Simultaneous auditory and tactile information processing

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Subjects were required to perform perceptual tasks when stimuli were presented simultaneously in the auditory and tactile modalities and when they were presented in one of the modalities alone. The results indicated that when the demands on cognitive processes are small, auditory and tactile stimuli presented simultaneously can be processed as well as when stimuli are presented in only one modality. In a task which required a large amount of cognitive processing, it became difficult for subjects to maintain high levels of performance in both modalities and the distribution of attention became an important determinant of performance. The data were consistent with a theory that cognitive, but not perceptual, processing is disrupted when subjects have difficulty performing two perceptual tasks simultaneously.

In designing any tactile communication system, consideration must be given to the degree of interaction between the sense of touch and other modalities. Only a few studies have focused on this problem (Brown, Galloway, & Gildersleeve, 1965; Brown, Galloway, & San Guiliano, 1965; Gescheider, Barton, Bruce, Goldberg, & Greenspan, 1969; Gescheider, Herman, & Phillips, 1970; Gescheider & Niblette, 1967; Loeb & Hawkes, 1962). Experiments conducted in our laboratory have consistently shown that when the contaminating effects of criterion shifting are eliminated, tactile thresholds for the detection of brief vibrotactile stimuli are raised no more than 1 or 2 dB by a simultaneous auditory tone. In a recent study, for example, it was found that auditory tones caused only slight decrements in the detectability of tactile stimuli even when the observer was required to make a difficult loudness recognition judgment of an auditory stimulus (Gescheider, Kane, Sager, & Ruffolo, 1974). Therefore, it appears that relatively efficient information processing can occur in both modalities when pairs of simple stimuli are presented simultaneously to the skin and ears.

The present study was designed to investigate further the conditions under which auditory and tactile information can be simultaneously processed. In each experiment, an attempt was made to alter the subject's ability to attend simultaneously to both modalities.

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EXPERIMENT I

In the study by Gescheider et al. (1974), subjects were told that tactile and auditory performance were of equal importance and that consequently they should carefully attend to both tactile and auditory stimuli. Under these conditions, when the subject had to perform tactile signal detection and auditory loudness recognition tasks for simultaneous tactile and auditory stimuli, tactile performance was as high as when no stimuli were presented in the auditory modality. It is possible that this result would not occur under a less favorable distribution of attention in which subjects were more highly motivated to perform correctly on the auditory than on the tactile task. The additional finding by Gescheider et al. that auditory performance was significantly higher when the subject had to attend only to auditory stimuli than when he had to attend to both tactile and auditory stimuli suggests that the distribution of attention in this study favored the tactile modality. In Experiment I, an attempt was made to vary the distribution of attention over the two modalities by changing the relative payoff for correct performance on the tactile and auditory tasks.

Method

Subjects. The subjects were three undergraduate students. Before the experiment, each subject was given not less than five 1-h practice sessions in detecting weak tactile signals and in recognizing two auditory stimuli that differed slightly in intensity.

Apparatus. Sinusoidal electrical signals generated by a General Radio 1304-B oscillator were applied to a Grason-Stadler 829E electronic switch to give a 500-Hz signal lasting 1 sec, with a rise and decay time of 25 msec. The output of the electronic switch was applied to a Grason-Stadler E3520B phase shifter, adjusted to

provide two independent signals in phase when applied to a Goodmans V-4" vibrator and a pair of Permoflux PDR-600 earphones. In each of the two channels, signal strength was manipulated by a decade attenuator box placed between the output of the phase shifter and the transducers. An impedance matching transformer was placed between the attenuator and the vibrator.

In a small audiometric testing room, the subject detected vibrotactile stimuli and judged the loudness of tones. A 1-sec observation interval was indicated to the subject by turning on and off a small white light. During each observation interval, an 80- or 82-dB SPL, 500-Hz tone was presented binaurally. On some trials, a 500-Hz tactile stimulus was also presented to the subject's fingertip through a vibrator contactor that was 6.5 mm in diam. The subject made a yes-no tactile response followed by a high-low auditory response by closing two bidirectional telephone switches. An observation interval was presented every 4 sec. Knowledge of results was given to the subject after each response through lights mounted near the observation interval light. The stimulus events in a series of observation intervals were programmed by a Tally R-50 tape reader.

