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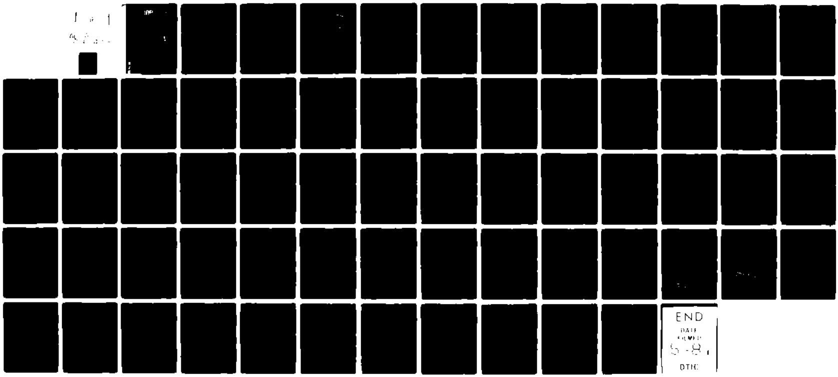

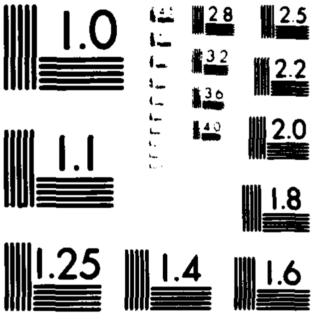

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Automatic and Controlled Attention
Processes in Auditory Detection

Steven E. Poltrock
University of Denver

Marcy Lansman and Earl Hunt
University of Washington

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Technical Report No. 9
February, 1981

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Abstract

An analogy can be drawn between visual search and auditory target detection. Three experiments were designed to compare performance in the two paradigms. In Experiment 1, the effects of consistent and varied mapping of stimuli and responses were examined in an auditory detection task. Subjects responded faster and made fewer errors under consistent mapping (CM) than varied mapping (VM) conditions, and the effect of memory set size decreased over practice in the CM condition. In Experiment 2, performances in single-channel, selective-attention, and divided-attention conditions were compared under VM conditions for auditory target detection. There were large differences among the three conditions in contrast to results previously obtained under CM conditions (Moray, 1975). These differences were much larger in the auditory detection task than in an analogous visual search task employed in Experiment 3. An analysis of individual differences in Experiments 2 and 3 indicated that there is no general ability to divide attention. The results are discussed in terms of automatic and controlled processes involved in recognition of target stimuli.

Automatic and Controlled Attention Processes in Auditory Detection

Early research on attention was largely concerned with the auditory modality. Presenting different messages simultaneously to the two ears seemed to be the ideal way to investigate the ability to divide attention between two channels of information. As theory and research in attention have matured, attentional models have been developed to explain visual as well as auditory phenomena, but study of the two modalities has often proceeded quite independently. The purpose of this article is to consider whether principles proposed to explain responses to visual stimuli also explain performance in dichotic listening tasks.

Recently, Shiffrin and Schneider (1977; Schneider & Shiffrin, 1977) have proposed a general theory of attention derived from research on visual search. Their theory postulates the existence of automatic and controlled search processes similar to those suggested by James (1890). Automatic processes are postulated to explain asymptotic performance when a consistent mapping exists between stimuli and responses. In a consistent mapping (CM) condition the target items remain the same from trial to trial. When extensive practice is provided under CM conditions subjects are able to detect a target accurately at extremely brief presentations. Shiffrin and Schneider suggested that the target elicits an automatic attentional response under CM conditions. When a varied mapping (VM) exists between stimuli and responses, or when practice is insufficient to develop an automatic response, target detection requires much slower presentation. Shiffrin and Schneider proposed that a controlled search is conducted under these conditions.

Schneider and Shiffrin pointed out that the differences between CM and VM can reconcile some paradoxical findings in the literature on visual search and short-term memory. It is now a classical finding that the time required to search for an alphanumeric target in a visual display is a linear function of the number of items contained in the array (e.g. Sternberg, 1966). Many studies, however, have not obtained this result (e.g., Egeth, Jonides, & Wall, 1972; Kristofferson, 1972). In many of the studies where the linear function was observed, the target stimulus was changed from trial to trial, while in studies where the function was not observed, a single target or a small set of possible targets was used in all trials. This parallels the distinction between CM and VM training that was studied explicitly in Schneider and Shiffrin's experiments.

The principal objective of the research reported here was to discover whether the CM-VM distinction also influences performance in auditory attention tasks. It is clear that Shiffrin and Schneider regard their theory to be quite general, and to apply to both auditory and visual modalities. Indeed, they have argued (Shiffrin & Schneider, 1977) that their extension of the Deutsch and Deutsch (1963) model accounts for the results of research in auditory selective attention. Research designed explicity to apply the CM-VM manipulation to the auditory modality should establish whether the automatic-controlled distinction is specific to visual search or is common to both visual and auditory modalities.

In Schneider and Shiffrin's experiments, subjects were required to detect a target letter or digit in a single visual display or in a rapid succession of displays. The important independent variables were the number of items in each display (frame size) and the number of possible target items (memory set size). Under VM conditions, the principal findings were that errors and reaction time (RT) increased with both frame size and memory set size. With sufficient practice under CM conditions, errors and RT were essentially unaffected by frame size and memory set size. Furthermore, when the sets of target and distractor items were exchanged after extensive practice in the CM condition, performance was severely disrupted. Apparently, the automatic response to target items continued after the target and distractor sets were exchanged.

Do consistent and varied mapping have similar effects in auditory tasks? To address this question, we can draw an analogy between visual search and auditory target detection. In both tasks, an observer must find designated target items among distractors. Auditory target detection requires the observer to listen to a sequence of stimuli, and respond when a target is presented. One of the independent variables from Schneider and Shiffrin's experiments, memory set size, has a direct analogue in the auditory detection task. Memory set size refers to the number of target items the person is listening for. The other independent variable, frame size, has no exact counterpart in the auditory modality. However, an analogy can be drawn between frame size and number of competing auditory messages. Thus a dichotic condition, in which stimuli are presented simultaneously to the two ears, would correspond to a frame size of two. Presentation of a single message to one or both ears would correspond to a frame size of one.

Previous research on auditory target detection provides little guidance regarding the effects of frame size and memory set size under CM and VM conditions. The most extensive investigations of auditory target detection have been conducted by Moray (e.g. Moray, 1975; Ostry, Moray, & Marks, 1976). He compared accuracy in dichotic and single-channel conditions, and found that accuracy is equal in these two conditions providing that two targets do not occur simultaneously in the dichotic conditions. Thus, one might say that in Moray's experiments "frame size" did not affect accuracy. However, it is important to note that participants in his experiments received extensive practice with a constant assignment of items to target and distractor sets. In other words, Moray used a consistent mapping condition.

Previous investigators have rarely used varied mapping procedures in auditory detection research. Thus, it is not clear whether Moray's results depended on the consistent assignment of items to the target and distractor sets. In the experiments reported below, performance in an auditory detection paradigm was investigated using both varied and consistent mapping.

EXPERIMENT 1

In Experiment 1, the effects of memory set size were examined under CM and VM conditions. Subjects listened to dichotically presented letters for either one or three target letters. The time to react to the presence of a target letter was recorded. If a serial search is necessary under VM conditions as Schneider and Shiffrin argued, then on each trial the subject would be required to successively compare each member of the dichotically presented pair to each item in the target set. For pairs that did not contain a target, two comparisons would be necessary for memory set size one and six comparisons would be necessary for memory set size three. The average number of comparisons necessary for positive pairs that did contain a target item would depend on whether an exhaustive or self-terminating search was employed. An average of two or six comparisons would be necessary for an exhaustive search, while an average of 1.5 or 3.5 comparisons would be necessary for a self-terminating search. In either case, VM would lead to a difference in RT between the one- and three-item memory sets and this difference would remain even after extensive practice.

