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LIMITED-CAPACITY CENTRAL ATTENTION MECHANISMS

A Dissertation Presented

By

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Limited-Capacity Central Attention Mechanisms

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The two experiments reported here identified 5 mental processes (preparation, encoding, retention, responding, and dual task performance) and inferred the processing-capacity demands of each. Two major questions were asked. (1) What were the relative amounts of capacity required by these mental processes? (2) How might capacity have been allocated among tasks making simultaneous demands?

Subjects were college students, 16 in each experiment. Each _S_ participated in 3 or 5 1-hr. sessions. The dual-task paradigm of Posner and Boies (1971) was employed in both experiments. The primary task was a visual letter-matching task--600 msec. after a visual warning signal, the first letter stimulus was displayed for approximately 30 msec. It was followed by a visual masking stimulus. The second letter stimulus came on 1200 msec. after the first. In Experiment I, _Ss_' task was to depress one key if the 2 letters were the same and another key if they were different. In Experiment II, the responses were _yes_ a single letter was one of a pair of letters or _no_ it was not. Index and second fingers of the right hand were used for these reaction time

(RT) responses.

The subsidiary task was an auditory RT task. In some conditions only 1 tone occurred; in others, 1 of 2 easily-disciminable tones occurred. Ss' task was always to depress 1 key for a high tone and another key for a low tone, using fingers of the left hand. Tones occurred at any of 8 positions relative to events in the letter task. Instructions on both tasks emphasized speed consistent with accuracy, but clear priority was given to performance of the letter task.

Interference with RTs on the tone task was used to infer the amount of capacity used by processing on the letter task. Fluctuations in RTs on the letter task and in error rates provided additional information.

Performing 2 tasks together required capacity, as evidenced by the differences in baseline tone RTs between tone alone and tone plus letter (T + L) conditions. Within the T + L conditions, the following inferences were drawn: Since tone RTs did not immediately increase following the warning signal, capacity was not required by preparation for the letter task. The increase in tone RTs and errors at the first letter stimulus indicated that encoding required capacity. Encoding interfered more with the 2-Tone task then the 1-Tone task, but the number of letters in the first stimulus (1 or 2) had no effect. Responses to tones between the 2 letters were fast, but they disrupted performance on the letter task. Large increases in tone RTs

near the second letter reflected the processing demands of responding. Longer responses did not necessarily require more processing capacity. Responses on both the letter task and the tone task appeared to require more processing capacity near the beginning and the end than in the middle.

The pattern of interference between the letter tasks and the tone tasks was inconsistent both with simple single-channel switching and variable-allocation models of the operation of central attention mechanisms. Alternative models were considered. Several limitations of the dual-task paradigm were noted, including the apparent inability of Ss to concentrate interference in the tone task, and the problem of determining the baseline against which to measure momentary demands for processing capacity.

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INTRODUCTION

The world is full of information, and at any one time the number of things a person might be doing is enormous. On the other hand, man is notoriously limited in the activities and mental processes that can be carried on simultaneously. Carrying on a conversation while driving a car is usually easy for a skilled driver, but making a difficult turn or responding to the sudden stop of a vehicle ahead will often interfere with the conversation. It may be possible to "whistle while you work" when the work is simple, but chances are that whistling ceases when the work increases in mental difficulty.

Some of the limitations on doing two things at once are peripheral physical limitations. It is impossible to begin rewriting a new page of a paper while crumpling up the old one and tossing it professionally into the wastebasket across the room. It is impossible to whistle while speaking, and to knit while driving. While peripheral physical structures certainly impose limitations on what things can be done simultaneously, there are also severe central limitations on doing two things at once--limitations which occur somewhere in the information processing sequence between the reception of stimuli and the execution of appropriate responses. For example, very few aspects of talking and driving a car could be called physically incompatible, yet there are severe limits to the talking a driver can do while trying to steer out of a sudden skid.

Posner and Keele (1970) have suggested that the limitations on a person's ability to engage in simultaneous mental activities be conceptualized as the intensive or spatial dimension of information processing. Besides requiring various amounts of time for completion, mental processes require various amounts of space in some central attention mechanism which has a finite amount of space (or processing capacity) available. Two activities which both take time may be performed simultaneously if their total demand for space does not exceed the amount of space available. If demands for space do exceed the amount available, then the performance of one or both of the activities will be interfered with. Allocating "space" or "processing capacity" in this sense is close in meaning to the common sense notions of paying attention and devoting mental effort.

