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Concurrent Automatic and Controlled Visual Search: Can Processing Occur Without Resource Cost?

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Can visual search tasks be combined without cost? To answer this question we had subjects search for one target character in a series of 12 rapidly presented frames. The type of processing, controlled or automatic, was manipulated by requiring search for variably mapped (VM) or consistently mapped (CM) target and distractor sets. Conditions included VM-only search (controlled processing), CM-only search (automatic processing), and simultaneous CM/VM search. Joint automatic and controlled search with emphasis on the controlled search task produced no loss of detection sensitivity in either task but did produce a large criterion shift in the automatic search task. Without instructional emphasis on the controlled search task, controlled search deteriorated. Subjects also showed a tendency to waste controlled processing resources when performing an automatic process. Automatic processing became less resource demanding with practice. However, controlled processing was always sensitive to resource reductions. The results show that subjects can sometimes perform dual search tasks without noticeable deficit when one of the tasks is automatic. The implications of these results are discussed.

A critical issue in attention concerns whether humans can develop processing capabilities that do not reduce limited attentional resources. An assumption that all processing activities consume a limited attentional resource implies that human processing capacity has a fixed upper bound. If every processing task reduces attentional resources by a fixed, task-specific amount, then maximal performance should be a function of subject resources available and resource costs of the component tasks (see Kahneman, 1973; Navon & Gopher, 1979; Wickens, 1980). If task resource costs are reduced with practice, then the upper bound on the number of tasks that can be combined increases with task practice. If, with practice, component tasks can be developed to the point that they require no attentional resources, then human processing capacity may have an effectively unlimited upper bound.

Dual-process attention theories propose that some processes develop that process stimuli without reducing attentional resources. Dual-process theories assume that there are two qualitatively different forms of human information processing. In this article these two forms will be referred to as *automatic* and *controlled* processing. Automatic processing is a fast, parallel, fairly

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effortless process that is not limited by short-term memory capacity, is not under direct subject control, and performs well-developed skilled behaviors. Controlled processing is a slow, generally serial, effortful, capacity-limited, subject-controlled process that must be used to deal with novel or inconsistent information (see Schneider & Shiffrin, 1977b; Shiffrin & Schneider, 1977). The proposal that there are two forms of information processing has had a long history in psychology (e.g., James, 1890) and has received considerable interest in recent years (Hasher & Zacks, 1979; LaBerge, 1973, 1975, 1976; Logan, 1978, 1979; Norman, 1976; Posner & Snyder, 1975; Shiffrin & Schneider, 1977).

According to the automatic/controlled processing framework, extended practice in situations where subjects can consistently respond to the stimulus should lead to the development of automatic processing that does not require limited, controlled processing resources. An extreme version of this position would hold that automatic processes can be carried out without any measurable cost. Thus, a subject should be able to maintain performance on two tasks simultaneously (assuming no incompatible responses; see Shiffrin & Schneider, 1977, p. 161), as long as at least one of the tasks is an automatic process.

The automatic/controlled processing framework does not imply that allocation of controlled processing could not benefit performance in a task that is highly automatic. If the two processes were independent then there would be some benefit for joint automatic and controlled processing as long as the fastest controlled process has a shorter latency than the slowest automatic process. Also, if experimental manipulations such as increasing confusability reduce the sensitivity of automatic processes more than the sensitivity of controlled processes, then there might again be a benefit for concurrent processing.

The critical issue is whether automatic processes can be developed that can reliably process stimuli without necessarily reducing the limited pool of available resources. If such automatic processes exist it would be possible to build up a complex processing system by adding stages of automatic processing and reserving the limited resources of controlled processing for times of need. In reading, for example, word encoding can be done with little allocation of attention. This allows the limited attentional resources to be allocated to semantic integration, a process that is probably not automatic (see Shiffrin & Schneider, 1977). Word encoding is probably more accurate for the skilled reader if attention is allocated to the encoding. But, given the redundancy in the text, allocation of resources to encoding would result in only a minor improvement in encoding and a serious reduction in semantic integration. The ability to encode words automatically while using processing resources for semantic integration makes learning from text possible.

Evidence from dual-task experiments suggests the existence of costless automatic processing after extended practice. These experiments assess resource costs by measuring performance decrements when subjects must do two tasks simultaneously. It is useful in reviewing this evidence to distinguish two types of dual tasks. A *between-task* dual-processing situation is one in which two unrelated tasks are carried out simultaneously (e.g., driving a car and carrying on a conversation). A *within-task* dual-processing situation occurs when two tasks are carried on simultaneously to accomplish one specified goal (e.g., word encoding and comprehension during reading).

Many between-task dual-processing experiments find no interference between tasks (see Kerr, 1973; Ogden, Levine, & Eisner, 1979; Wickens, 1980). Subjects have been able to perform complex dual tasks with little or no measurable interference. For example, subjects are able to read while writing (Downey & Anderson, 1915), read one passage while transcribing dictation (Hirst, Spelke, Reaves, Caharack, & Neisser, 1980; Spelke, Hirst, & Neisser, 1976), shadow verbal messages while playing a piano (Allport, Antonis, & Reynolds, 1972), and fly complex aircraft formation maneuvers while digit cancelling (Colle & De Maio, Note 1).

Within-task dual-processing studies frequently show that "lower level" processes become less demanding of resources as practice continues. For example, in the learning of telegraphic skills (Bryan & Harter, 1899), receivers initially expend their resources trying to identify letters. With practice their efforts are shifted to identifying words, then phrases, then whole sentences, and eventually operators spend their resources interpreting the concept of the message being transmitted. The sequences of learning to read (LaBerge & Samuels, 1974) and motor-skill acquisition (Welford, 1976) also suggest that lower level component tasks require less attention with practice.

The automatic/controlled processing theory specifies circumstances in which cost-free automatic processes should develop: Extended consistent practice should lead to automatization of the skill being trained and hence a reduction in the resource demands of the processes used to accomplish those tasks. In conditions where stimulus processing is not consistent, automatic processing should not develop and demands for limited resources should remain high (see Schneider & Fisk, 1982).

The present experiments varied the relationship of targets and distractor sets to assess performance during automatic or controlled processing. In the consistently mapped condition (CM), the target and the distractor sets were kept disjoint and the stimulus sets were selected from different categories (letters and digits). CM target stimuli never appeared as distractors. In the variably mapped condition (VM), a stimulus could be a target on one trial and a distractor on the next. CM conditions presumably lead to the development of an automatic process referred to as "automatic detection" (see Schneider & Shiffrin, 1977b). VM conditions yield controlled processing called "controlled search."

The present series of experiments was designed to test whether automatic and controlled processing can be carried out simultaneously without cost. A between-task paradigm was adopted. Subjects performed the automatic (i.e., CM) or controlled (i.e., VM) tasks either singly or combined in dual-task conditions. Experiment 1 examined the development of the dual-task time-sharing ability. Experiments 2A, 2B, and 2C showed how performance changes as instructional emphasis shifts from the automatic to the controlled task. Experiment 3 showed that subjects can simultaneously carry out automatic and controlled processing without any cost in sensitivity. Experiment 4 showed that subjects cannot perform simultaneously two controlled processing tasks without a substantial loss in sensitivity.