In contrast, if CM leads to an automatic attentional response, then serial comparison of each target item with each stimulus pair should be unnecessary after sufficient practice. Rather, a target item should evoke an automatic attentional response. In this case, we would expect the RT difference between one-item and three-item memory set size conditions to diminish with practice. Furthermore, reversing the target and distractor sets should be extremely disruptive after CM training has established automatic responding.

Method

Subjects

The subjects were 22 students at the University of Washington. Each participated in six one-hour sessions over a two-week period. Subjects were recruited through advertisements in the campus newspaper, and were paid $3.00 per hour. Eleven subjects were assigned to the CM and 11 to the

VM conditions. For the CM group, the target set remained constant for the first four days of the experiments. For the VM group, targets and distractors were changed in every block of trials. Counterbalancing of stimulus materials required the division of CM and VM groups into two subgroups containing five or six objects each. Members of each subgroup were tested simultaneously.

Stimuli and Design

The stimuli were the letters A, B, G, H, I, L, R and U, spoken in a male voice. The durations of the stimuli ranged from 310 msec for the letter G to 378 msec for the letter U. Pairs of letters were presented dichotically with computer-synchronized stimulus onsets. The onsets of successive pairs were separated by 700 msec. In each stimulus block, 150 pairs of letters were presented. Twenty of these pairs contained a target letter. The same letter was never presented to both ears simultaneously, and two targets were never presented simultaneously. In fact, the spacing between consecutive targets ranged from 4 to 11 letter pairs. The ear to which a target letter was presented was chosen randomly with the restriction that 10 targets were presented to each ear. During blocks where there were three possible target items, the target presented at each position was chosen randomly.

The 16 blocks required for each session were recorded on auditory tape. Four tapes were recorded for the CM condition and two for the VM condition. For two of the four CM tapes, the target items were drawn from the set (A, B, G, H) and the distractors were drawn from (I, L, R, U). For the other two CM tapes, the target and distractor sets were reversed. On the VM tapes, the targets were drawn from the entire set of eight letters; four distractors were chosen randomly from the remainder of the set for each block. On both VM and CM tapes, the number of possible target items (one or three) alternated from block to block. On half of the tapes in each condition the first block contained one target item. On the other half, the first block contained three target items.

The target letters were counterbalanced over blocks. In the CM condition, each of the four target letters was a target in 8 of the 16 blocks. In two blocks it was the only target letter and in six blocks it was one of three target letters. In the VM condition, each of the eight letters appeared as a target in four blocks. In one block it was the only target letter and in three blocks it was one of three target letters.

In the first four sessions of the experiment, the two subject groups in the VM condition listened to the two VM stimulus tapes. These two tapes were alternated from session to session and counterbalanced the order of the number of targets. Similarly, the CM group with (A, B, G, H) as targets and the CM group with (I, L, R, U) as targets listened to two tapes alternated over sessions. In the fifth and sixth sessions, target and distractor sets were reversed for the two CM groups. Thus, the group that had received (A, B, G, H) as targets during the first four sessions now received (I, L, R, U) as targets, and vice versa. In the fifth and sixth sessions, the VM groups also listened to CM tapes. One VM group listened to the tapes with (A, B, G, H) as targets and the other VM group listened to the tapes with (I, L, R, U) as targets.

Apparatus

The stimulus tapes were produced under computer control. Each of the stimuli was digitized at a 10-KHz sampling rate and normalized by a PDP 11/10 computer at the University of Denver. The computer controlled the output of the stimuli which were recorded using a Teac 4-channel recorder. Whenever a target letter was output, a brief pulse was recorded on a third channel of the tape in synchrony with the letter onset.

The experiment was conducted at the University of Washington under control of a NOVA 800 computer. The stimulus tapes were played on a similar Teac 4-channel recorder. The output of the third channel led to a voice key which activated a contact sensed by the computer. Thus, the computer was synchronized with the tape. The computer controlled the display of target letters on oscilloscopes, recorded the response time to each target, and recorded false alarms.

Each subject was seated in a sound attenuating chamber facing an oscilloscope and a response key panel. The stimuli were presented via Telephonics TDH-39 headsets at a comfortable listening level.

Procedure

At the beginning of the experiment, subjects were instructed that letter names would be spoken rapidly to both ears, and their task was to press a single response key whenever certain target letters occurred. Each subject was told to respond with the index finger of the dominant hand. The target and distractor sets were described to subjects in the CM groups and the complete letter set was described to subjects in the VM groups.

Each subject listened to 16 blocks of 150 letters pairs during each session, plus an extra practice block during the first session. At the beginning of each block, an auditory message identified one or three target letters. In addition, throughout each block the target letters were continuously displayed on an oscilloscope in front of each subject. At the beginning of the fifth session, subjects were informed that the target and distractor sets would be changed for Sessions 5 and 6.

Results

Scoring Responses

Each response was categorized as either a response to a target (a hit) or a response when no target was presented (a false alarm). A response was scored as a hit if (a) it occurred during a temporal window beginning 200 msec before and ending 2500 msec after the target onset, and (b) it was the first response in such a temporal window. All other responses were categorized as false alarms. A miss was scored whenever no response was scored as a hit for that target. The RT for a hit was defined as the time between target onset and response. In calculating mean RTs, hit responses were omitted which exceeded the mean RT plus three standard deviations for that subject in that condition.

The data from the first day of the experiment for six subjects in the VM condition were lost due to a power failure. Accuracy and RT data for the VM condition on Day 1 are based on the remaining five subjects.

Reaction Times

Figure 1 shows mean RT as a function of practice for the CM and VM groups, and for memory set sizes one and three. First consider the data from Days 1 through 4. It is clear from Figure 1 that the mean RT for the VM group was considerably slower than mean RT for the CM group, as Schneider and Shiffrin found for visual stimuli.

For the VM condition, a repeated measures analysis of variance (ANOVA) was conducted on RT for Days 2 through 4; Day 1 was eliminated due to missing data. Mean RT in the VM condition was over 100 msec longer for three targets than for one target, *F*(1,10) = 296, $p < .001$, and mean RT decreased steadily over the four days, resulting in a significant main effect of days, *F*(2,20) = 23, $p < .001$. However, the difference in RT between memory set sizes one and three remained relatively constant over days, resulting in a nonsignificant interaction, *F*(2,20) = 2.6, $p > .05$.

For the CM condition, an ANOVA of RT for Days 1 through 4 was conducted. Again, RT was longer for three targets than for one target, *F*(1,10) = 54, $p < .001$. In addition, mean RT decreased over days, though not as much as in the VM condition, resulting in a significant main effect of days, *F*(3,30) = 6.2, $p < .005$. Perhaps the most interesting difference between the CM and VM conditions is the interaction between days and memory set size. In the CM condition the difference in RT between set sizes one and three declined monotonically from 83 msec on Day 1 to 26 msec on Day 4, producing a highly significant interaction, *F*(3,30) = 14.7, $p < .001$.

On Days 5 and 6 all subjects experienced consistent mapping of stimuli and responses. To examine the effects of the change in conditions, mean RTs for CM and VM groups on Days 4 and 5 were analyzed using a mixed design ANOVA in which the between-subjects factor was the mapping condition (CM or VM) and the within-subjects factors were days and memory set size. In both days and both conditions the mean RT was slower for three targets than one target, producing a significant effect of memory set size, *F*(1,20) = 186, $p < .001$. However, the mean RTs averaged over groups or over days were approximately equal, resulting in nonsignificant main effects.

Subjects in the VM group showed an immediate improvement in performance on Day 5, whereas the CM group was highly disrupted by the reversal of the target and distractor sets. As a result, the Mapping Condition X Day Interaction was highly significant, $F(1,20) = 64$, $p < .001$. In addition, the Mapping Condition X Memory Set Size Interaction was highly significant, $F(1,20) = 13.9$, $p < .005$, because the effect of memory set size was so large in the VM condition on Day 4. Indeed, the most interesting result was the change in the memory set size effect over days. For the VM condition the difference between set sizes one and three declined from 113 msec on Day 4 to 53 msec on Day 5. In marked contrast, for the CM condition the difference between set sizes increased from 26 to 68 msec. The ANOVA confirmed that this three-way interaction between mapping condition, day, and set size was highly significant, $F(1,20) = 48$, $p < .001$.