Two broad questions about limited-capacity central attention mechanisms were the focus of the research reported here. First, what are the relative amounts of capacity required by different processes, and do, in fact, all mental processes require capacity? Second, how might a central mechanism operate to allocate the limited capacity among the tasks at hand?

Before the first question can be addressed, a method is needed for measuring the processing capacity requirements of an activity. One widely-used method is a dual-task procedure in which one task is the primary task and the other is a subsidiary measuring task (see Brown, 1964). Ss are asked to attempt to perform the primary task without interference by the subsidiary task. Performance on the subsidiary task is used as a measure of the processing capacity left over from the performance of the primary task. That is, the greater amount of processing capacity required by the primary task, the poorer performance should be on the subsidiary task.

Various subsidiary tasks have been used to infer the difficulty or the mental effort required by various main tasks. For example, Bahrick, Noble, and Fitts (1954) studied the learning of a visual-motor task with signals which occurred in either random or repetitive sequences. Although the learning rates for both groups were similar, the group with repetitive sequences did better on a subsidiary mental arithmetic task than the group with random sequences. Brown and Poulton (1961) used a mental arithmetic task to measure spare capacity from driving a car. They found that arithmetic scores were worse when driving in a residential area than when not driving, and worse still when driving in a busy shopping area. Baddeley (1966) found that Ss' ability to generate random sequences of letters depended on the difficulty of a concurrent primary sorting task. The more alternative categories into which cards had to be sorted, the greater was the redundancy of the letter sequences generated. Tracking has been employed as a subsidiary task to assess the processing capacity requirements of different stages of a memory task (Trumbo and Milone, 1971; Martin, Marston, and Bergman, 1972) and overt vs. covert response processes (McLeod, 1973). On the other hand, Trumbo and Noble (1970) used various tracking tasks as main tasks and measured their effects on a subsidiary verbal learning task.

One problem with the above subsidiary tasks is that the scores obtained are usually averaged over a fairly long time period, during which it is assumed that some process is occurring on the main task. Relative amounts of processing capacity required can then only be compared between tasks or between large segments of the same task. Under these conditions, it is difficult to specify exactly what mental processes of the main task require processing capacity, and when they require it. Also, very small amounts of processing capacity used by the main task may go undetected if the nature of the two tasks is such that the time at which allocation of capacity can occur is flexible. For example, Trumbo and Noble (1970) found that shadowing a series of lights by pressing a button corresponding to the light just seen did not interfere with the learning of a 16-item list of nonsense syllables. However, performance on the shadowing task was not evaluated, and the learning task did show slightly (although not statistically significantly) more errors than the control group with no button-pressing task. <u>S</u>s could easily have delayed responses to the lights until enough capacity was available from the learning task. Thus, Trumbo and Noble, even though they showed no significant interference in the learning task from the subsidiary shadowing task, did not use a sensitive enough procedure to warrant the conclusion that the shadowing task required no capacity.

The procedure employed here is a version of the probe technique used by Posner and Boies (1971), Posner and Klein (1972), Ells (1973), and Comstock (1973). In this procedure, the primary task was a visual reaction time (RT) task in which <u>S</u>s responded <u>same</u> or <u>different</u> on the basis of two letters presented sequentially. The subsidiary task required speeded responses to tones. As in the other subsidiary tasks mentioned above, the amount of processing capacity required by the primary letter task can be inferred by performance on the tone task. Increases in RTs or errors in responding to tones would indicate that mental processes which occurred at the same time in the letter task were requiring more processing capacity. The use of two RT tasks in a dual-task paradigm has several advantages. RT is a sensitive measure which should make the detection of small amounts of interference possible. Interference can be easily detected if it occurs on either the primary task or the probe task. Tasks requiring speeded performance make it likely that Ss will process the relevant information efficiently and as soon after it becomes available as possible. The timing of visual events can be arranged so that it is possible to specify fairly well what mental processes composing the main task are occurring at what points in time (see below), and auditory probes can be presented at exactly those times. Thus, fluctuations in processing capacity requirements within the main task can be assessed.