Procedure. The probability of a tactile stimulus was .5 during each session. Preliminary to each session, the subject's sensitivity was determined and vibration amplitude was set at a value that would result in d' values between 1.0 and 1.5 for the experimental trials. On a random half of the trials, the auditory stimulus was 80 dB SPL, and on the other trials it was 82 dB SPL. Each of eight sessions was divided into two blocks of 250 trials. Each block of trials consisted of one of two payoff conditions. In the condition designed to encourage auditory attention, the subject received .4 cent for each correct auditory response and .1 cent for each correct tactile response. In the tactile attention condition, the subject received .4 cent for each correct tactile response and .1 cent for each correct auditory response. The order of the payoff conditions was counterbalanced over the experimental sessions.

Results and Discussion

The mean d' of the three subjects for the detection of vibrotactile signals was 1.30 when payoff was high for vibrotactile performance and low for auditory performance, and 1.31 when payoff was low for vibrotactile performance and high for auditory performance. Auditory performance was slightly higher when payoff favored auditory performance (mean percent correct was 75.4) than when payoff favored vibrotactile performance (mean percent correct was 73.2), but the difference was not statistically significant. As in our earlier study (Gescheider et al., 1974), inducing the subject to attend to a 1-sec auditory signal that is presented at the same time as a 1-sec tactile signal does not disrupt the subject's ability to detect the tactile signal.

The results of the present experiment, in combination with those of our earlier experiment (Gescheider et al., 1974), support the hypothesis that subjects can process simple stimuli presented simultaneously to two modalities about as well as when they have to make responses to stimuli in only one modality. Our results cannot be explained by assuming that the tasks were so easy that they required little attention. Throughout the experiments, stimulus parameters were adjusted to result in only moderately good psychophysical performance, even though subjects were well trained and highly

motivated. To maintain stable performance through an experimental session required continuous concentration on the part of the subject.

The results of a study by Eijkman and Vendrik (1965) on the detection of intensity increments for lights and tones also seem to support the conclusion that subjects can simultaneously perform two relatively difficult psychophysical tasks nearly as well as they can perform one of the tasks alone. On a trial, the subject had to attend both to a light and a tone and report for each modality whether he detected an increment in stimulus intensity. Stimulus increments were presented independently and in random order for the eye and the ear. Performance was found to be as high for the simultaneous detection of light and tone increments as for performance in control conditions where the subject had to make responses to stimuli in only one of the modalities.

In an analysis of the allocation of attention to sensory modalities, Shiffrin and Grantham (1974) claim that focused attention results in superior performance to divided attention only for tasks that put large demands on memory and decision-making processes. Shiffrin and Grantham make the distinction between "perceptual processing," which occurs automatically to provide information for short-term memory store, and "cognitive processing," which consists of activities such as scanning, rehearsal, coding, and decisions carried out on the information in short-term store. Performance decrements associated with loss of attention are attributed to problems in cognitive processing. Thus, the manner in which the subject allocates attention becomes very important only for tasks in which adequate performance is dependent on the efficient processing of relatively larger amounts of information that are rapidly decaying in short-term store. In contrast, attending to more than one sensory modality or several messages within the same modality should not result in a performance decrement as long as strains are not placed on cognitive processes of memory and decision making.

The model in which attentional effects are due to cognitive rather than perceptual effects was first developed to account for the effects of attention on processing information in different channels within a single sensory modality. The model was first proposed by Deutsch and Deutsch (1963) to account for the effects of attention on simultaneously processing more than one auditory message. The model has been applied to visual processing (Shiffrin & Gardner, 1972) and tactile processing (Shiffrin, Craig, & Cohen, 1973). In similar models for perceptual processing presented by Norman (1968) and Hochberg (1970), the effects of attention are also localized in cognitive rather than in early perceptual processes.

Two characteristics of the present experiment and others in which performance was not disrupted when attention was allocated to more than one modality (Eijkman & Vendrick, 1965; Gescheider et al., 1974; Shiffrin & Grantham, 1974) should be noted. The stimuli in these studies had low information content (e.g., simple light pulses, tones, noise bursts, and vibrations of the skin). In addition, extensive demands were not made on cognitive processes such as short-term memory, coding, rehearsal, or decision making. The results of these studies are consistent with Shiffrin and Grantham's hypothesis that the early perceptual stages of information processing are unaffected by attention while the subsequent stages of cognitive processing are greatly affected by how the subject attends to the task.