Accuracy

Figure 2 shows percent of missed targets as a function of practice for CM and VM groups, and for memory set sizes one and three. In many ways the miss rate data parallel the RT data. For Days 1 through 4 the miss rate was substantially higher for the VM group (about 15% overall) than the CM group (about 3%).

For the VM condition an ANOVA of miss rates for Days 2 through 4 was conducted. Miss rate in the VM condition declined over days, producing a significant main effect of days, $F(2,20) = 9.0$, $p < .005$. Furthermore, the miss rate was higher when listening for three targets than when listening for one target, $F(1,10) = 9.3$, $p < .05$. However, the effect of memory set size did not change over days, $F < 1$.

For the CM condition an ANOVA was conducted for Days 1 through 4, and no significant effects were obtained. The miss rate was relatively low on all four days, and there was little difference between miss rates for set sizes one and three.

The reversal of targets and distractors on Day 5 resulted in an increase in the miss rate for the CM group. For the VM group, the change to a consistent target set resulted in a substantial decrease in miss rate. Miss rates for Days 4 and 5 of the CM and VM groups were analyzed using a mixed design ANOVA in which the between-subjects factor was mapping condition and the within-subjects factors were days and memory set size. None of the main effects were significant, though the memory set size effect approached significance, $F(1,20) = 4.3$, $p < .10$. However, the Mapping Condition X Day Interaction was significant, $F(1,20) = 23$, $p < .001$, as was the three-way interaction between mapping condition, day, and memory set size, $F(1,20) = 17$, $p < .001$.

False alarm rates, shown in Figure 3, were computed by dividing the number of false alarms by 1040, the number of stimulus pairs in each condition that did not contain a target. The false alarm rates were low, never exceeding 1% (or 10 false alarms) in any condition. On Days 1 through 4 there was little difference between false alarm rates for the CM group (.5% overall) and the VM group (.6%). However, false alarm data on Days 5 and 6 paralleled data on RT and misses; false alarms increased for the CM group, for whom targets and distractors had been reversed, and decreased for the VM group, who had been switched to a consistent set of targets.

Discussion

Although we have drawn an analogy between auditory detection and visual search, there are several important differences between the two paradigms. For example, an entire visual display appears virtually simultaneously, while an auditory stimulus is extended in time. Thus, it is not clear which temporal segments of the auditory stimuli evoke the response. Furthermore, in many visual search tasks, each stimulus presentation constitutes a discrete trial. In Experiment 1, pairs of stimuli were presented in a continuous sequence, so targets could not be changed before every stimulus presentation. Thus, even in the VM condition the target set remained constant for blocks of 150 trials.

In spite of these differences, Experiment 1 showed the effects of consistent and varied mapping to be quite similar for the two paradigms. Performance under CM conditions was far superior to that in VM conditions, as indicated by both RT and accuracy. Equally important, the effect of memory set size was much greater in the VM condition, where it remained relatively constant over the first four days, than in the CM condition, where it decreased steadily from Day 1 to Day 4. Finally, the reversal of targets and distractors caused a marked decrement in both speed and accuracy of performance for the CM group. For the VM group, the switch to a consistent set of targets and distractors resulted in an improvement in speed and accuracy. All of these results are consistent with the findings of Schneider and Shiffrin (1977; Shiffrin & Schneider, 1977).

Can we conclude that "automatization" occurred in the CM condition and a serial search was conducted in the VM condition? The principle evidence for automatization is the absence of a memory set size effect. However, even on Day 4 there was still a difference of 26 msec in RT between the two memory set sizes. Is this difference sufficiently small to justify the conclusion that detection was automatic? Actually, this result is consistent with data obtained in visual search studies. Schneider and Shiffrin found small differences in RT between memory set sizes of one and four (1977, Experiments 1 and 2) using digits as targets and letters as distractors. Larger effects of memory set size have been obtained when targets and distractors are drawn from the same categories. For example, in our laboratory we found effects of frame size and memory set size in a CM condition after 12 days of practice at visual search for target letters among distractor letters (Yantis, Hunt, & Wright, Note 1). Thus, the effects of memory set size are comparable in auditory and visual CM conditions.

Perhaps, the critical observation is that the effect of memory set size decreased steadily for the CM condition, but remained relatively constant in the VM condition. This observation suggests that changes in the detection process are reducing the effect of memory set size. Finally, the performance deficits observed when the target and distractor sets were switched indicate that the developing detection process is dependent on a fixed target and/or distractor set. Taken together, these results suggest that automatic attentional responses to the target stimuli were developing.

We conclude that the distinction between CM and VM is an important determinant of the speed and accuracy of responses to auditory stimuli. In light of the CM-VM distinction, it is interesting to review the literature on auditory detection. In most of this research, targets were drawn from one class of stimuli and distractors were drawn from another. Most commonly, targets were digits and distractors were letters or vice versa. Thus, these experiments involved CM conditions in which target and distractor sets corresponded to well-learned categories. However, the amount of practice provided to subjects has varied widely. For example, in an experiment reported by Ostry, Moray, and Marks (1976, Experiment 1) subjects responded to the same target set for ten 1-hour sessions. In contrast, Ninio and Kahneman (1974) conducted only 45 trials per subject.

If CM conditions encourage development of automatic attentional responses to auditory stimuli, then the results obtained from CM studies of auditory detection should be crucially dependent on the amount of practice subjects received. A review of the literature suggests that those researchers whose subjects received extensive practice emphasize the efficiency of time-sharing between the ears, while those researchers whose subjects received little practice emphasize deficits in dichotic as compared to single-channel conditions.

Moray (1975) reviewed a number of studies of auditory detection in which subjects received extensive practice (often over 40 hours) under CM conditions. For the divided-attention conditions, Moray computed accuracy in detecting a signal in one channel conditional upon the response to the signal in the other channel. Accuracy conditional upon a correct rejection was equal to accuracy in either single-channel or selective-attention conditions. This result indicates that after sufficient practice subjects can respond with equal accuracy while attending to one or two channels, as long as they are not required to respond to targets in both channels at once. "Frame size" does not affect accuracy under these conditions. However, accuracy conditional upon a hit or a false alarm was low, indicating that detection of a target is impaired by simultaneous perception of a target in the other channel. This result also seems consistent with the notion of an automatic attentional response. If one or more targets elicit a single attentional response, then simultaneous presentations of two targets may often pass unnoticed.

With less practiced subjects, Treisman and Fearnley (1971) found effects of both memory set size and frame size on RT to detect an auditory stimulus. These researchers measured the time to decide whether an auditorily presented stimulus or pair of stimuli contained a digit. They varied frame size by presenting either one or two stimuli at a time, and varied memory set size by either cuing which digit might occur (memory set size one) or providing no cue (memory set size ten). Subjects received 240 trials on each of four days in this task. Treisman and Fearnley reasoned that if subjects used a serial search to compare each member of the target set to each of the stimuli, then the difference between cued and uncued conditions should be much greater when stimuli were presented in pairs then when they were presented singly. Although they found a difference between cued and uncued conditions, this difference was about equal for pairs and single stimuli, in clear contradiction to a serial search model. However, the effectiveness of the cue is evidence against automatic target detection, so neither model appears completely correct.

Finally, we turn to an experiment in which very little practice was provided. Ninio and Kahneman (1974) measured RT and accuracy in detecting an animal name embedded in a presentation of ten common words or pairs of words. Each subject participated in only 45 trials. Ninio and Kahneman compared performance in a divided-attention condition, where pairs of words were presented dichotically, to performance in a single-channel condition, where words were presented to one ear only. They found that both accuracy and speed were greater in the single-channel than the divided-attention conditions, in contrast to the findings reviewed by Moray (1975). Apparently, subjects were unable to develop automatic attentional responses in 45 trials, despite the consistent mapping of targets and responses.

