage rather than by stimulus or response modalities.

The distinction between verbal (auditory) and spatial (visual) resources that we have emphasized appears to be related to the well-known differences in function of the cerebral hemispheres. However, our attempts to find differential laterality effects comparing MD and PD have not been successful for either visual laterality (left and right of fixation) or auditory laterality (concurrent auditory input to the two ears). Of course, null results such as these must be interpreted with caution. Nevertheless, given the conclusion that two tasks that are both verbal (i.e., both presumably processed in the left hemisphere) can vary in mutual interference on the basis of semantic category (Hirst and Kalmar, 1987), it is not surprising that the PD and MD tasks we have examined may also differ in a way that is not attributable to hemisphere function. In general, these recent findings may be pointing toward an abstract view of resource independence that is not necessarily tied either to physical modality or to gross anatomic structures such as cerebral hemispheres. An approach for modeling phenomena of this type has recently been developed by Schneider and Detweiler (1987).

As indicated, our use of the term "resource" does not imply that we accept all of the theoretical attributes that have been attached to this term. Indeed, our data suggest that, at least for this context, resource composition can be manipulated without changing modality of input, as proposed by Wickens et al. (1983). Furthermore, the metaphor of resources as energy pools is not congruent with the conclusions of Experiments 3 and 4, which indicate that passive storage of some types of material can interfere with tasks embedded in the retention interval. Thus although the term "resource" is used descriptively in our discussion, it has lost much of its original theoretical content (see also Navon, 1984).

In contrast to the multiple "resource" analysis supported by these data, most textbooks in cognitive psychology propose a single-system theory of working memory (see Klapp et al., 1983 for a review). The standard claim is that all of working memory—like the span of ordered recall—is limited to seven "chunks." This claim may be unreasonably pessimistic about human performance in situations such as decision making, in which extensive amounts of information are involved in a decision or action plan. The standard theory suggests that once working memory is filled to its seven-chunk capacity, additional tasks involving memory cannot be handled. However, it is not difficult to devise situations in which memory loads and task performance can co-occur without much interference. For example, performance in a planning task was not reduced significantly by the presence of a memory requirement involving passwords (Klapp, 1986), and arithmetic tasks can be performed with a memory load similar to that used in Experiment 3 (Klapp et al., 1983, Experiment 6). These data are consistent with a multiple-resource viewpoint in which memory loads may be isolated from the other tasks.

CONCLUSIONS AND APPLICATIONS

These experiments have applied aspects of multiple-resource theory to short-term working memory. The results suggest that there are at least two systems of working memory that differ in resource composition, and that this difference appears in both processing and storage. The determination of which resource is used depends on task demands, even when input and output modalities are held constant.

This extension of aspects of multiple-resource theory to working memory suggests approaches to improving situations in which people must perform complex tasks involving potential memory overloads. Our data indicate that people might be able to distribute loads across relatively independent subsystems of working memory. This might be achieved through improved task configuration or through training. Our data also speak to the issue of whether task design or training is the approach more likely to succeed. The finding that allocation of tasks to memory systems can depend on task demands (PD versus MD) for constant physical arrangements suggests that stimulus modality (e.g., auditory versus visual) and response modality (e.g., manual versus vocal) may not fully determine the allocation of tasks to memory resources. Therefore, training may be at least as useful as task configuration in inducing optimal use of working memory resources. In particular, we note that part-task training may be counterproductive in situations involving working memory limits because it might induce strategies for use of memory that are optimal in single-task but not in dual-task situations. For example, two tasks in isolation may both be performed best using verbal memory storage. When performed in combination, however, this memory allocation could be more interfering than would be the case if verbal resources were used for one component task and spatial resources for the other component.

Thus the theoretical conclusion that independent systems of working memory exist opens up areas of applied research that could potentially affect training methods. However, the theory offers only general guidelines, so that demonstrating the effectiveness of application of these insights for particular task configurations remains a project for the future.

ACKNOWLEDGMENTS

This research was supported in part by Contract F33615-83-K-0039 with the Air Force Human Resources Laboratory. Larry Reed was the contract monitor, and his advice is acknowledged with appreciation. Additional support was provided by the small grants program of the California State University Foundation. Many students have contributed to this and related research; we especially thank Molly Beyers, Alexandria Phillipoff, Dennis Reeves, Joseph Schwarz, and Diana Smith. Other students who assisted include Piyale Comert, Leah Dibel, Denise Hersh, Charles Park, Robert Sanchez, Andrew Shattuck, Cheryl Underwood, and Elaine With. We thank Michael Venturino and three reviewers for comments on an earlier version of this paper. Portions of the data of Experiment 3 were presented at the October 1983 meeting of the Human Factors Society in Norfolk, Virginia.

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