EXPERIMENT II

In Experiment II, an attempt was made to devise a task requiring continuous attention to an auditory message of sufficient duration and complexity so that when attention could finally be shifted to the tactile modality tactile information held in short-term storage would be lost. In the auditory task, the subject was required to listen to a train of successive brief tones that varied slightly in intensity. The number of tones in a train was varied from trial to trial. At the end of a train, the subject had to indicate whether the last tone and the third from last tone were the same or different in intensity. On some trials, the subject also had to indicate whether or not a tactile stimulus had been presented in the train. Under these circumstances, performance in detecting tactile stimuli was expected to be much lower when the subject had to attend to both auditory and tactile stimuli than when he had to attend only to tactile stimuli.

Method

Subjects. The subjects were three undergraduate students. Each subject was trained for not less than five 1-h sessions in detecting tactile stimuli and in recognizing auditory stimuli that differed slightly in intensity.

Apparatus. The stimulus-generating equipment was the same as that used in Experiment I.

Procedure. A train of 100-msec observation intervals, each separated by a 900-msec interstimulus interval, was indicated to the subject by a train of 100-msec light pulses from a small white light. In Task T, the subject had to indicate immediately following the train of observation intervals whether or not a tactile stimulus was presented in one of the intervals. The duration of the tactile stimulus was 100 msec. A brief 200-Hz tone was presented as a ready signal 1.5 sec before the start of each train of observation intervals. The same tone was presented 900 msec after the end of the train as a signal for the subject to make his tactile response. Reaction time for tactile judgments was measured with this signal as a reference. In Task A, an 80- or 82-dB SPL, 500-Hz tone was presented binaurally during each observation interval and the subject had to indicate whether the last and third from last tone in the train were the same or different in intensity. In Task TA, the

subject had to attend to both modalities. The subject was instructed to indicate as quickly as possible at the end of a train whether or not he detected a tactile stimulus in one of the observation intervals. He was then to indicate whether the last and third from last tone were the same or different in intensity. In an attempt to force the subject to attend continuously to the auditory stimuli, pulse train length was varied randomly from trial to trial without the subject's knowledge at values of 3, 5, 6, and 8 observation intervals. The subject made the yes-no tactile response and the same-different auditory response by closing two bidirectional telephone switches. Reaction time was measured for tactile judgments by a Hunter Klockounter. The time interval between observation interval trains was approximately 4 sec. Knowledge of results was given to the subject after each response through lights mounted near the observation interval light.

The probability of a tactile stimulus was .5 during each session. Preliminary to each session, the subject's sensitivity was determined and vibration amplitude was set at a value that would result in d' values of approximately 1.0 for Task T. Within each of six sessions, the subjects performed Task T, Task A, and Task TA for blocks of 180 trials. The order in which the tasks were performed was counterbalanced over the six sessions.

Results and Discussion

The values of d' were calculated for performance in detecting tactile signals in the two conditions of the experiment and are plotted as a function of observation interval train length in Figure 1. It can be seen that detection of a tactile stimulus in a train of observation intervals is not impaired by forcing the subject to attend simultaneously to both auditory and tactile channels. Performance in detecting tactile stimuli is nearly the same under the TA and T conditions for all observation interval train lengths. On the other hand, auditory performance was slightly impaired when the subject had to perform the auditory and tactile tasks simultaneously. The proportions of correct auditory responses for Task A

Figure 1. Tactile signal detectability as a function of the length of a train of observation intervals for Task T and Task TA when the T and the TA trials were presented in blocks.

Table 1
Proportions of Correct Auditory Responses
for Task A and Task TA

	Subjects		
	B.J.	D.S.	R.H.
Task A	.792	.913	.848
Task TA	.647	.891	.792

and Task TA are seen in Table 1. Application of the z test for the differences between proportions indicated that, for each subject, the proportion of correct responses was significantly higher for Task A than for Task TA.