In no previous studies of auditory detection has the possible set of target items changed from trial to trial. In all cases, targets have been drawn from one category and distractors from another. We are arguing that under these CM conditions, the effects of frame size and memory set size depend on the amount of practice the subject receives. Experiment 1 demonstrated that the effect of memory set size diminishes with practice, and previous research suggests that the frame size effect behaves similarly. In the studies Moray reviewed, where subjects had extensive practice, there was no effect of frame size. In the Treisman and Fearnley study, where subjects received a moderate amount of practice, there were effects of both frame size and memory set size, but the effects were smaller than would be predicted by a serial search model. Possibly, the detection process was partially automated. Ninio and Kahneman, whose subjects received very little practice, found a large effect of frame size.

EXPERIMENT 2

Now we turn to an examination of the effects of frame size under VM conditions. Subjects should be unable to develop automatic attentional responses to targets under VM conditions. Schneider & Shiffrin (1977) concluded that in VM conditions targets are detected by means of a serial, self-terminating search. They found that errors and RT increased when frame size increased under VM conditions. However, when subjects were instructed to attend to specific locations, performance was relatively unaffected by the presence or absence of distractors in the unattended locations (Shiffrin & Schneider, 1977, Experiment 4). Apparently, subjects can control the locations examined by the serial search process. Hence, an increase in frame size affects visual search performance only if more locations must be searched or, equivalently, attention is divided among more locations.

Continuing the analogy between visual search and auditory detection, we expect dichotic stimulation to produce decrements in performance, compared to a single-channel condition, when attention is divided between the two messages, but little or no decrement when attention is focused on one message. To examine these hypotheses, in Experiment 2 auditory target detection was conducted in three conditions: (a) pairs of letters were presented dichotically and targets were presented equally often to both ears (divided-attention condition); (b) pairs of letters were presented dichotically and targets were presented only to the attended ear (selective-attention condition); and (c) single letters, including targets, were presented only to one ear (single-channel condition).

A recurrent theme in this research has been to derive and test predictions regarding auditory target detection from research on visual search. However, it is clear that there are major differences between the two paradigms, as noted earlier. Thus Experiment 3 matched all the conditions of Experiment 2 as closely as possible, but with visual stimuli, in order to examine visual frame size effects. Taken together, Experiments 2 and 3 permit direct comparisons of auditory and visual frame size effects. In fact, these experiments were conducted with the same subjects and can be thought of as a single experiment; they are separated only for expository ease.

The most interesting comparisons provided by Experiments 2 and 3 are of individual difference in performance. A common assumption in the applied literature is that a time-sharing ability exists which influences performance with both auditory and visual stimuli in a wide range of tasks. However, recent empirical evidence fails to support this assumption (eg., Hawkins, Rodriguez, & Reicher, Note 2). Since the same subjects participated in both experiments, it was possible to ask whether a divided-attention ability affects target detection in both modalities by comparing individual abilities to cope with increases in stimulus load.

Method

Subjects

Eighty-five subjects, ranging in age from 18 to 60 participated in this study. They were recruited through an ad in the University of Washington newspaper, and were paid $4.50 per 1 ½-hour session for three sessions. The same subjects participated in Experiments 2 and 3.

Stimuli

Three stimulus tapes were constructed in a manner similar to that reported for Experiment 1. On each tape there were 12 blocks of trials composed of four blocks in each of the three conditions: single channel, selective attention, and divided attention. The first six blocks on each tape included two consecutive blocks for each condition. For single-channel and selective-attention conditions, subjects attended the right ear for one of the two consecutive blocks and the left ear for the other. The last six blocks reversed the order of the first six blocks. The order of conditions was counterbalanced according to a latin square over the three tapes.

The letter set for Experiment 2 was (A, B, G, H, I, J, K, L, R, T, U, Y). Each letter was a target in one block of each tape and a distractor in the remaining 11 blocks. In addition, each letter was a target once in each condition over the three tapes.

In each block, a total of 150 letters or letter pairs were presented.

As in Experiment 1, 20 targets were presented in each block. The spacing between targets was the same as in Experiment 1. Thus, two targets never occurred simultaneously. Distractors were selected randomly from the remaining 11 letters.

Procedure

As in Experiment 1, subjects were instructed to listen for target letters and press a key whenever one occurred. However, subjects were asked to listen for only one target letter in each of the 12 blocks presented in a session. At the beginning of each block an auditory message instructed the subject to listen for a particular letter in the attended ear or in either ear. As a reminder, the target letter also was presented on one or both sides of an oscilloscope screen.

Subjects listened to a different tape in each session, and the order of the tapes was the same for all subjects. These procedures were followed to avoid confounding order effects with individual differences.

Results and Discussion

Scoring Responses

A response was scored as a hit if it occurred during a window beginning 150 msec and ending 1500 msec after the target onset. All other responses were categorized as false alarms, and a miss was counted for every target without a hit response. In calculating mean RTs, those hit responses were omitted which exceeded the mean RT plus three standard deviations for that subject in that condition.

Three subjects missed more than 25% of the targets in the single-channel condition and were excluded from all further analyses. In addition, computer problems resulted in the loss of data from 11 subjects on Day 1 and 10 subjects on Day 2. Three subjects quit the study after Day 2. Means and analyses of variance were computed from the data of the remaining 58 subjects.

Reaction Times

Table 1 shows mean RT for single-channel, selective-attention, and divided-attention conditions for each day and averaged over days. It should be noted that day was confounded with target letter in this experiment, since a particular letter served as a target in a particular condition on only one day. Thus, all the variability over days may be due to the confusibility of particular target and distractor letters. For example, this confounding probably accounts for exceptionally long RTs in the divided-attention condition on Day 2, since "A" was a target in that condition on that day, and tended to fuse with "J" or "K" on the other channel.

As expected, mean RT was much longer in the divided-attention condition than the single-channel condition. However, mean RT also was longer in the selective-attention condition than the single-channel condition, though not as long as in the divided-attention condition. An ANOVA confirmed these observations. The effects of days, conditions, and the interaction were all highly significant, $F(2,114) = 28$, $F(2, 114) = 569$, and $F(4, 228) = 75$, respectively, $p < .001$. Furthermore, paired comparisons using Duncan's Multiple Range Test showed that all three conditions were significantly different from one another, $p < .001$.

Thus, an increase in frame size causes an increase in RT for auditory target detection when attention is divided between stimulus channels. Surprisingly, RT also increases when attention is focused on a single channel.

Should we conclude that auditory stimuli do not permit effective control of the locations to be searched? An alternative explanation is that simultaneous presentation of two auditory stimuli interferes with the processes required for stimulus identification. Such a masking effect could increase the time required to identify the stimuli in each channel.

Accuracy

The percent of misses and false alarms are shown in Table 2 for each condition and each day. For both kinds of errors the results parallel the RT results. The most errors of both kinds occurred in the divided-attention condition and the fewest errors occurred in the single-channel condition. Separate ANOVAs for false alarms and misses confirmed these observations. For misses, the main effects of days, conditions, and their interaction were all highly significant, $F(2, 114) = 32$, $F(2, 114) = 311$, and $F(4, 228) = 35$, respectively, $p < .001$, and all pairs of condition means were significantly different from one another, $p < .001$. For false alarms, the main effects of days and conditions were highly significant, $F(2, 114) = 10.2$, and $F(2, 114) = 53$, respectively, $p < .001$. The Days X Conditions Interaction was marginally significant $F(4, 228) = 2.7$, $p < .05$. All pairs of condition means were significantly different from one another, $p < .01$.

EXPERIMENT 3

Experiments 2 and 3 were the same in nearly all respects except for stimulus modality and rate of presentation. Thus, the same predictions hold for Experiment 3 as for Experiment 2. Presentation of two stimultaneous stimuli was expected to produce a performance decrement when attention was divided between the stimuli. However, little or no decrement was expected when attention was focused on one stimulus location.

If an ability to divide attention is an important source of *variability between subjects*, then the correlation between single-channel and divided-attention conditions in each experiment should be substantially less than the reliabilities of those measures. An ability to divide attention also might produce a higher correlation between the auditory and visual divided-attention conditions than between the auditory divided-attention condition and the visual selective-attention condition.