The experiments used a multiple-frame procedure (Schneider & Shiffrin, 1977b; Sperling, Budiansky, Spivak, & Johnson, 1971). Subjects searched a series of 12 frames for the presence of a single character. The multiple-frame procedure allowed independent manipulation of processing time, processing load, and number of channels. In all of the conditions no more than one target was presented per trial. Experiments already indicate that the processing of simultaneous targets (Duncan, 1980; Moray, 1975; Shiffrin & Schneider, 1977) results in a deficit. This can be interpreted as structural interference due to postdetection processing, and was not studied in this series of experiments.

General Method

Equipment

All experiments were controlled by a Digital Equipment Corporation PDP 11/34 computer. The stimuli were presented on Tektronix Model 604 and 620 cathode-ray tubes (CRTs) with P-31 phosphors. Each subject wore a headset through which white noise and error feedback tones were transmitted.

Stimuli

Subjects were presented a sequence of 12 frames. The configuration of each frame was such that four elements were positioned to form a square around a central fixation dot. The elements used in the various experiments were uppercase letters of the English alphabet, digits, or random dot masks. The characters were constructed from dots on a rectangular grid 32 dots wide × 48 dots high. The center of each character was displaced .79° horizontally and .79° vertically from the focus dot. Each character subtended .58° in width and .67° in height. The random dot masks were similarly constructed. There were five different random dot masks, each constructed by randomly placing 43 dots on the 32 × 48-dot matrix. The refresh rate of the dots making up the stimuli was 10 msec. No character or mask was ever presented in the same display position in two successive frames. Subjects sat approximately 40 cm from the display. The random dot masks were presented between each frame to mask out the previous characters (see Design section). The room was dimly lit (.4 footcandles

[4.3 lx] incidental light) with the dots easily visible on the display (.005 footlamberts [.017 cd/m²] per dot).

There were two sets of seven characters (1, 2, 3, 5, 6, 8, 9, and A, C, E, M, R, S, Z). These letters and digits were chosen as stimuli because of their relatively equal confusability within the set as determined in pilot studies.[1] One set served as the CM target set (see Design section), the other served as both the CM distractor set and the VM set. Stimulus sets were crossed across subjects. The present experiments used a category difference (i.e., digits vs. letters) to facilitate the development of automatic detection in the CM condition (see discussion in Shiffrin & Schneider, 1977, pp. 136–145).

Design

In the single-task conditions, subjects were required to keep one character in memory for comparison against the four displayed characters of each frame. Four parameters specified the conditions for each experiment. The frame search was either *diagonal* or *nondiagonal.* In nondiagonal search (Experiment 1), all of the displayed items had to be compared to the memory set. In diagonal search (Experiments 2A, 2B, 2C, 3, and 4), only characters on one diagonal (upper left to lower right, or upper right to lower left) had to be compared to the memory set. The *frame time* was the duration from the onset of one frame to the onset of the next frame (including the duration of any between-frame masks). The *consistency of mapping* between the memory set and the distractor set was either consistent or varied. In the CM condition the memory-set items only occurred as targets—never as distractors—and were from a different category than the distractors. In the VM condition, memory-set items on one trial could be distractors on another and vice versa.

Three types of search condition were manipulated between blocks: single VM search, single CM search, and dual CM/VM search. In single-search conditions the subjects were to search, depending on the condition, only for the CM or VM memory-set item. In the dual condition, the memory-set display preceding each trial presented a VM item and two periods. The periods indicated that any of the seven items from the CM set might occur during the trial. In the dual-search condition subjects were told to place all of their emphasis on the VM search and to report CM items if they saw them (except in Experiment 2B). In the dual CM/VM condition the occurrence of CM and VM targets was varied randomly between trials with the restriction that an equal number of CM and VM targets were to occur during the block. No more than one target could occur during a trial in either dual or single conditions.

All experimental conditions were manipulated within subjects. Response accuracy was the dependent variable used for all experiments. Subject responses that occurred less than 150 msec after the occurrence of a target were deleted. The subjects were given up to 2.5 sec to respond following the last frame of the trial.

Procedure

In Experiments 1, 2A, 2B, and 2C the subjects were generally run in pairs, the two subjects seeing the same visual material on different CRTs. In Experiments 3 and 4, subjects were generally run in a group of four, with each subject's display independent of the others. Each trial was preceded by a presentation of the memory set. In single VM or CM trials the memory-set character was displayed on the screen. In dual CM/VM trials two dots and the VM-set character were displayed. The dots were presented in place of the CM set to encourage subjects to place all their emphasis on the VM task. At the beginning of each trial, subjects were given up to 30 sec to study the memory set. Subjects initiated each trial by pushing a button with their left index finger. The display sequence began after the subject pushed the initiation button or after 30 sec had elapsed. Presentation of the frame sequence was preceded by a 500-msec display of the fixation dot. When a subject erred, the error was indicated at the end of the trial by a tone given through the subject's headset and a red light illuminated on the response box.

Subjects were strongly encouraged to place all their emphasis on the VM task in dual CM/VM conditions (except in Experiment 2B). Subjects were encouraged to try to maintain VM performance in the dual CM/VM condition at the same level as in the VM-only condition, even at the possible cost of severe deficits in CM performance.

Subjects

All subjects were paid for their participation, were right handed, had 20/20 or corrected 20/20 vision, and were students at the University of Illinois. All subjects reported that English was their native language.

Experiment 1: Training Nondiagonal Search

This experiment maps out practice effects in the single and dual CM and VM tasks. A general training effect should lead to improvements in both CM and VM conditions. If, in addition, automatic processing develops in the CM conditions, then these conditions should exhibit a much greater degree of improvement. Also, the development of automatic processes should cause the CM task to become more resource insensitive or cost free.

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[1] A series of pilot studies was carried out to select a set of equally confusable letters. We started selecting a set of letters from Townsend (1971) confusion matrices and added and deleted specific letters until we had the best equally confusable set of seven dissimilar letters for our font. Note that, because letter similarity has a major effect on the rate of development of an automatic process, proper letter selection and counterbalancing of letter effects are important in obtaining clear CM/VM differences.

Method

Procedure. The conditions of this experiment were memory-set size one, frame size four, and nondiagonal search; they included single CM, single VM, and dual CM/VM search. Subjects were required to identify the position of the target. Subjects responded by pushing one of four buttons on the lower right of the keyboard, which formed a square corresponding to the display positions of the stimuli. The initiation button was located in the upper left portion of the keyboard.

The characters were displayed for 50, 130, or 200 msec, and the intervening dot masks were displayed for 50 msec, giving total frame times of 100, 180, and 250 msec. The frame times were varied between blocks.

In this experiment all trials contained a target. The subject's task was to determine in which display position the memory-set item had occurred and to push the corresponding button on the response keyboard. The subjects used their right index finger to make their response. The target could occur in any display position. A position response was used in these experiments because position accuracy and detection accuracy are highly correlated (see Experiment 3). The use of a forced-choice position response reduced problems of criterion shifts. A target was presented on every trial to speed learning rate and provide more observations per block of trials.

At the end of any trial on which the subject incorrectly specified the target location, a 1-sec error tone occurred. Feedback was given to the subjects concerning their cumulative accuracy for the current block. In the dual CM/VM condition the error feedback was given only on the VM trials and the cumulative accuracy represented only the VM performance. This cumulative feedback was given by presenting a two-digit number indicating the percentage of accuracy; it was presented along with the memory set.