In the experiments reported here, four general kinds of information processing can be specified and studied with reference to the sequence of visual events composing one trial on the letter task. These are preparation, encoding, retention, and responding. In addition, the processes involved in allocating capacity among concurrent tasks can be studied by comparing control conditions in which only one task is performed with conditions in which two tasks are performed together.

Preparation. Each trial of the letter task began with a warning signal, which was followed after 600 msec. by the presentation of the first letter stimulus (a single letter in Experiment I). During this interval, which has been called the foreperiod or warning interval, it is assumed that Ss engage in preparation for the letter task. It is a well-documented finding that the presentation of a warning signal reduces RT to the subsequent signal. The optimal foreperiod has varied somewhat in different experiments, but generally RTs decrease as foreperiods are increased out to between 150 and 500 msec. With longer foreperiods, RTs tend to remain fast, especially when a constant foreperiod is used throughout a block of trials (Bertelson, 1967; Nickerson, 1968; Posner and Wilkinson, 1969).

What are the characteristics of the process of preparation? It seems to be a nonspecific alerting process which requires no processing capacity. Posner and Boies (1971) and Posner and Klein (1972) found that even though the warning signal predicted the onset of visual events, tone RTs did not reflect interference from preparation. Instead, tone RTs were faster after the warning signal than before it. Posner and Boies suggested that preparation is a kind of increasing alertness or willingness to respond regardless of the stimuli. The evidence further suggests that preparation has its effects at a central stage of processing. With increasing foreperiods, the decreases in RT to unmasked stimuli are accompanied by stable or increased error rates (Bertelson, 1967; Posner, Klein, Summers, and Buggie, 1973). The latter authors interpret their results to mean that the rate of buildup of information about the stimulus is not affected by preparation. Rather, preparation results in some later system sampling that information sooner; thus, responses tend to be initiated on the basis of less complete information, and more errors tend to be made. Moreover, preparation does not exclusively affect response stages. In a visual signal detection task requiring no speeded response, Klein and Kerr (in press) found that discriminability improved with increasing foreperiods in a manner analogous to improvements in RT with increasing foreperiods. With response stages and stimulus information buildup ruled out, the effects of preparation must be ascribed to an intermediate central stage of processing.

Inclusion of a warning interval prior to the sequentially presented letters in the experiments to be reported here is important because it isolates the process of preparation. If no other warning signal were presented, the first letter would serve as one. Under these conditions, it would be difficult to separate the effects of preparation from the effects of processes associated with the identification and retention of the letter. Given a warning signal, preparation processes occur prior to the first letter. If Posner and his coworkers are correct in their contention that preparation has central alerting effects, then Experiment I should replicate the finding of Posner and Boies (1971) that subsidiary tone RTs were faster following the warning signal than before it. It is also reasonable to assume that preparation effects will have reached a maximum during the 600 msec. foreperiod and that subsequent processes in the letter task will occur at a constant level of preparation.

Encoding. The second mental process which can be identified in the letter task is encoding. When the first letter stimulus is presented, information is extracted by procedures referred to as encoding or pattern recognition (see Neisser, 1967, for a summary of theories of pattern recognition) until the stimulus is identified or "makes contact with memory." Of course, encoding could mean different things depending on the information which needs to be extracted in order to perform the task at hand. For a letter-matching task similar to the one employed in the research to be reported here, Posner and Boies (1971) operationally defined the encoding of a letter as the processes which make responding same or different to two letters faster with successive presentation than with simultaneous presentation. Letter RTs were a decreasing function of the interval between the two letters, appearing to asymptote at an interval of about 250 msec. Thus, after about 250 msec. enough information had been extracted from the first letter to make matching it to the second letter maximally efficient.

One question concerning the nature of the encoding process is addressed here--does encoding require processing capacity? Many approaches to this question have been taken in the past, and the results have been contradictory. Before discussing the results obtained with the subsidiary tone task procedures, the results of two other approaches will be briefly cited. While both have considered the capacity required by encoding, it will be seen that neither approach can clearly answer the question.

The dichotic listening literature (see Moray, 1970b, for a review) is perhaps the largest collection of data which has been interpreted with respect to the capacity requirements of encoding. The most common procedure has been to present two concurrent auditory messages, and to require Ss to repeat back, or shadow, one of the messages (usually a prose passage). The question is then, what is encoded from the unattended message? If the content of the unattended message has no effect on behavior, this might be taken as evidence that encoding information from the unattended message required more capacity than could be allocated while simultaneously shadowing another message. Alternatively, if the content of the unattended message does affect behavior, then either enough capacity was available to encode some information from the unattended message, or else encoding did not require capacity.