Method

The method for Experiment 3 was essentially the same as for Experiment 2 except that visual rather than auditory stimuli were used. In the single-channel condition, single letters were presented to either the right or left of the center of a computer-controlled oscilloscope. Within a block the position of presentation was constant. In the selective- and divided-attention conditions, pairs of letters were presented simultaneously to the right and left of the center. Letters were defined on 7 x 7 dot matrices, 4.38 mm square and 1.23 mm apart. Viewed from a distance of 40 to 70 cm, a letter pair projected a visual angle of .8 to 1.4 degrees.

Order of presentation of conditions and stimuli within conditions duplicated that of Experiment 2. In pilot experiments, we found that this task was trivially easy when stimuli were presented at the rate of one letter or letter pair every 700 msec used in Experiments 1 and 2. Therefore, stimuli were presented at a rate of one letter or letter pair every 400 msec.

Results and Discussion

Due to computer failures part of the data were lost for one subject on Day 1, and all the data were lost for four subjects on Day 3. In addition, three subjects did not return for Day 3 of the experiment. Means and ANOVAs were computed from the data of the remaining 77 subjects.

Reaction Times

The mean RT for the single-channel, selective-attention, and divided-attention conditions are presented in Table 3 for each day. As in Experiment 2, day was confounded with target letter, and is included in the analysis to control for the combined effects of day and targets.

As in Experiment 2, mean RT was longest for the divided-attention condition and shortest for the single-channel condition. An ANOVA confirmed that the three conditions were all different from one another. The effect of days, conditions, and the interaction were all significant, $\underline{F}(2, 152) = 4.7$, $\underline{p} < .01$, $\underline{F}(2, 152) = 136$, $\underline{p} < .001$, and $\underline{F}(4, 304) = 21$, $\underline{p} < .001$, respectively.

Furthermore, paired comparisons showed that all three conditions were significantly different from one another, $\underline{p} < .001$.

As in the auditory modality, an increase in visual frame size causes an increase in RT for visual target detection. The increase in RT is largest if attention must be divided between stimulus locations, but occurs even when attention is focused on a single channel. Again, it is unclear whether the performance decrement in the selective-attention condition is due to ineffective control of search location or lateral masking. The principal difference between the results of Experiments 2 and 3 is the size of the effects. The mean RT was 156 msec longer in the divided-attention condition than the single-channel condition in Experiment 2, but only 29 msec longer in Experiment 3.

Accuracy

The percent of misses and false alarms are shown in Table 4 for each condition on each day. Both error rates were much lower in Experiment 3 than in Experiment 2. Furthermore, the error rates did not display the same consistent pattern observed in the RT results for both experiments ana in the error rates for Experiment 2. Again, the error rates were largest in the divided-attention condition. However, the differences between the single-channel and selective-attention condition were small. Separate ANOVAs for misses and false alarms confirmed these observations.

For misses, the effect of condition was highly significant, $\underline{F}(2,152) = 9.0$, $\underline{p} < .001$. However, the effect of days was nonsignificant, $\underline{F} < 1$, and the interaction was marginally significant, $\underline{F}(4, 304) = 2.4$, $\underline{p} < .05$. Paired comparisons showed that miss rate was higher in the divided-attention condition than either the single-channel or selective-attention conditions, $\underline{p} < .05$.

However, miss rates for the single-channel and selective-attention condition were not significantly different from one another.

For false alarms, only the effect of condition was significant, _F_(2, 152) = 4.3, $p < .05$. Again, paired comparisons showed that false alarm rate was higher in the divided-attention condition than either the single-channel or selective-attention condition, $p < .05$, but the difference between the single-channel and selective-attention conditions was nonsignificant.

CORRELATIONAL ANALYSES

Correlational analyses were based on mean RTs averaged over the three days of each condition in Experiments 2 and 3. Data for 82 subjects were used in these analyses. Three subjects who missed more than 25% of the auditory targets in the *single-channel condition* were omitted from the analysis for both visual and auditory data. For 24 subjects, data were lost on one day of one of the experiments due to computer failure or attrition. For these subjects means in each condition were estimated on the basis of the data from the remaining two days. These estimates were derived using least-squares regression constants derived from the 58 subjects with complete data for all three days. The estimates can be assumed to be quite accurate, since the correlation between the 3-day mean and any given 2-day mean was greater than .96 for all measures.

The correlation matrix for mean RTs in Experiments 2 and 3 is shown in Table 5, with reliabilities in the diagonal. The most notable characteristic of this matrix is that the correlations among the three measures obtained with the same stimulus modality are extremely high, exceeding .88 in every case. RTs in the selective-attention and divided-attention conditions were almost perfectly predicted by RT in the single-channel condition. These correlations suggest that all three conditions require common processes that are more important in determining individual performance than processes specific to any one condition. For example, although RT in the divided-attention condition of Experiment 2 was 156 msec longer than RT in the single-channel condition, the ordering of individuals based on RT was very similar in the two conditions.

On the other hand, correlations between auditory and visual RT measures were much lower, ranging between .54 and .60. If an ability to divide attention is an important determinant of RT, then correlations between auditory and visual RTs in the divided-attention condition should be higher than other correlations across modalities. However, correlations between auditory and visual RTs were approximately equal for all pairs of conditions. For example, the correlation between RTs in the two divided-attention conditions (.55) was about equal to the correlations between RTs in the visual divided-attention and auditory single-channel conditions (.54) and in the auditory divided-attention and visual single-channel conditions (.58). Thus, there is little evidence that a general ability to divide or focus attention significantly influences the relationships between performance on tasks in the two modalities.

These observations suggest that individual differences in the RT data could be explained by two ability factors, one determining RTs in the three auditory conditions and the other determining RTs in the three visual conditions. This model was tested using maximum likelihood methods of confirmatory factor analysis (Jöreskog, 1973). The maximum-likelihood solution obtained using the LISREL IV program, is shown in Figure 4. A two factor model fit the data quite well. The correlation between the auditory and visual factors was .61. Deviations from the model were statistically insignificant, $\underline{chi}^2(8) = 10.18$, $\underline{p} < .25$.

Since there were only six RT measures, it was impossible to test a model in which there were separate factors for the single-channel, selective-attention, and divided-attention conditions in addition to the auditory and visual factors. However, the two factor model fit the data so well that additional factors are clearly not required. Instead, a model with only one factor was tested to examine whether even two factors were required. Deviations from the one-factor model were statistically significant, $\underline{chi}^2(9) = 232$, $\underline{p} < .001$. The two-factor model accounted for the data significantly better than the one-factor model, $\underline{chi}^2(1) = 222$, $\underline{p} < .001$.

The factor analyses of the RT measures supported conclusions based on examination of the correlation matrix itself: Individual differences in ability to divided or focus attention are relatively unimportant in determining performance on these auditory and visual detection tasks. However, it is useful to distinguish between speed of processing auditory and visual stimuli.

GENERAL DISCUSSION

Comparisons of Experiments 1 and 2 with Experiments 3 and with research on visual search (e.g., Schneider & Shiffrin, 1977) reveal remarkable similarities; remarkable because of the gross differences between auditory and visual stimuli. Consider the CM condition of Experiment 1. Subjects in the CM condition were both accurate and fast, and the effect of memory set size on accuracy and RT declined steadily and rapidly. When the target and distractor sets were switched, mean RT, the effect of memory set size, miss rate, and false alarm rates all increased to levels higher than at the beginning of the experiment. These observations all parallel results obtained by Schneider and Shiffrin (1977; Shiffrin & Schneider, 1977).

Schneider and Shiffrin attributed these results to development of an automatic attentional response that is activated when a target is presented. As target responses become automated fewer controlled comparisons are required between stimuli and members of the target set, thereby reducing the effect of memory set size. When target and distractor sets are switched, automatic responses to distractors interfere with detection of the new targets. In addition, inhibitory processes may have developed that interfere with recognition of the new target stimuli.