Each block contained 10 practice trials and 48 data trials. In dual-task conditions, half of the trials were CM and half were VM. A replication consisted of 9 blocks (3 frame times × 3 search conditions). There were 10 replications. Subjects completed about 11 blocks per session.

Four subjects participated in the present experiment. These subjects also participated in Experiments 2A, 2B, 2C, and 3.

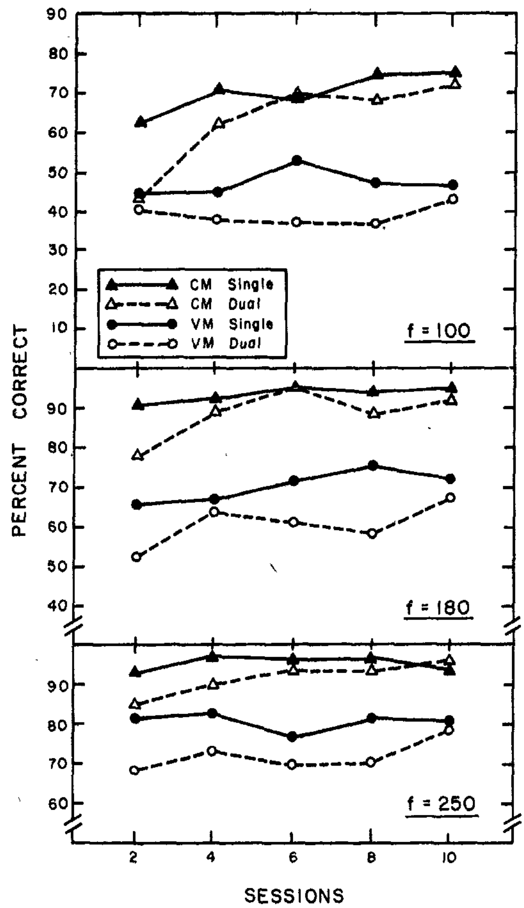

Figure 1. Experiment 1 corrected position identification across sessions for single- and dual-task performance. (CM = consistently mapped; VM = variably mapped.)

Results and Discussion

Figure 1 shows the position accuracy adjusted for guessing (percentage correct minus one-third percentage error) as a function of training (replications). The guessing correction assumed that a subject either correctly detected the target location or guessed randomly among all four locations. Three-way analyses of variance were carried out treating practice and frame time as fixed factors and subjects as a random factor with a criterion significance level of .05. The single CM condition improved significantly with practice, $F(9, 27) = 3.07$. The dual-task CM condition improved sharply with practice, $F(9, 27) = 5.07$. There was a significant effect of frame time for both the CM and VM tasks, suggesting that, with the possible exception of the 250 msec conditions, subjects were not at ceiling.

The single VM condition did not show significant improvement with practice, $F(9, 27) = 1.12$, $p > .3$. The dual VM condition was below the single VM condition. However, the dual VM condition did improve with practice, $F(9, 27) = 2.50$, and was approaching the single VM condition near the end of the experiment.

In the last two replications (Replications 9 and 10; 192 observations per point in the dual task, 384 in the single task), the dual

CM performance was 1% below the single CM performance and the dual VM performance was 3% below the single VM performance. These differences were not significant. Thus the data show that the CM and VM dual task decrements were largely eliminated with practice.

Subjects maintained their dual CM performance and improved it so that it matched the single-task performance, even though they were encouraged to protect their VM performance and not explicitly told what CM character to search for.

Performance in VM search tasks has been shown to be resource limited, decreasing either with increasing task demands or decreasing processing time (see Schneider & Shiffrin, 1977b, Experiment 1; Shiffrin & Schneider, 1977, Experiment 4d). The lack of a CM dual task deficit, combined with little change in the resource-limited (and emphasized) VM task, suggests that automatic processing can be carried out with little or no resources.

In the early replications of the experiment, subjects were unable to maintain dual VM performance at single-task levels. Note that the stimulus sequence presented on a dual-task VM trial is exactly the same as the stimulus sequence presented on a single-task VM trial. Thus these results suggest that at least early in practice there is either a cost of enabling the automatic CM search or that subjects are "wasting" some of their resources by carrying out controlled processing on the CM search task despite the instructional set to focus on VM search. The term *wasting* is used because the resource insensitivity of the well practiced CM search suggests that additional attentional allocation to the CM task has little utility, so that diversion of resources from the VM task will reduce performance in the VM task without helping performance in the CM task.

It is important to note that the reductions in dual-task decrements were obtained only after extensive practice. Subjects had 5,220 trials in the experiment, half of which were CM trials. The results illustrate the necessity of providing subjects with extensive training when assessing dual-task trade-offs in automatic processing.

Experiments 2A, 2B, and 2C: Dual CM/VM Search With a Diagonal Procedure

These experiments examined the subjects' ability to perform simultaneous automatic and controlled processing in different locations. Subjects were asked to divide their attention between a CM and VM diagonal. Experiment 1 showed little CM or VM deficit after extensive dual-task practice in which subjects searched for targets in each of four positions. Experiments 2A, B, and C on the other hand, required subjects to search for CM targets on one diagonal and VM on the other.

These experiments also examined the effects of switching emphasis between CM and VM tasks and of varying target probability. Since automatic/controlled processing theory assumes that automatic processing requires little or no attentional resources, CM detection sensitivity should not deteriorate as emphasis and controlled processing resources are shifted away from the CM task. However, when emphasizing the CM task, resources on the VM tasks are reduced, and performance should deteriorate.

If one is varying target probability, it is not clear how to control it when shifting from single- to dual-task conditions. If the overall target probability is maintained at .5 for both single- and dual-task conditions, and both CM and VM targets occur equally often in the dual-task condition, then the VM target probability is .5 in the single-task condition and .25 in the dual-task condition. If we maintain the process-specific target probability at .25, the probability of any target would be .25 in the single condition and .50 (.25 VM, .25 CM) in the dual-task condition. We ran both controls in the present experiments.

Experiment 2A maintained an overall target probability of .5 in both single- and dual-task conditions; subjects were instructed to give emphasis to VM search. Experiment 2B switched dual-task emphasis to CM search. Experiment 2C maintained the process-specific target probability of .25 in single- and dual-task conditions, and subjects were instructed to give emphasis to VM search.

Method

The present experiments used a diagonal search procedure. The CM target items appeared on only one diagonal and the VM items on the other. Only one target could appear per trial. The assignment of diagonals was counterbalanced across subjects.

The subjects were instructed to emphasize the VM diagonal during dual CM/VM search in Experiments 2A and 2C. The CM diagonal was emphasized in Experiment 2B. Feedback (error tones and cumulative accuracy scores) was given only on the emphasized diagonal on dual CM/VM blocks. In Experiments 2A and 2B the probability of a process-specific target (CM or VM) was .5 in the single-task conditions and .25 in the dual-task conditions, thus maintaining the probability of any target at .5 in single- and dual-task conditions. Experiment 2C maintained the process-specific target probability at .25, resulting in the probability of any target being .25 in the single condition and .5 in the dual-task condition.