Early studies tended to emphasize the lack of ability to report anything but gross physical characteristics or highly pertinent words from the unattended message. For example, Cherry (1953) found that pure tones and changes from a male to a female speaker were recognized, while changes in language and content were not. Moray (1959) repeated a list of 7 words 35 times in the unattended ear;

in a recognition test 30 sec. later, Ss did not recognize the repeated words at greater than chance level. Ss did notice their own names on the unattended ear, however. Treisman and Geffen (1967) asked Ss to make a tapping response whenever they heard a target word in either ear. Only 8% of the targets from the unattended ear resulted in taps, while 87% from the shadowed ear did.

These results might be taken as evidence that encoding does not occur without a fairly large amount of processing capacity, but there are problems with this interpretation. Not only did Ss have to encode the information in the unattended message, but they also had to make a decision about it, remember it, or initiate a response to it before any effect of the unattended message would be detected. It may have been that these later processes took capacity, while encoding occurred automatically or with only a small amount of capacity. In fact, when memory and response factors are held to a minimum, evidence for rather detailed analysis of the unattended message has usually been found. For example, shadowing was more difficult when the unattended message contained a synonym of the word to be shadowed (Lewis, 1970). Real words in the unattended message interfered more with memory for the attended message than did nonsense words (Davis and Smith, 1972). Even when previously shock-associated city names and other city names were embedded in an unattended message and Ss signaled no awareness of them, galvanic skin responses rose at the presentation of any city name (Corteen and Wood, 1972; Corteen and Dunn, 1974).

In summary, the dichotic listening studies provide evidence that a great deal of encoding of information from one message can go on while shadowing another. However, shadowing is a very imprecise task. It is never clear just when it requires capacity, when various mental operations occur, or when shadowing performance is impaired. For these reasons, the conclusions which can be drawn about the processing capacity requirements of encoding are very limited. All that can be said is that if encoding requires capacity, then the shadowing task, demanding as it may be, still leaves enough processing capacity for encoding.

Like the dichotic listening studies, much of the evidence on the encoding of visual information has been interpreted as showing no processing capacity limitations. A few examples follow. In a field of geometric shapes, Ss responded that all shapes were the same or that one shape differed just as rapidly whether the array contained 2 or 14 shapes (Donderi and Zelnicker, 1969; Donderi and Case, 1970). In visual detection tasks with foveal but spatially separated arrays of letters, simultaneous presentation of an entire array for x msec. resulted in no worse detection of a target than sequential presentation of the items for x msec. each (Eriksen and Spencer, 1969; Shiffrin and Gardner, 1972;

Shiffrin, Gardner, and Allmeyer, 1973). Finally, in a Stroop color-word test Keele (1972) found that key pressing responses based on colors were not influenced by the irrelevant forms which contained the colors, even when the forms spelled a neutral word. However, it was concluded that form information had been encoded, because forms which spelled color names resulted in greatly inflated RTs to the colors.

All of these results suggest that more than one source of visual information can be encoded at the same time. Again, however, the evidence is not conclusive about whether encoding requires processing capacity. There is some evidence of serial processing of multidimensional stimuli, which can be taken as indicating a limited capacity for the encoding of visual information (see Estes, 1966; Rumelhart, 1970). It seems likely that in making simple detections such as those required for the above tasks, the visual system operates in an inherently global manner. If the first stages of visual encoding involve "preattentive processes" which detect certain differences and segregate objects for further analysis by integrating information from across the entire visual field (Neisser, 1967), then perhaps it is not surprising that adding forms to the field does not always degrade performance. Even if visual encoding automatically includes the extraction of information from various locations and on various stimulus dimensions, that does not necessarily imply that the encoding processes do not use some capacity which would otherwise be available for use by other central processes.