Although the detectability of tactile signals was not reduced by requiring the subject to attend simultaneously to auditory and tactile stimuli, it can be seen from Figure 2 that tactile reaction times were substantially lower in Task T than in Task TA. This finding probably reflects the fact that the total amount of information processed was greater in the TA than in the T conditions. The decrease in reaction time as the length of the observation interval train increases might be a complex function of such factors as the gradual development of response set, and an increase in information processing rate over successive observation intervals within a trial. However, from the present data it is not possible to make conclusive statements about this reaction time effect.

Requiring the subject to perform a complex auditory discrimination task while attempting to detect tactile stimuli may have little effect on tactile performance because of offsetting factors produced by adding the auditory task. All of the subjects reported that although they found Task TA to be more difficult than Task T they felt they were more alert during blocks of TA trials than during blocks of T trials. It is possible that the increased arousal level in Task TA is sufficient to compensate exactly for increased information processing demands on the subject.

An experiment was conducted to determine whether the TA task would be more difficult than the T task when the subject's level of alertness was the same for both tasks. During an experimental session, TA and T trials were randomly presented rather than being presented in blocks of trials. In this situation, it is not likely that alertness level would greatly fluctuate, as the type of trial rapidly changes in a random order. During each of eight experimental sessions, 160 TA trials and 160 T trials were presented to five subjects. The subjects were inexperienced, and no less than five 1-h practice sessions were given before the experiment. The number of observation intervals in a train was 3, 5, 6, or 8. Hearing or not hearing the tones informed the subject as to whether the trial was TA or T. For each subject, tactile stimulus intensity was adjusted so that d' on T trials

would be approximately 1.0. The data for one subject was discarded because an error in adjusting stimulus intensity was made by the experimenter which produced a d' of nearly 2.5 instead of 1.0. The results of the remaining four subjects plotted in Figure 3 indicate that requiring the subject to continually track auditory pulses in a loudness discrimination task may slightly disrupt his ability to detect tactile stimuli. The disruption is far from complete, however. The mean d' values of .83 and .60 for the T and TA conditions, respectively, would correspond to a shift in sensitivity of only about 1 dB (Gescheider, Wright & Polak, 1971). Furthermore, the percent correct tactile responses was only slightly higher for the T condition

Figure 2. Reaction time as a function of the length of a train of observation intervals for Task T and Task TA.

Figure 3. Tactile signal detectability as a function of the length of a train of observation intervals for Task T and Task TA when the T and TA trials were randomly presented.

(64.5) than for the TA condition (61.0). The difference was statistically significant, however.

The results of our two experiments are not inconsistent with the model for attention shared between modalities presented by Shiffrin and Grantham (1974). In our experiments, the subject had to perceive, encode, and store the intensity levels of each auditory stimulus in a train of observation intervals. At the end of the train of stimuli, a decision had to be made as to whether the last and third from last stimuli were the same or different in intensity. Although a considerable allocation of attention is required for adequate performance of this task, the results suggest that the small amount of cognitive processing needed for detecting the tactile signal can occur with little disruption by the auditory task. Performance in the auditory task which required a considerable amount of cognitive processing was slightly disrupted when the subject simultaneously attended to the tactile modality in order to detect tactile stimuli. The smallness of this effect was probably due to the fact that the tactile detection task made relatively light demands on cognitive resources.

EXPERIMENT III

The purpose of Experiment III was to determine how well complex auditory and tactile information could be processed simultaneously. The subject was required to perform the auditory discrimination task employed in Experiment II while simultaneously performing the equivalent discrimination task for tactile stimuli. It was anticipated that the simultaneous demands on short-term memory in both modalities would result in substantial disruption in performance.

Method

Subjects. The subjects were two students and one faculty member at Hamilton College. Each subject was given three to five 1-h training sessions before the experiment.

Apparatus. The apparatus was the same as that used in Experiment II. As in Experiment II, 100-msec stimuli were presented in a train of 100-msec observation intervals, with each interval separated by 900 msec. Each interval contained a 500-Hz auditory stimulus and a 500-Hz vibrotactile stimulus. Within a train, 80- and 82-dB SPL tones and 15- and 20-dB SL vibrotactile stimuli were presented in random order. At the end of each train of stimuli, the subject was required to report, for both modalities, whether the first stimulus and the third from last stimulus were the same or different in intensity. The number of observation intervals in a train was varied randomly from trial to trial at values of 3, 5, 6, 8, 9, 11, and 12.