If automatic attentional responses develop in CM conditions as hypothesized, then several predictions are suggested that were not adequately examined in Experiment 1. First, with sufficient practice the effect of memory set size should approach zero asymptotically. In fact, memory set size did not affect accuracy after the first session, but produced a 26-msec effect on RT even on the fourth day. Perhaps Experiment 1 did not provide enough practice for target responses to become completely automated. Second, automatic attentional responses should eliminate any effect of frame size, such that RT and accuracy for divided-attention are equal to RT and accuracy for selective-attention. In fact, the research reviewed by Moray (1975) supports this prediction. Following extensive practice under CM conditions, target detection was equally accurate in single-channel, selective-attention, and divided-attention conditions. Finally, automatic attentional responses should cause false alarms to targets in a nonattended channel. Further research is in progress to test these predictions.

Now consider the VM condition of Experiments 1 and 2. Certainly there was no evidence of automatic attentional responding in this condition. In Experiment 1, RT was much longer and errors were more frequent in the VM condition than in the CM condition. Furthermore, the effects of memory set size on RT and accuracy did not change with practice. Experiment 2 confirmed that RT and accuracy also are affected by frame size, as represented by single-channel, selective-attention, and divided-attention conditions. Again, these observations parallel results obtained by Schneider and Shiffrin (1977) for visual search in a VM condition. Furthermore, the results of Experiments 2 and 3 were strikingly similar, differing only in the magnitude of the effects.

Schneider and Shiffrin (1977) attributed performance in the VM condition to a controlled, serial, self-terminating search process. The results of Experiments 1 and 2 appear consistent with the models they proposed. According to these models, subjects compare each possible target with the stimuli, and respond as soon as a target is identified. In Experiment 1, RT was longer for three targets than for one target because the mean number of comparisons conducted for each stimulus pair containing a target was 1.5 for one target and 3.5 for three targets. In Experiment 2, RT was longer for divided-attention than for selective-attention because 1.5 comparisons were conducted instead of one. The estimated time for a comparison according to these models is about 55 msec for Experiment 1 and 180 msec for Experiment 2.

The mean within-subject variabilities in RT also are consistent with the serial, self-terminating models. RT should be more variable for three targets than for one target, and more variable for divided-attention than for selective-attention. Increasing the channels or targets increases the maximum number of comparisons required for target detection, but does not affect the minimum number of comparisons. For example, in the divided-attention condition of Experiment 2 the target should be detected as a result of the first comparison on half the trials and the second comparison on the remaining trials. In Experiment 1, the mean standard deviations of RT in the VM condition were 189 msec for one target and 231 msec for three targets. In Experiment 2, the mean standard deviations were 130, 148, and 202 msec for the single-channel, selective-attention, and divided-attention conditions, respectively. Thus, increasing the number of channels or targets increased the variability, as required by serial, self-terminating models.

Although the serial, self-terminating models provide an adequate qualitative description of the results, other search models cannot be eliminated by these data. An important prediction of serial models is that memory set size and frame size affect performance equivalently. The prediction is being tested by research in progress.

In addition to the similarities already noted between the auditory and visual tasks, comparisons of Experiments 2 and 3 reveal some important differences between search processes in the two modalities. First, the differences in RT and accuracy between the single-channel and selective-attention conditions suggest that an unattended stimulus causes greater interference in audition than vision. In Experiment 3 (visual modality) the mean RT for selective-attention was 8 msec longer than for the single-channel condition. The miss and false alarm rates were not significantly different for the two conditions. In contrast, in Experiment 2 the mean RT was 65 msec longer for selective-attention than for the single-channel condition, and error rates were significantly higher in the selective-attention condition. These results are consistent with subjective impressions and experimental evidence that simultaneously presented auditory stimuli tend to fuse (e.g., Poltrock & Hunt, 1977), whereas simultaneous visual inputs do not. Perhaps the visual counterpart to dichotic letter pairs would be two letters superimposed in the same visual location.

In previous studies of auditory target detection, performance in divided-attention conditions has been compared to performance in both single-channel and selective-attention conditions. If the purpose is to study the subject's ability to divide attention between two locations, then the more appropriate comparison is with the selective-attention condition, since difficulties due to fusion and masking should be equal in these conditions. Here, as in the comparison between single-channel and selective-attention conditions, the differences were much greater for auditory than visual stimuli. In Experiment 2 (auditory stimuli), the difference in RT between selective-and divided-attention conditions was 91 msec. In Experiment 3, the difference was only 21 msec. The additional processes required to compare a single target letter to two, as compared to one, stimulus items take much more time in the auditory than the visual modality. There was also a much greater increase in miss rate from selective- to divided-attention conditions for Experiment 2 than for Experiment 3.

It is interesting to note that the difference between RTs to visual and auditory stimuli in the single-channel conditions was only 49 msec, although the duration of the auditory stimuli was over 300 msec and RT was measured from stimulus onset. This small difference in RTs suggests that subjects identified the auditory stimulus on the basis of a small temporal segment. However, a much slower presentation rate was required for the auditory stimuli, suggesting the existence of an auditory refractory period following stimulus identification.

The correlational relationships among the RT measures of Experiments 2 and 3 provide an interesting counterpart to the nomothetic results. These correlations suggest that performance is not determined or influenced significantly by an ability to divide attention between two stimulus channels. Rather, there appear to be separate, though correlated, abilities to detect visual targets and auditory targets. Performance in the divided-attention conditions were nearly perfectly predicted by performance in the associated single-channel conditions. Actually, these are the results one would expect if detection in all conditions results from a controlled search process. RT in each condition reflects the efficiency of the search process in that modality. Certainly, different modalities of presentation may require different search processes or affect the efficiency of the search process, and may influence people differently. However, if the same search process is used in all conditions in the same modality, but simply directed to different locations, then the efficiency of that one process will determine the RT in all conditions. Thus, the correlational and nomothetic results lead to compatible conclusions.

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Footnotes

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Table 1

Reaction time to targets as a function of day and condition in Experiment 2.

	Day			
Condition	1	2	3	Mean
Single Channel	489	488	480	486
Selective Attention	582	528	544	551
Divided Attention	665	685	575	642

Table 2

Percent of misses and false alarms as a function of day and condition in Experiment 2.

	Day			
Condition	1	2	3	Mean
		Misses		
Single Channel	4.9	4.0	4.5	4.5
Selective Attention	12.2	6.3	5.8	8.1
Divided Attention	26.3	31.3	16.0	24.5
		False Alarms		
Single Channel	.46	.32	.40	.39
Selective Attention	.61	.49	.50	.53
Divided Attention	1.10	.91	.68	.90

Table 3

Reaction time to targets as a function of day and condition in Experiment 3.

	Day			
Condition	1	2	3	Mean
Single Channel	437	441	432	437
Selective Attention	452	438	445	445
Divided Attention	480	468	450	466

Table 4

Percent of misses and false alarms as a function of day and condition in Experiment 3.

	Day			
Condition	1	2	3	Mean
		Misses		
Single Channel	2.2	2.8	2.2	2.4
Selective Attention	1.3	1.7	2.6	1.9
Divided Attention	3.8	2.8	3.0	3.2
		False Alarms		
Single Channel	.16	.28	.24	.22
Selective Attention	.16	.23	.25	.21
Divided Attention	.29	.27	.32	.29

Table 5

Correlation matrix of reaction times, summed over days, for Experiments 2 and 3.