During Experiment 2A subjects participated in single VM, single CM, and dual CM/VM with emphasis on VM search. There were nine blocks per replication (three frame times × three search conditions). There were 10 replications, which required about 11 hr. per subject. The first 7 replications were considered practice.

In Experiment 2B subjects were told to emphasize CM performance. Only the dual CM/VM task was run. There were three blocks per replication and five replications, which required 2 hr. per subject. Subjects' single-task performance was stable in Experiment 2A. The Experiment 2A single-task data were compared to the Experiment 2B dual-task results.

In Experiment 2C subjects performed the same task as Experiment 2A, but the process-specific target probability was maintained at .25. In addition, Experiment 2C had two single VM conditions varying between blocks. One required VM search on the VM diagonal and included CM items on the CM diagonal. The to-be-ignored CM items in this condition occurred in a quarter of the trials and only on trials without a VM target. The subject was instructed to ignore these CM items. This condition provided a control for the possible effects of having CM stimuli on trials during the VM block and provided VM detection data for a condition in which subjects clearly realized they were to ignore all CM stimuli.[2] The other single VM condition was similar except that CM items were never presented. Subjects were not informed of the distinction between the two VM conditions. The results of the two single VM conditions were equivalent (see Results and Discussion section).

Subjects were cued at the beginning of each trial whether they were in a single CM, single VM, or dual VM condition. The search conditions were manipulated between blocks. There were 12 blocks (3 frame times × 4 search conditions) per replication. Six replications were completed in about seven sessions per subject. The first three replications were considered practice.

In all experiments the memory set was one, the frame size was four, and the frame times were 90, 130, and 180 msec (50 msec of which was a between-frame mask). There were 58 trials per block; the first 10 trials were considered practice. Subjects responded by indicating the target position and a confidence rating (1–4) of their position response. Subjects were given 6 sec for both responses. The subjects were the same students who participated in Experiment 1.

Results and Discussion

The corrected position-identification scores (proportion correct minus incorrect position identifications on the diagonal, given that the target was presented on the diagonal)[3] for Replications 8–10 of Experiment 2A are presented in Table 1. For the VM-emphasis condition there was a 10% dual-task deficit for the VM condition; this did not reach significance, $F(1, 3) = 1.18$. There was a 14% dual-task deficit for the CM condition (which was greater with shorter frame times) that reached significance, $F(1, 3) = 77.05$. Subject confidence ratings indicated that the subjects were confident of detections and were otherwise unsure of their response.

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[2] The rationale for running a single VM condition with to-be-ignored CM items occurring was to determine whether the occurrence of CM targets on some trials would make it more difficult to maintain attention on the VM diagonal on the next trial in the block. The single VM condition with CM items also controls for the possibility that subjects misinterpreted the instructions in the dual condition, which the VM task emphasized. In the dual-task conditions subjects may perceive the instructions to be contradictory. They are requested to allocate all of their resources to the VM task but to respond to any CM target that is seen. Discussion of the two single VM condition results can be found in Schneider & Fisk (Note 2).

[3] In correcting for guesses we assumed that the probability of a correct location, $P(\mathrm{CL})$, is composed of the true location accuracy (P) plus the guess rate that is divided between the two positions of the diagonal, $(1 - P)/2$. In the single-task condition the observed incorrect position identification on a diagonal, given that the target was not presented, was equal to the guess rate, $(1 - P)/2$. Hence $P(\mathrm{CL}) = P + (1 - P)/2$, and $P = P(\mathrm{CL}) - (1 - P)/2$. For the dual-task conditions we assumed that subjects have a bias (G) to guess on the given diagonal, and the observed $P(\mathrm{CL}) = P + (1 - P)G/2$. The observed same diagonal guess is equal to $(1 - P)G/2$. The corrected location accuracy is the observed location accuracy minus the proportion of same diagonal guesses, $P = P(\mathrm{CL}) - (1 - P)G/2$. These corrections compensate for a criterion shift resulting in increased guesses on one diagonal increasing the observed proportion of correct location judgements on that diagonal. They do not provide a pure sensitivity measure, since a high criterion (beta) would reduce P directly.

Table 1
Position Accuracy: Experiments 2A, 2B, and 2C

Frame time (msec)	Single VM	Dual VM	Difference, VM	Single CM	Dual CM	Difference, CM
			VM Emphasized, Experiment 2A			
90	.50	.50	.00	.76	.51	.25
130	.84	.63	.21	.94	.81	.13
180	.82	.72	.10	.96	.92	.04
M	.72	.62	.10	.89	.75	.14
			CM Emphasized, Experiment 2B[a]			
90	—	.15	.35	—	.75	.01
130	—	.10	.74	—	.94	.00
180	—	.35	.47	—	.97	−.01
M	—	.20	.52	—	.89	.00
			VM Emphasized, Experiment 2C			
90	.41	.38	.03	.65	.41	.24
130	.48	.59	−.11	.94	.78	.16
180	.65	.66	.01	.96	.86	.10
M	.51	.54	−.03	.85	.68	.17

Note. VM = variably mapped; CM = consistently mapped.
[a] Dual-task difference scores for Experiment 2B used single-task accuracy levels obtained in Experiment 2A.

When emphasis was switched to the CM diagonal (Experiment 2B) there was a large (52%), significant, $F(1, 3) = 41.14$, deficit in dual-task VM detections (see Table 1). Three of the four subjects were at chance for the unemphasized VM diagonal for frame times of 90 and 130 msec. (The other subject detected 38% and 27% of the VM targets in the 90 and 130 msec conditions, respectively. There was no difference between dual- and single-task CM performance for this subject.) There was no deficit, $F(1, 3) < 1$, in dual CM compared to single CM performance.

In Experiment 2C the two VM conditions (with and without to-be-ignored CM items appearing on some trials) were not significantly different, $F(2, 6) < 1$, and were combined. The dual VM condition was slightly superior (3%) to the single VM condition, but this difference was nonsignificant, $F(1, 3) < 1$. The dual CM position accuracy dropped an average of 17% relative to the single CM condition, which was significant, $F(1, 3) = 29.86$.

Comparing the single VM conditions in Experiments 2A and 2C (average .72 vs. .51), we see that the reduction of single VM target probability resulted in a .21 reduction in location accuracy, which was significant, $F(1, 3) = 24.83$. This suggests that the apparent (though nonsignificant) dual VM task deficit observed in Experiment 2A was due to a reduction in the VM target probability when shifting from the single- to dual-task condition. There were no significant differences between the single CM conditions, $F(1, 3) < 1$, or the dual VM conditions, $F(1, 3) = 2.53$, in Experiment 2A and 2C. There was a significant 7% drop in dual CM location accuracy between Experiments 2A and 2C. We interpret the dual CM drop as subject bias not to respond to targets on the CM diagonal (see Experiment 3).

The results of Experiment 2C show that if the VM task is emphasized subjects can perform dual CM and VM search without any deficit in VM localization, and with CM performance well above chance. This supports the hypothesis that subjects can perform fairly accurately on the automatic task (CM search) with no deficit in the simultaneous controlled-process task (VM search).

The results of Experiment 2B also support the hypothesis that allocation of controlled-processing resources to an automatic task (CM search) may result in a small CM location benefit (14%, Experiment 2B vs. Experiment 2A) at a very severe cost (52%, three out of four subjects at chance) in concurrent controlled processing.