A better test of the processing capacity requirements of encoding would be to employ a dual-task paradigm with one visual and one nonvisual task. Interference with encoding in the presence of a difficult concurrent task, or interference with the concurrent task in the presence of encoding, would be evidence that encoding required capacity. Some evidence of interference with encoding does exist. Detection of a letter k was found to be worse when Ss were also engaged in a digit transformation task (Kahneman, Beatty, and Pollack, 1967). Both immediate forced-choice recognition of digits and comparative judgments of line lengths were impaired when Ss were also remembering a long list of consonants (Shulman and Greenberg, 1971). Criticism of these studies, as of the dichotic listening studies, rests on the fact that interference with encoding was only inferred from poorer performance on the recognition, detection, or judgment tasks. It could easily have been that other processes in these tasks, such as decision making or response selection, were impaired by the requirements to do a concurrent memory or transformation task.

Measuring performance on a concurrent task, when encoding is or is not taking place, would seem to provide the best chance of detecting interference from encoding without the confounding effects of other processes. Posner and Boies

(1971), and Posner and Klein (1972) attempted to do just that with the probe technique outlined above. They found that RTs to auditory probes were not inflated during the time that encoding of a single visual letter was occurring, and they concluded that encoding did not require capacity. One methodological problem with these studies, however, is that the first letter was displayed for substantial lengths of time. Thus Ss could have processed the probe information as soon as it occurred and encoded the letter information at their leisure, the only necessity being to encode it before the second letter came on and a response was required.

Comstock (1973) included a condition in which the letter was displayed very briefly and was followed by a visual masking stimulus to effectively end the availability of the visual information (see Averbach and Coriell, 1961; Averbach and Sperling, 1968) and define the time interval during which encoding needed to be initiated. RTs to auditory probes did increase an average of 45 msec. when probes were presented simultaneously with the first letter, suggesting that encoding the letter did require a detectable amount of processing capacity. However, there were problems with that experiment which make some sort of replication desirable. First, a procedural problem resulted in discarding 1/4 of the data from the masked condition and casting some doubt on the remaining 3/4 (see Comstock, 1973, Footnote 3). Second, a much larger increase in probe RTs occurred 100 msec.

following the first letter, so it would be possible to interpret the increases as the result of retention processes rather than encoding processes. No probes were presented between 900 and 200 msec. prior to the second letter, when retention would be continuing, so this possibility could not be checked. Third, overall probe RTs were very long and no preparation effects were found, so it was possible that Ss were not performing the tasks as efficiently as possible.

The effects of encoding were examined again in the experiments reported here. It was predicted that if encoding a letter required processing capacity, RTs to tones presented simultaneously with the first letter would be longer than RTs to tones presented when S was alert but not encoding.

Retention. Between the encoding of the first letter stimulus and the presentation of the second, S must at least retain the information which he has just encoded. That active retention, or rehearsal, of information requires processing capacity is fairly clear. In short-term memory studies, requiring Ss to do some interpolated activity between presentation and recall (Peterson and Peterson, 1959) has been shown to impair recall performance. This can be interpreted as showing that the amount of capacity left over after the interpolated activity was performed was not sufficient for the process of rehearsal. Several studies have reported that the more difficult the interpolated tasks (that is, the more processing capacity required by the interpolated tasks), the more they interfered with retention. This was true for interpolated numerical transformation tasks (Posner and Rossman, 1965), key pressing tasks (Crowder, 1967), and difficult detection tasks (Lindsay and Norman, 1969). Several other studies have measured interference in the interpolated task, or subsidiary task, from rehearsal. For example, Stanners, Meunier, and Headley (1969) asked Ss to recall trigram triads after a 7-sec. retention interval. Simple RTs to a buzzer during the retention interval were longer than when no retention was required, and they were longer the more difficult the trigrams were to pronounce. Similarly, Martin, Marston, and Kelly (1973) measured performance on a subsidiary tracking task or a simple RT task and found worse performance when the lists to be retained were longer or were more difficult to organize.

In the letter task employed in Experiment I, the retention task is extremely easy, since only one letter needs to be retained, and only for 1200 msec. Even though the experiments cited above give strong evidence that retention requires processing capacity, most of them called for the retention of many items. In fact, in at least one study (Shulman and Greenberg, 1971), high memory loads produced interference, while low memory loads did not. Posner and

Boies (1971), and Posner and Klein (1972), however, did find that probe RTs increased during the retention interval, even when only one letter had to be retained. These increases occurred either as soon as the first letter was turned off or by 500 msec. prior to the onset of the second letter. The increases were present even when RTs to probes which occurred during the retention interval but were not responded to until after the second letter were not considered. Thus, some process which occurred during the retention interval required processing capacity. While it is likely that this process was retention, it is also possible that it was some sort of preparation for the second letter or for making a response.