		Auditory			Visual		
		Single	Selective	Divided	Single	Selective	Divided
	Single	.99					
Auditory	Selective	.92	.98				
	Divided	.88	.89	.96			
	Single	.58	.60	.58	.99		
Visual	Selective	.56	.57	.56	.97	.99	
	Divided	.54	.56	.55	.96	.97	.99

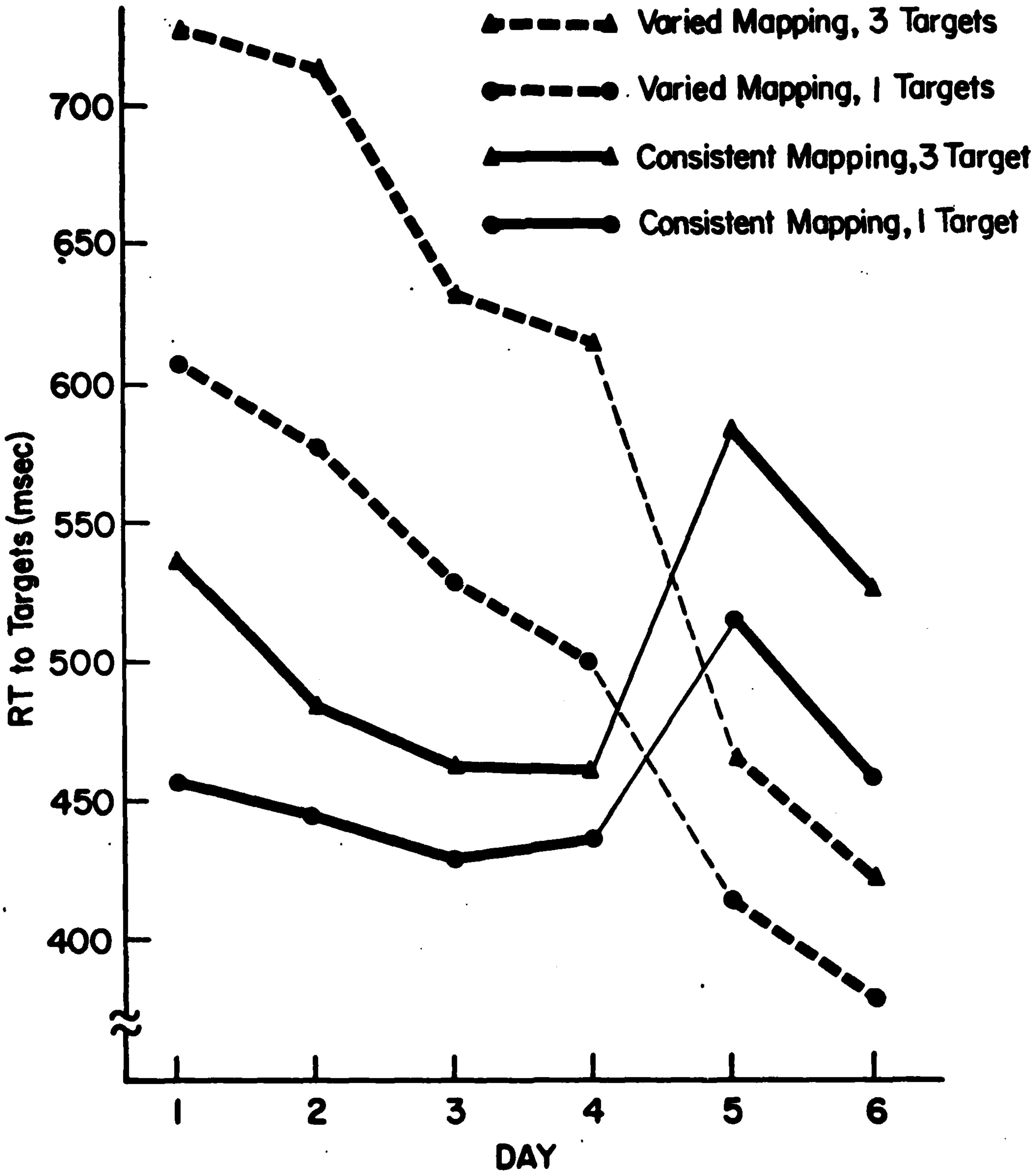
Figure Captions

Figure 1. Mean RT to targets as a function of practice for consistent and varied mapping groups, one and three targets, Experiment 1.

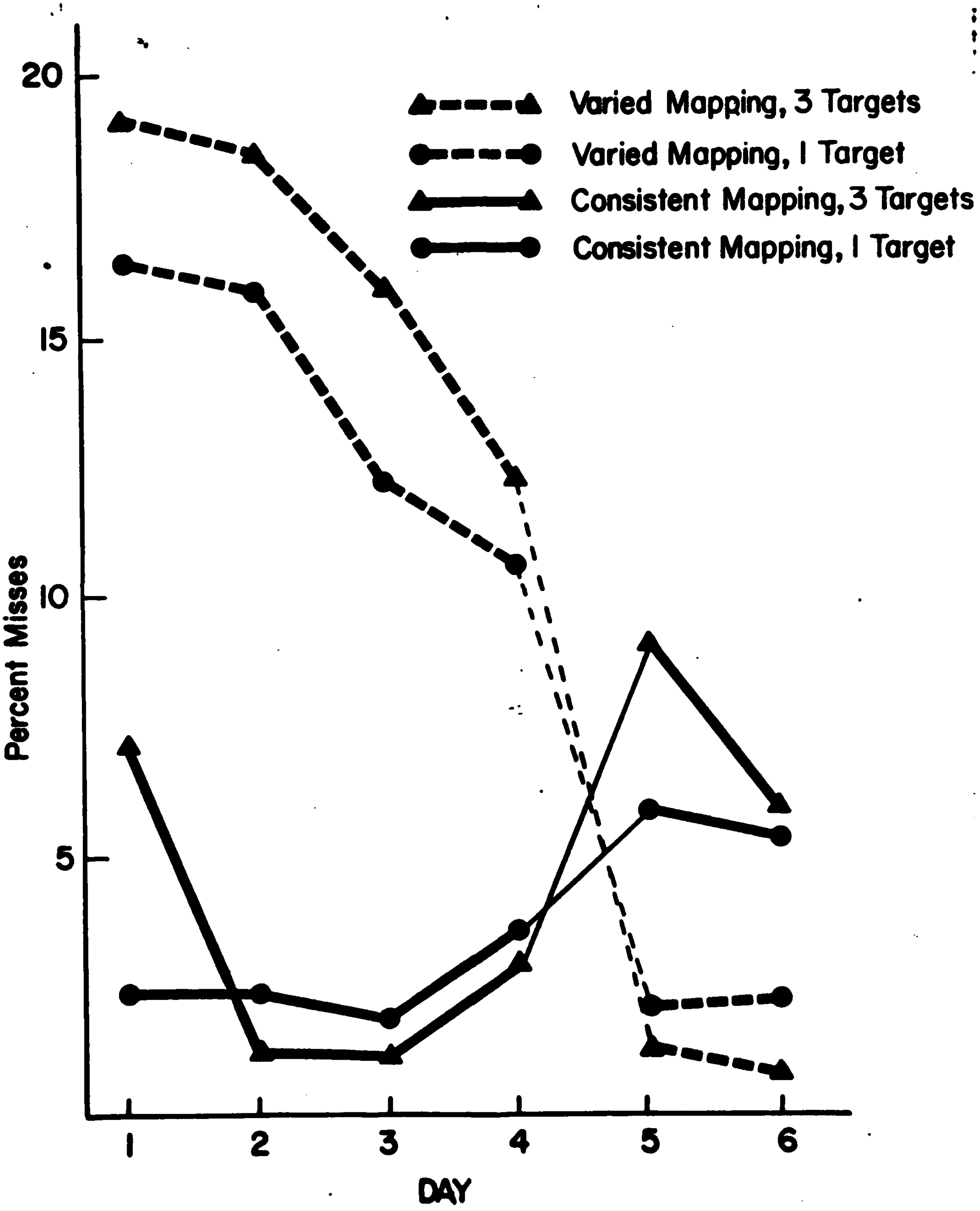
Figure 2. Mean percent misses as a function of practice for consistent and varied mapping groups, one and three targets, Experiment 1.