The present results run counter to the hypothesis that CM detection is unaffected by emphasis. Dual CM performance was poorer than single CM performance when emphasis was on the VM diagonal. The results are also counter to those of Experiment 1, which showed no dual CM deficit. The differences between results from Experiment 1 and from Experiments 2A, 2B, and 2C suggest two interpretations. First, subjects may not be able to carry out automatic and controlled processing in different regions without cost. In Experiment 1, both types of processing were applied to the same positions. In Experiments 2A, 2B, and 2C, each type of processing was applied to a separate diagonal. An inability to allocate the processing modes to different locations would explain why only Experiments 2A, 2B, and 2C showed a dual-task deficit after extensive practice. The second interpretation is that the deficit was caused by shifts in subject bias. When subjects emphasized the VM diagonal in Experiments 2A, 2B, and 2C, they may have increased their criterion for responding on the CM-diagonal positions, thus reducing CM hit rate. In Experiment 1 all positions were equally emphasized so subjects would not make position-specific shifts in criterion. The error-correction procedure corrects for guesses but not for misses caused by setting a high criterion (see Footnote 3).

Experiment 3: Division of CM and VM False Alarms

With the measures used in the previous experiments, a substantial shift to a more conservative criterion for CM responses in dual tasks could result in a substantial decrease in the measured CM performance. The corrections used in Experiments 1 and 2A, 2B, and 2C correct only for guesses according to the stated models. If a subject has a severe criterion shift and produces, for example, no responses on the CM diagonal, a decrement in the CM position accuracy will occur. In fact, one subject in Experiment 2A made no responses in one of the dual CM diagonal conditions when the VM task was emphasized, indicating a substantial, conservative criterion shift. The methods in Experiment 2C allow one to conclude that the VM search is equivalent in single VM and dual VM conditions but do not allow one to determine whether the dual CM task deficit is due to criterion or sensitivity changes. Experiment 3 separates sensitivity and criterion shifts in the dual-task conditions.

Method

The procedure for the present experiment was similar to Experiment 2C. Subjects participated in single VM (with and without CM items, as in Experiment 2C), single CM, and dual CM/VM search conditions. The process-specific target probability was .25, making the probability of any target occurring .25 in the single-task conditions and .5 in the dual-task conditions.

The present experiment required subjects to indicate the target position and, independently, whether they thought a given trial contained a CM target, VM target, or no target. Thus, the data of this experiment allowed CM and VM false alarms to be differentiated in the dual-task conditions. The subjects were the same four who participated in Experiments 1 and 2A, 2B, and 2C.

The search conditions were manipulated between blocks. The memory set was one, the frame size was four, and the frame times were 90, 130, and 180 msec. Subjects participated in seven replications. Each replication contained 12 blocks (3 frame times × 4 search conditions) with 58 trials per block (10 practice). The first four replications were treated as practice.

Results and Discussion

Figure 2 presents the detection-sensitivity results using the A' measure (Craig, 1979; Norman, 1964). A' is a measure of the area under the receiver operating characteristic curve ranging from .5 for chance detection to 1.0 for perfect detection. The A' measure is a more distribution-free measure of detection sensitivity than d', and seems a more appropriate measure when false-alarm rates get very low, as they do in some of the present conditions. Note that false-alarm data were calculated from nontarget trials only. A false alarm on one diagonal was treated as a correct rejection of the other. One of the four subjects made no CM responses (no hits or false alarms) in the dual task when frame time was 90 msec. Hence, A' could not be calculated for that subject. Figure 2 and the analyses represent data on the remaining three subjects' block data, Replications 5–7.[4] The hit and false-alarm rates are presented in Table 2. Data for individual subjects are presented in Table 3. Subjects were treated as a random factor, frame time and search condition as fixed factors. As in Experiment 2C there was no difference in detection accuracy between the two VM conditions (without CM items, .861 A'; with CM items, .846 A'), and all analyses collapsed the data from these conditions.

The A' data show no significant sensitivity decrement in either the CM or VM dual-task conditions. The CM A' difference was −.004 (single CM − dual CM), which was nonsignificant, $F(1, 2) = 3.49$, $p > .05$. The dual-task VM difference, .017 A' (single VM − dual VM), was also nonsignificant, $F(1, 2) = 9.72$, $p > .05$. The lack of significant results is not due to insufficient power. The error variance for both CM and VM A' tests was small (VM, .00109; CM, .0000509) making the power quite high. The present experiment would have detected even a small (e.g., .05 A', .25 d') difference with a probability of at least .8 (see Keppel, 1973, p. 534, for power calculation procedure). Also, the lack of decrement can not be attributed to ceiling or floor effects, since frame time was significant in all conditions. For the 90-msec frame time condition, which tested performance near the center of the A' range,

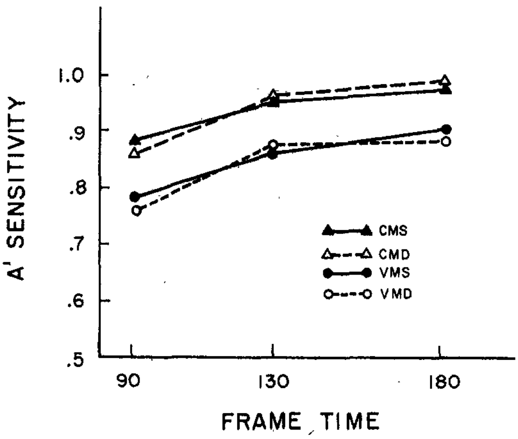

Figure 2. Experiment 3 detection A' sensitivity. (CMS = consistently mapped, single; CMD = consistently mapped, dual; VMS = variably mapped, single; VMD = variably mapped, dual.)

Table 2
Measures of d', Beta, and Position Accuracy: Experiment 3

Frame time (msec)	Single VM	Dual VM	Single CM	Dual CM
	d'			
90	1.00	.88	1.64	1.55[a]
130	1.90	1.93	2.91	3.07
180	2.29	2.16	3.42	3.84
M	1.73	1.66	2.66	2.82
	Beta			
90	1.95	1.87	1.22	11.76[a]
130	4.76	2.83	2.03	9.12
180	3.78	7.02	2.07	5.64
M	3.50	3.91	1.77	8.84
Mean hits	.68	.65	.86	.65
Mean false alarms	.16	.16	.12	.00
	Position accuracy			
90	.37	.37	.63	.30
130	.60	.54	.88	.76
180	.65	.62	.89	.86
M	.54	.51	.80	.64

Note. VM = variably mapped; CM = consistently mapped.
[a] Excludes Subject 1, who gave no responses in this condition.

the dual-task VM decrement was .03 and the CM decrement was .02. Both differences were nonsignificant.