Procedure. In each of eight sessions consisting of 336 trials, one-third of the trials consisted of presenting both auditory and tactile stimuli and requiring the subject to make a judgment of the tactile stimuli followed by a judgment of the auditory stimuli. On half of the remaining trials, only auditory stimuli were presented and judged; on the other half, only tactile stimuli were presented and judged. The order of presentation of the three stimulus conditions was random over an experimental session. The stimulus content of the first observation interval of a train informed the

subject of the experimental condition for a particular trial. In four of the sessions the subject was instructed to attend primarily to the auditory stimulus on trials when stimuli were presented in both modalities, while in the other four sessions the subject was instructed to attend primarily to the tactile stimuli on such trials. The subjects were instructed that it was very important to be correct in the modality that was emphasized, but that they should also do as well as possible in the secondary modality. The order of the two attention instructions was counterbalanced over the eight sessions.

Results and Discussion

It is seen in Figure 4 that both auditory and tactile performance were highest when stimulation was presented in only one modality. Performance for T and A trials was not significantly influenced by the instructions concerning which modality to emphasize on TA trials, and therefore the data were combined for the two types of sessions. Performance in the attended modality was somewhat disrupted by simultaneously presenting stimuli in the other modality. It was found that performance in the secondarily attended modality was never significantly different from chance level. Thus, performance which is nearly perfect when stimuli are presented in one modality can be completely disrupted by presenting stimuli in two modalities and requiring the subject to attend primarily to the other modality. The effects of attention instructions appear to be nearly identical for judgments of auditory and tactile stimuli.

In a subsequent series of experimental sessions, two subjects participated in tasks in which they were instructed to consider their performance equally important in both modalities. The subjects were inexperienced and were therefore given three 1-h practice sessions before the experiment. In each of four sessions consisting of 360 trials, a random half of the trials consisted of presenting both auditory and tactile stimuli and requiring the subject to make

Figure 4. Auditory and tactile performance as a function of the length of a train of observation intervals for Task T, Task A, and Task TA when the subject was instructed to attend to tactile stimuli and when he was instructed to attend to auditory stimuli.

judgments of both. On a random half of the remaining trials, only auditory stimuli were presented and judged, and on the rest of the trials, only tactile stimuli were presented and judged. For the trials on which stimuli were presented in both modalities, the order in which they were judged was counterbalanced over the four sessions.

The data in Figure 5 are from the condition in which the subject was instructed to attend equally to stimuli in each modality. In Conditions A and T, where attention was focused on one modality, performance levels were very high and approximately the same for auditory and tactile stimuli. The order of response in the TA trials did not have a significant effect, and the data were therefore combined for presentation in Figure 5. When attention was distributed over the two modalities, both auditory and tactile performance was substantially disrupted. Although shared attention for both modalities resulted in a drop in performance from slightly more than 90% correct to slightly less than 75% correct responses, performance always remained considerably above the chance level. It is possible that in the shared attention condition the subject was able to maintain performance in both modalities at about the same level above chance by attending to only one modality on a particular trial and by attending to each modality on about the same number of trials over the experimental session. If this hypothesis were true, the percentage of correct responses in a modality should

Figure 5. Auditory and tactile performance as a function of the length of a train of observation intervals for Task T, Task A, and Task TA when the subject was instructed to attend equally to tactile and auditory stimuli. The asterisk indicates the performance measure.

be considerably lower on trials where the response was correct rather than incorrect in the other modality. The percentage of correct tactile responses was 68.9 when the auditory response was incorrect and 73.9 when the auditory response was correct. The difference was significant at the .01 level. The percentage of correct auditory responses was 69.2 when the tactile responses were incorrect and 73.2 when the tactile responses were correct. This difference was also significant at the .01 level. Thus, the results fail to support the hypothesis that on a particular trial the subject attends to only one modality. In fact, it appears that there is a tendency for the subject to have a higher probability of being correct in one modality if he is correct rather than incorrect in the other modality. Perhaps positively correlated auditory and tactile performance levels could be due to fluctuation in general alertness that has a common effect in both modalities.

It appears that the subject can attend to both modalities on a particular trial but that the effectiveness of his behavior depends on the cognitive processing demands of the task. In the TA task of the present experiment, sharing attention causes more disruption of performance than was observed in the shared attention experiments involving the less complex tasks of signal detection and recognition. Furthermore, the distribution of attention over the two modalities which had no effect on signal detection and recognition performance in Experiment I was found to have a major effect in the present experiment, in which complex tasks were performed in both modalities.