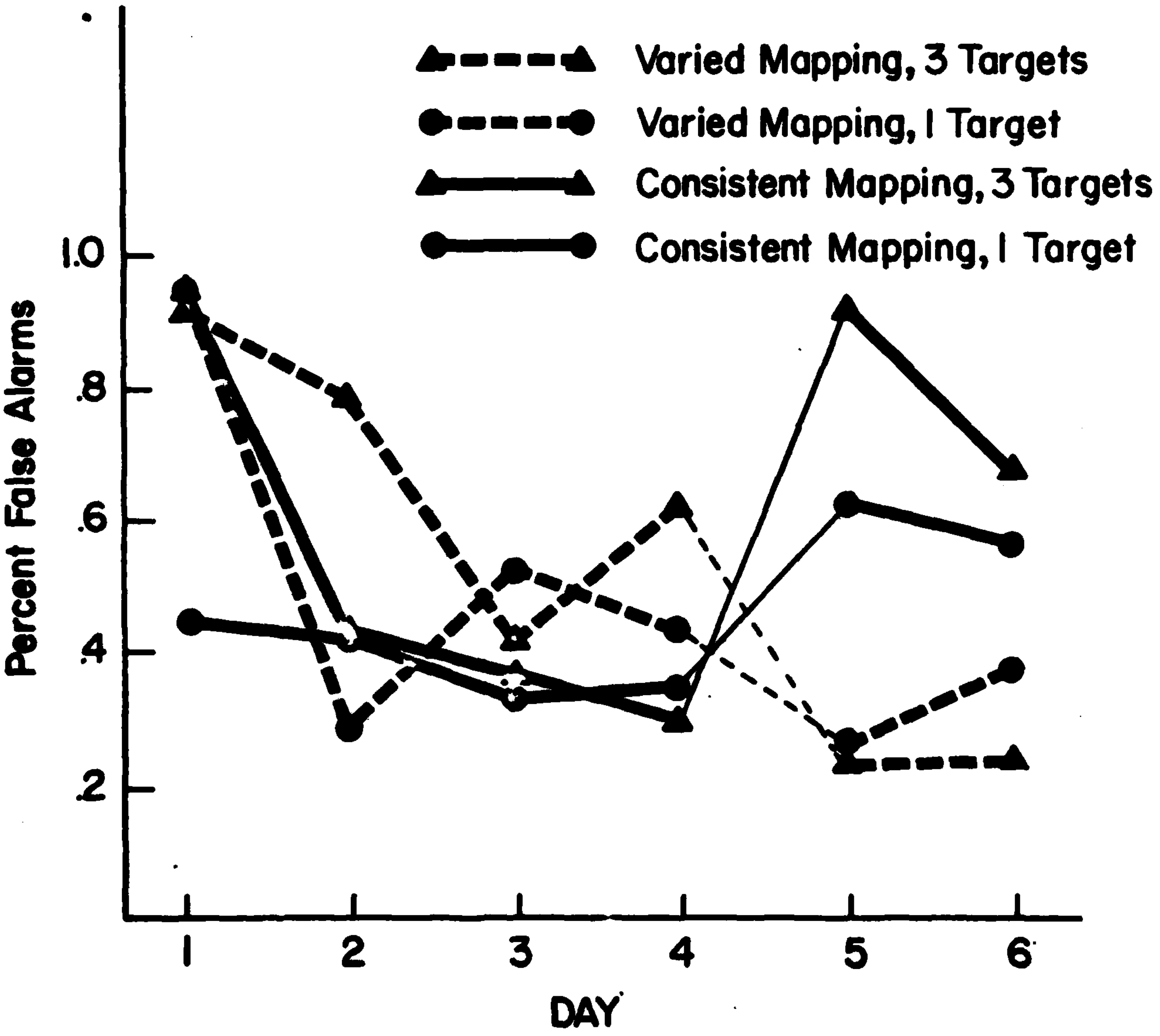
Figure 3. Mean percent false alarms as a function for practice for consistent and varied mapping groups, one and three targets, Experiment 1.

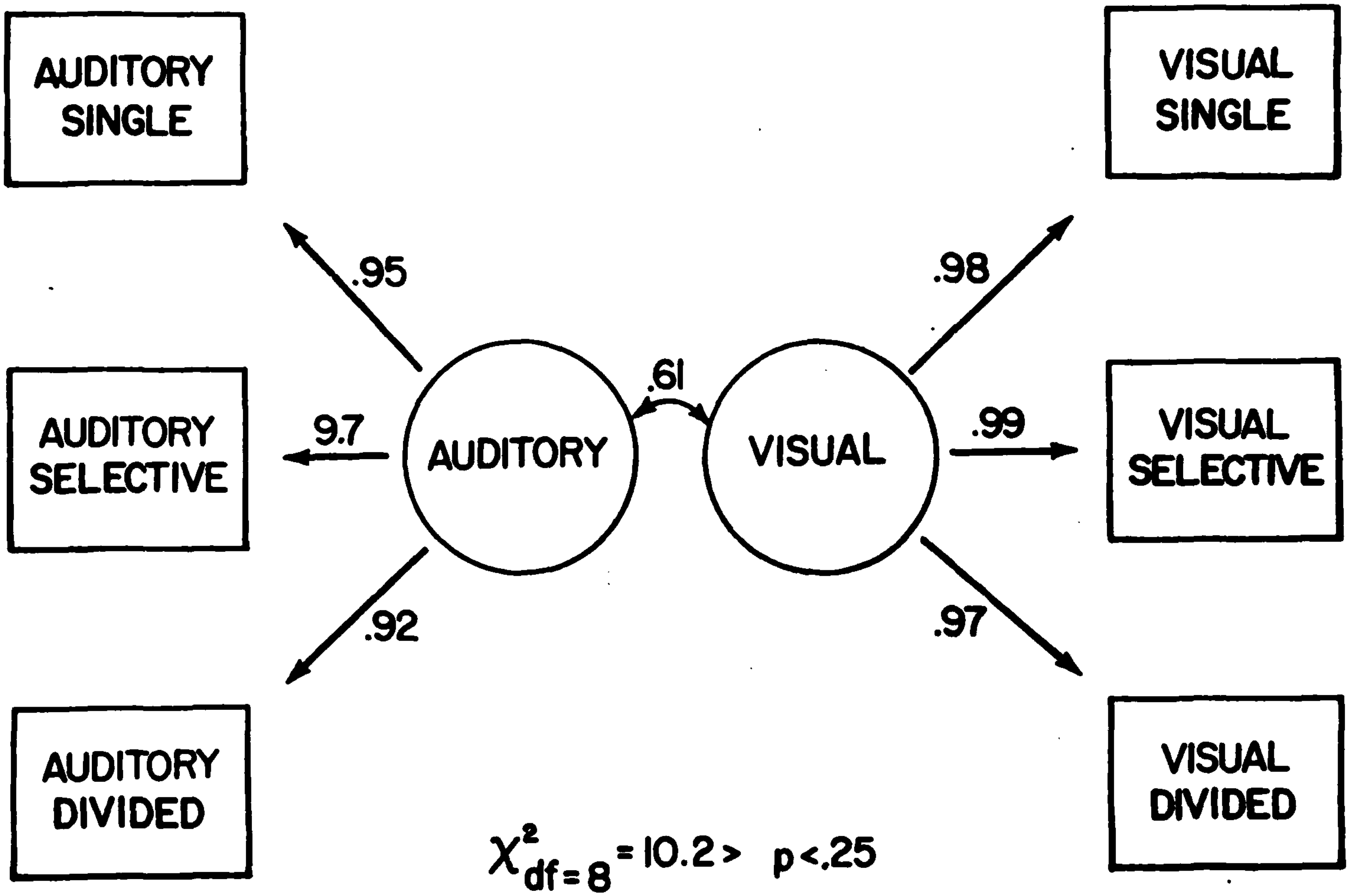
Figure 4. Fit of the two-factor LISREL model to the RT data from Experiments 2 and 3.



Varied Mapping, 3 Targets
Varied Mapping, 1 Targets
Consistent Mapping, 3 Target
Consistent Mapping, 1 Target
700
650
600
550
500
450
400
RT to Targets (msec)
1
2
3
4
5
6
DAY


Varied Mapping, 3 Targets
Varied Mapping, 1 Target
Consistent Mapping, 3 Targets
Consistent Mapping, 1 Target
20
15
10
5
Percent Misses
1
2
3
4
5
6
DAY


Varied Mapping, 3 Targets
Varied Mapping, 1 Target
Consistent Mapping, 3 Targets
Consistent Mapping, 1 Target
Percent False Alarms
1.0
.8
.6
.4
.2
1
2
3
4
5
6
DAY



$\chi^2_{df=8} = 10.2 > \quad p < .25$

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