If a d' statistic is used (see Table 2), there is also no dual-task deficit. In most of the CM dual-task conditions subjects made no false alarms. This makes calculation of d' indeterminate. For calculating d' and beta we assumed a false-alarm rate of .01 if the observed level was below this amount. This results in an underestimate of dual-task d' and beta. The data show no d' dual-task deficit either in the VM (single VM − dual VM = .07 d') or CM (single CM − dual CM = −.16 d') performance. There is little dual-task deficit using the proportion of hits minus false alarms as a dependent mea-

[4] It should be noted that if we include the data for Subject 1 and estimate that subject's A' dual-task CM detection performance (in the 90-msec frame time condition) to be at chance ($A' = .5$), the statistical interpretations of the data are unaffected. Including this subject's data does not affect the statistical analyses.

sure (single VM − dual VM = .02; single CM − dual CM = .09). If we use corrected location accuracy (see Footnote 3) there is a dual-task CM deficit (single CM − dual CM = .16) but this would be expected if subjects had a bias not to respond on the unemphasized diagonal. The position accuracy correlated with detection accuracy (hits − false alarms), .973, suggesting that localization and detection accuracy are largely measuring the same effects in these experiments. The CM location dual-task deficit in this experiment was comparable to that observed in Experiments 2A and 2C. The lack of a detection deficit in the present experiment suggests that the CM location

Table 3
Individual Subjects' Hit and False Alarm (FA) Data, Experiment 3

Frame time (msec)	Single VM (without CM)	Single VM (with CM)	Dual VM	Single CM	Dual CM
		Subject 1			
90					
Hit	.78	.64	.72	.75	0
FA	.60	.52	.57	.39	0
130					
Hit	.78	.77	.83	.77	.46
FA	.28	.31	.19	.04	0
180					
Hit	.83	.75	.70	.83	.50
FA	.21	.11	.14	.03	0
		Subject 2			
90					
Hit	.72	.69	.69	.78	.52
FA	.15	.17	.15	.17	.03
130					
Hit	.87	.83	.80	.95	.96
FA	.05	.04	.04	.02	.03
180					
Hit	.97	.78	.82	.91	.92
FA	.02	.03	.01	.06	0
		Subject 3			
90					
Hit	.33	.43	.30	.71	.43
FA	.03	.06	.04	.07	0
130					
Hit	.64	.47	.45	.77	.75
FA	.01	.01	.03	.06	0
180					
Hit	.71	.56	.58	.92	1.00
FA	.01	.03	.01	.03	0
		Subject 4			
90					
Hit	.40	.56	.53	.94	.42
FA	.29	.22	.40	.39	0
130					
Hit	.72	.58	.72	1.00	.86
FA	.20	.28	.17	.19	0
180					
Hit	.78	.61	.53	1.00	1.00
FA	.19	.10	.12	.01	0

Note. VM = variably mapped; CM = consistently mapped.

deficits in Experiments 2A and 2C were due to subject bias against responding to the CM diagonal.

These results show that when subjects are asked to strongly emphasize the VM diagonal, there is a large criterion shift on the CM diagonal. Table 2 shows a very substantial criterion shift in the CM conditions, but not in the VM conditions. The dual-task CM criterion shift (dual CM − single CM) in beta with an assumed false-alarm rate of .01 (when the observed rate was 0) was 7.07 units. There was essentially no criterion shift in the VM conditions (dual VM − single VM = .41). The CM hit and false-alarm rates dropped as would be expected with a substantial criterion shift (see Table 2). The VM hit rate dropped only slightly (.03) from single- to dual-task conditions.

The present results support the strong statement that automatic processing can be done without any measurable cost in sensitivity, even if the two processes operate in different retinal locations. This lack of a dual-task decrement is not due to ceiling effects or weak statistical tests. The present lack of dual-task sensitivity decreases could not be the result of statistical dependencies in the data reducing observed dual-task false-alarm rates. The false-alarm rate was determined only by trials when no target was presented. Hence even if a subject detected every VM target and therefore never made a CM false alarm on a VM trial, the false-alarm rate would be unaffected.

In order to obtain no dual-task decrements, subjects had to place all their emphasis on the VM task and practice extensively. This emphasis caused a very large criterion shift, making subjects much more conservative about responding on the CM diagonal. It should be noted that subjects had extensive search experience (19,530 trials) before data were recorded in the present experiment. We expect that similar results could have been found after less training, but examination of this question must await further research.

Experiment 4: Dual Controlled Processing

The final experiment examined performance when controlled processing was required in two simultaneous VM tasks. It has already been shown that controlled processing performance drops with increases in the number of positions subjects must process on each frame, even after extended practice (see Schneider & Shiffrin, 1977b). However, it would be useful to examine controlled processing deficits utilizing the same methods as in Experiment 3. The purpose of this experiment was to examine single and dual controlled processing performance. The "attention is a skill" theory (Hirst et al., 1980) suggests that dual VM search could also be done without deficit after sufficient training; automatic/controlled processing theory predicts that the dual-task deficit for VM tasks should remain, even after extended training.

Method

This experiment contained three VM search conditions. In the single search condition subjects were required to search a given diagonal for the occurrences of the VM memory-set item. There were two "dual" search conditions. One dual condition contained a memory-set size of one with the memory-set item randomly occurring on either diagonal. The other dual condition used a memory-set size of two—with each memory-set item assigned to a different diagonal. The memory-set display configuration indicated the current search condition to the subjects. Subjects indicated the position of the target, if any, then indicated the diagonal on which they thought the target had occurred (or indicated that it was a no-target trial). Subjects' performance was scored in terms of VM hits and false alarms on each diagonal separately. A VM false alarm for one diagonal was treated as a VM correct rejection for the other diagonal. The single VM condition consisted of 75% target-absent and 25% target-present trials. In the dual conditions, 50% of the trials did not contain a target, on 25% of the trials the targets occurred on one diagonal, and on 25% of the trials they occurred on the other.

In the first seven replications, subjects (in the dual conditions) were instructed to emphasize just one of the diagonals in their search (the diagonal they searched in the single-task condition). The diagonal to be emphasized was counterbalanced across subjects. After the unequal emphasis condition, subjects received five replications in which they were to divide emphasis equally between the two diagonals.

Four new subjects were recruited. These subjects were summer students at the University of Illinois. The memory-set size was one in the single-task condition and one or two in the dual-task condition. The frame size was four, and frame times were 90, 130, and 180 msec. There were 12 replications of 18 blocks each (2 memory-set sizes × 3 search conditions × 3 frame times) with 58 trials that included 10 practice trials.

Results and Discussion

The analyses were carried out on the A' scores on replications after performance had asymptoted (Replications 4–7, emphasized diagonal condition; 9–12, equal emphasis both diagonals condition). Subjects were treated as a random variable, frame times and search conditions as fixed variables. The A' results are presented in Figure 3. Subjects were able to maintain performance on the emphasized diagonal with an average A' decrement of .001 for memory-set size one and .017 for memory-set size two. There was a substantial A' decrement for the unemphasized diagonal of .182 for memory-set size one, $F(1, 3) = 18.5$, $p < .05$, and .298 for size two, $F(1, 3) = 12.9$, $p < .05$. For the unemphasized diagonal, memory-set size two and a 90-msec frame time, three of the four subjects were at chance performance.

The emphasized diagonal location accuracy data show the same patterns as the A' data. The VM location accuracy dropped slightly from single VM (64%); to VM, emphasized, memory-set size one (57%); to VM, emphasized, memory-set size two (53%). The unemphasized location accuracy was near chance for size one (13%) and size two (4%).

In the equal emphasis condition there was also a substantial dual-task A' deficit of .054 for memory-set size one and .095 for size two. The decrement from the single-task performance and the previously emphasized or unemphasized diagonal in the dual-task condition was significant in all cases ($p < .05$). Dual-task A' performance was slightly better (.035) on the previously emphasized than unemphasized diagonal, but these differences were not reliable.