CONCLUSION

The results of the present study indicate that when demands on cognitive processes are small, auditory and tactile stimuli presented simultaneously can be processed as well as when stimuli are presented to only one of the modalities. However, as the amount of required cognitive processing increases, it becomes increasingly difficult to maintain high levels of performance in both modalities and the distribution of attention becomes an important determinant of performance. The findings are consistent with the theory proposed by Shiffrin and Grantham (1974) to account for variable amounts of disruption reported for experiments in which subjects process different information simultaneously presented to different sensory channels.

It is significant that only when the subject performed a task making substantial demands on memory did the simultaneous performance of a second task have a disruptive effect. This disruption occurred to a small extent in Experiment II, where the auditory memory performance was slightly impaired by requiring the subject to detect tactile

stimuli, and to a greater extent in Experiment III, where the subject had to simultaneously perform auditory and tactile memory tasks. The data of our experiments are consistent with the hypothesis that memory performance, rather than perceptual performance, is disrupted when two tasks are performed simultaneously. Recall that in Experiment II performance in the auditory memory task was impaired when the subject simultaneously performed the tactile detection task while the reverse effects were minimal. Lindsay and Norman (1969) also found that requiring subjects to simultaneously process information in two channels appears to disrupt memory rather than perceptual performance. Lindsay and Norman had subjects perform a short-term memory task and a detection task both individually and simultaneously. It was found that memory performance was impaired when stimuli in the detection task were difficult to detect and that detection performance was not affected by simultaneously performing the memory task.

Although the results of the present study are consistent with the model of Shiffrin and Grantham, they do not imply that the allocation of attention can never greatly affect stimulus detection performance. It is true that detection performance is determined primarily by stimulus factors and factors having to do with sensory processes, but at least some small amount of cognitive processing is required for the subject to function in the stimulus detection situation. For example, on a particular trial, the subject must decide whether the magnitude of a sensory observation exceeds his decision criterion. He must also store his decision and eventually make a response. Detection performance may be relatively resistant to the effects of changes in the allocation of attention simply because only a small portion of the total available cognitive resources is needed for these processes.

In a recent analysis of such problems, Norman and Bobrow (1975) made the point that the results of any kind of information processing are limited by the nature of the data and by the available information processing resources. In the case of human information processing, resources are such things as processing effort (Kahneman, 1973), memory capacity, and communication channels, while data have to do with the stimulus and its representation in memory. In their model, any psychological task can be characterized by a particular performance-resource function that shows how performance increases as cognitive resource allocation to the task increases. When the function reaches asymptote, performance becomes data limited rather than resource limited. Further increases in the allocation of cognitive resources have no effect, but the final level of performance is limited by the quality of the data. The performance-resource function for the detection

task appears to reach asymptote quickly, and thus detection performance becomes data limited at a point where only a small amount of cognitive resources is used. Consequently, disruption of detection performance by another task should occur only when the demands on cognitive resources by the competing task are so great that the detection process is forced to operate within the resource-limited portion of its performance-resource function. The slight disruption of tactile stimulus detection performance by the auditory memory task found in Experiment II is consistent with this model. Larger effects were reported by Lindsay, Taylor, and Forbes (1968) for situations in which subjects were required to perform several difficult discrimination tasks at the same time. They interpreted their results as evidence of a constant processing capacity employed in both single and multidimensional discrimination.

The simultaneous performance of tactile and auditory perceptual memory tasks in Experiment III appear to depend on resource-limited processes. When the subject was told to attend primarily to one modality, high performance in that modality required such a large amount of the available cognitive resources that performance in the other modality, which also required much of the resources, had to suffer to the extent of being hardly better than chance responding. It seems that when the subject was told to attend equally to both modalities, cognitive resources were equally allocated to the two processes. The two tasks which were equally difficult when performed alone were both disrupted by the same amount when they were performed together. The results of Experiment III imply that, in resource-limited tasks which are simultaneously performed, the subject can adjust the allocation of cognitive resources over a wide continuum.

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(Received for publication February 21, 1975;
revision received June 13, 1975.)