The unemphasized diagonal location accuracy pattern matches the A' results. The average location accuracy across frame times was 66% for the single VM condition and dropped to 44% for the dual memory-set size one condition and 30% for the dual memory-set size two condition. The difference between the previously emphasized and unemphasized diagonals was less than 2%, showing that subjects did equally divide their resources.

There were no practice effects in the dual-task equal emphasis conditions (the linear trend in location accuracy over the last four replications was only .005 improvement over replications). We interpret the lack of improvement in the dual-task condition as indicative of asymptotic performance.

The present results show large sensitivity deficits for two VM detection tasks. In particular, substantial dual-task sensitivity decrements occurred in the same procedures as those used in Experiment 3. However, in Experiment 3, dual automatic and controlled processing did not result in sensitivity decrements. Although further training could conceivably have altered these findings, the

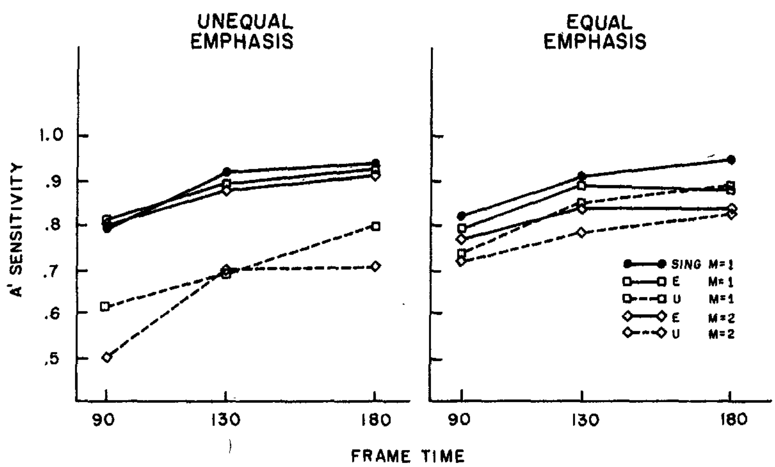

Figure 3. Experiment 4 single and dual VM search. (Solid lines represent the emphasized [E] diagonal; dashed, the unemphasized diagonal [U]. In the equal emphasis condition, the E and U represent the emphasis placed during the previous replications. Sing = single.)

fact that the effects were stable over the last four replications suggests that the observed deficits are permanent.

General Discussion

The results confirm the hypothesis that automatic and controlled processing can be carried out jointly without cost. Experiment 1 showed that practice resulted in performance improvement in the CM conditions only. CM improvement rate was slow, and subjects' dual-task CM performance was still improving after 2,510 trials of CM search. In contrast, the Experiment 1 single VM search did not improve with practice. The small improvement in dual VM performance was probably due to subjects' learning not to allocate resources to the concurrent CM search task. By the end of Experiment 1 there were no significant differences between single- and dual-task location accuracies when subjects processed all locations.

Experiments 2A, 2B, and 2C examined location accuracy when CM and VM processing were on different diagonals. The results (Experiments 2A vs. 2C) showed that VM single-task position accuracy was sensitive to target probability. Experiment 2C showed that subjects could perform dual VM and CM search emphasizing the VM diagonal with no reduction in VM performance and with some (17%) reduction in CM performance. Experiment 2B showed that if emphasis was shifted to the CM condition, CM performance was maintained but VM performance dropped severely to near chance levels.

Experiment 3 replicated the position accuracy data of Experiment 2C but showed that the dual-task CM location deficit was the result of a severe criterion shift biasing the subject not to respond on the CM diagonal. There was no evidence of a dual-task detection sensitivity deficit in either the VM or CM conditions.

Experiment 4 showed that subjects could not perform dual VM searches without deficit, and this deficit did not reduce with practice.

Figure 4 provides a representation of possible signal (target-present trials) and noise (target absent) distributions and response-criterion placements that could produce the results of Experiments 2A, 2B, 2C, 3, and 4. In Experiment 2C, when subjects changed from the single to dual CM/VM conditions with emphasis on the VM condition, CM hit rate declined in the CM conditions. The shift from the left to the center column of Figure 4 predicts a small decrease in CM hit rate due to a criterion shift on the CM task. When, in Experiment 2B, subjects shifted emphasis to the CM diagonal, CM hit rate was maintained and VM performance dropped to near chance. This is represented in the right column of Figure 4. In the CM

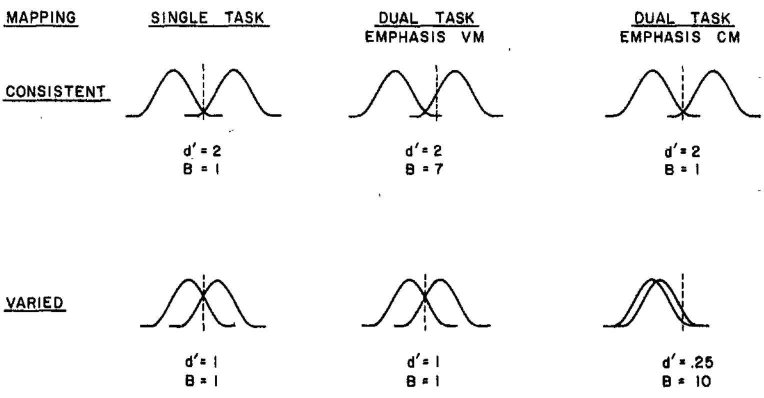

Figure 4. Interpretation of noise and signal distribution for single- and dual-task conditions. (In each case, the left distribution represents the distribution of activations on nontarget trials and the right distribution represents target trial activations. The line represents the criterion for a target present response. VM = variably mapped; CM = consistently mapped.)

condition (top row) shifting from the single (left) to the dual CM/VM search with emphasis on the CM condition did not change either criterion or sensitivity, hence CM hit rate was maintained. However, in the VM condition that emphasized the CM task, there was a reduction in the resources available for the VM process. This reduced VM sensitivity (lower right) resulting in a substantial reduction in hit rate.

The interpretations of Experiment 3 are illustrated in the left and center columns of Figure 4. In shifting from single- to dual-task conditions with emphasis on the VM tasks, the CM detection sensitivity was maintained, and there was a large conservative criterion shift. In the VM condition there was no change in either criterion or detection sensitivity when shifting from single to dual tasks (lower left and center).

In Experiment 4, there was always a substantial dual task deficit in combining two VM search tasks. Due to the need to divide resources between tasks, detection sensitivity would be less in dual-task (Figure 4, lower right) than in single-task conditions (lower left).

Automatic processing appears to reliably activate nodes in memory even when attention is not allocated to the process. We reach this conclusion because detection sensitivity does not decline as subjects emphasize the nonautomatic task. Hence, at some level in memory, the automatic memory activation must be equivalent whether or not attention is allocated to the processing. The results support dual-process theories proposing that the activation of memory nodes can be automatic and can occur without any attention allocated to the task (LaBerge, 1973, 1975, 1976; Posner & Snyder, 1975; Shiffrin & Schneider, 1977).

The presence of automatic processes that are insensitive to reductions in controlled processing resources suggests that there is no fixed attentional capacity limitation for dealing with consistent information. To the extent that automatic processes activate other automatic processes, there is no fixed upper bound to how complex a process can be carried out without attention. Searching for a feature, letter, word, or semantic category should be possible without reducing attentional capacity. By building up complex processes through a cascade of automatic component processes, controlled processing resources need not be reduced. Hence, controlled processing capacity does not place an upper bound on processing complexity. In other experiments (Fisk & Schneider, Note 3) we have shown that subjects can perform semantic category search without reducing resources available for a simultaneous short-term memory digit recall task.

Even after extensive training, however, joint controlled processing cannot be done without deficit. Combining two similar controlled processing tasks resulted in a large sensitivity deficit even after extensive practice (Experiment 4). It is possible that extending training for months longer could have enabled subjects to be better at jointly carrying out controlled processes. However, the lack of practice effects in VM studies (see Kristofferson, 1972; Schneider & Shiffrin, 1977b, p. 39) suggests that extending the practice would not change the results. The present results seem incompatible with the "attention is a skill" hypothesis (Hirst et al., 1980; Spelke et al., 1976), which in one form seems to propose that extended time-sharing training is sufficient to eliminate interference. At the least, such a hypothesis needs considerable refinement in light of the current results.

These conclusions are based on results from a target-detection paradigm, and one must be cautious in extrapolating to other tasks. The present experiments never presented two simultaneous targets that both required a response. The automatic process is target detection and not responding to the target. In CM search, responding to two simultaneously presented targets does result in poorer performance (Duncan, 1980; Moray, 1975; Schneider & Shiffrin, 1977a, Experiment 3). The present experiments tested a particular type of automatic processing referred to as the "automatic attention response" (see Shiffrin & Schneider, 1977).[5]

[5] The experiments utilized a category search procedure in which CM items were drawn from one category (e.g., digits) and VM from another (e.g., letters). Although the category shift probably facilitated automatic processing development, the consistency of mapping was

One must be cautious in extrapolating from these results to all automatic and controlled processing tasks. However, similar demonstrations using more complex tasks (e.g., shadowing a verbal message while playing a piano, Allport, Antonis, & Reynolds, 1972) suggest that the present results might be extrapolated generally to situations involving joint use of automatic and controlled processing.

Between-Task Implications

The automatic/controlled processing framework predicts that costless automatic processes exist. Whether automatic processes are "free" or just "cheap" (Navon & Gopher, 1979) in terms of resource cost depends on the operational definitions of the words. The present results found no measurable sensitivity cost.

It is conceivable that there is an inherent (though small) cost in enabling any automatic process to be carried out. Between-task experiments requiring independent processing of two stimuli frequently show a simple additive effect of performing the dual tasks. For example, Logan (1979) found that the presence of a simultaneous short-term memory digit task slowed visual search reaction times. The memory load beyond one item did not increase reaction times. It is conceivable that resources may be required to enable or "set up" an automatic process, but that the execution of the processing itself may not require resources. The automatic process can be conceptualized as a production system (e.g., Newell, 1980) that will fire when its enabling condition and appropriate sensory stimuli are active in short-term memory. The automatic process itself may not consume resources, but maintaining the enabling condition may. This enabling cost might best be conceptualized as maintaining a chunk in memory. The cost of maintaining a dual-process chunk may be no greater than that of maintaining a chunk enabling a single process. This may be analogous to the approximately equal cost of maintaining a word versus a letter in short-term store (Miller, 1956). The apparently costless nature of automatic processing may be due to either (a) automatic search itself requiring no resources or (b) there being no difference in cost between maintaining a memory chunk to enable a single versus a dual process. The hypothesis that automatic enabling conditions can be chunked suggests that some task-specific time-sharing training may be necessary in order to attain costless automatic and controlled processing performance. This is consistent with the somewhat reduced dual-task performance we saw in the first session of practice with new conditions (Experiments 2A, 2B, 2C, and 3). The hypothesis also agrees with the literature showing a benefit of task-specific time-sharing training (Hirst et al., 1980; Logan, 1979; Spelke et al., 1976).

The presence of large criterion shifts illustrates the importance of separating criterion and sensitivity shifts in dual-task paradigms. In Experiment 3 the automatic processing criterion shifted from a beta of 1.8 to at least 8.8 in the single- and dual-task conditions. The presence of such large criterion shifts can confound performance measures that do not explicitly separate the criterion. For example, in Experiment 2C the reductions in position accuracy are likely to be due to a criterion shift causing subjects to inhibit responding on the CM diagonal. The potential for criterion shifts in automatic processes makes interpretations of complex dual-task procedures difficult (see Duncan, 1980). In tracking, for example, a more conservative tracker seems equally sensitive to tracking error but has a higher criterion as to the size of the corrective movement, thus resulting in a reduction of gain of tracking error (Wickens, 1976).

Our results suggest that subjects have a tendency to waste controlled processing resources on automatic processing tasks. Therefore, to optimize overall performance, dual automatic/controlled processing experiments should emphasize the controlled processing task. When subjects allocated attention to the CM task (Experiment 2B), the VM-task performance substantially deteri-

probably the necessary condition for having no dual-task trade-off (see Shiffrin & Schneider, 1977). In an experiment similar to Experiment 1 we had subjects perform simultaneous CM and VM search in which both sets were letters; we found no dual-task trade-off (see Schneider and Fisk, Note 2, Experiment 2).

orated, and the CM performance improved only slightly from when it was unemphasized. Experiment 3 showed that the CM performance drop in Experiments 2A and C was most likely the result of a severe criterion shift. These results suggest that future experimental instructions and feedback should strongly encourage subjects to place all emphasis on the controlled processing task in order to maintain controlled processing performance. If the controlled processing task is not emphasized, subjects may allocate resources to the automatic task, reducing controlled processing performance and not improving automatic processing performance. When training operators for dual-task performance in real-world environments, operators may have to be convinced not to waste controlled processing resources on tasks that are already automatic.

Within-Task Implications

The automatic/controlled processing framework suggests that controlled processing can develop an automatic processing stage, and then limited controlled processing resources can be allocated to higher level stages. Controlled processing can be interpreted as "training wheels" for the development of automatic processing (see Schneider & Shiffrin, 1977a, pp. 148–151). Limited controlled processing resources are used to develop cost-free automatic processes. In reading, for example, word encoding becomes automatic after sufficient training and does not require limited controlled processing resources. When word encoding is automatic, limited controlled processing resources can be used for higher order semantic purposes. Substantial "overtraining" may be necessary to make the word-encoding processes automatic, but after sufficient training word encoding is equivalent, or sometimes superior, to letter encoding (see Estes, 1977).

The observed tendency of subjects to waste limited controlled processing resources on a task that can be accomplished by automatic processing may inhibit subjects from developing complex processing capabilities. For example, even after subjects develop automatic word-encoding capabilities, poor readers may waste limited controlled processing resources on the word-encoding task. LaBerge and Samuels (1974) reported that for beginning readers to increase chunking, the demand for accuracy may have to be relaxed. The present experiments pressured subjects to completely ignore automatic processing performance in order to keep them from wasting controlled processing resources on the automatic processing task. Since controlled processing may be necessary for the development of automatic processing, and might be slightly more accurate than automatic processing in some situations, it is not surprising that subjects have a tendency to continue to allocate controlled processing to an automatic processing task.

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