To insure that a greater proportion of responses to tones presented during the retention interval would be completed before the onset of the second letter, Experiment I employed a 1200 msec. retention interval. This interval was 200 msec. longer than the intervals used in most previous studies. It might be expected that some RTs would be longer during the retention interval than when S is fully prepared but not engaged in retention.

Responding. When the second letter comes on, S must compare it with the first letter, decide whether the two letters are the same or different, select the appropriate key to press, and press it. In the letter tasks used here, all of the processes between the onset of the second letter and S's response are grouped together and called "response processes." The attention literature leaves no doubt about the processing capacity requirements of response processes. The necessity to respond always imposes major limitations on the amount of concurrent information processing which can be done. Many theories of dual-task performance have accounted for the data in certain situations by assuming that response selection processes are the only processes which require central processing capacity (Smith, 1967; Keele, 1970 and 1973). Even theories which allow any process to use capacity, stress that response processes usually require the largest portion (Kahneman, 1973; Moray, 1967).

The key press responses used in the experiments reported here required no precision of movement and no corrective movements. Under such circumstances, the actual execution of a response has been found to require little if any processing capacity (Posner, 1969; Ells, 1973). However, the response-associated processes performed between the onset of the second letter and the initiation of the key press should require processing capacity. Posner and Boies (1971), Posner and Klein (1972), and Comstock (1973) all found that RTs to probes presented near the second letter were increased by as much as 250 msec. relative to probe RTs which were responded to before the second letter came on. In other situations, the amount of capacity required by response processes has been found to decrease with decreases in the number of possible responses (Ells, 1973) and also to decrease with the increasing similarity of a stimulus to sensory feedback from the response ("ideomotor compatibility," Greenwald, 1972; Greenwald and Shulman, 1973). More processing capacity was required when a mental transformation of the first stimulus was required before matching (Posner and Klein, 1972).

One process occurring between the second letter and the response in the letter task employed here is the decision whether the letters are the same or different. In similar visual letter tasks, _same_ responses have almost always been found to be significantly faster than _different_ responses (e.g., Bindra, Donderi, and Nishisata, 1968; Nickerson, 1973). It has frequently been suggested that _same_ responses are faster because they are the result of a fast identity checking process which is separate from the process which results in _different_ responses (Bamber, 1969; Beller, 1970; Silverman, 1973) or because one signal produces a temporary facilitation in the processing of similar stimuli (Posner, Klein, Summers, and Buggie, 1973; Posner and Snyder, in press). Many of the studies cited in previous paragraphs suggested that easier decisions required less capacity. Are _same_ responses easier than _different_ responses? It would be interesting to discover if, besides requiring less time, _same_ responses also required less processing capacity.

The probe technique has not been used to address this question, but it would be expected that if same and different responses do differ in their processing capacity needs, then the difference will be reflected in RTs to probes which come on near the second letter.

Dual task performance. The original intent of the probe technique was to pair a subsidiary task with a primary task for the purpose of investigating processing capacity requirements of specific processes, such as preparation, encoding, retention, and responding, in the primary task. This technique, however, also provides information on how a central mechanism might operate to allocate the limited processing capacity among the tasks at hand.

Thus far, processing capacity and time have been used loosely to refer to two separate dimensions of information processing. The question now remains, what sort of mechanism might be operating to result in such limitations of processing capacity? Models which attempt to describe processing limitations in dual-task situations differ widely depending on the situations or phenomena for which they were designed (see Kahneman, 1973; Norman, 1969; Swets and Kristofferson, 1970, for summaries of major positions). The most influential models (Broadbent, 1958; Treisman, 1969) rest almost exclusively on evidence from auditory tasks, shadowing in particular. Other models have described certain features of dual-task performance based on studies of the psychological refractory period (see Smith, 1967; Welford, 1959; Bertelson, 1966), or the perception of temporal order (Kristofferson, 1967a,b; Sternberg and Knoll, 1973). However, these models are not complex enough nor specific enough to explain the data from a dual-task situation such as that employed in the studies reported here. The model proposed by Kahneman (1973) is the broadest in terms of the kinds of phenomena for which it can account, but its value seems to be greatest in describing and organizing data, rather than in predicting results of new situations. It is likely that trying to confirm or disconfirm predictions based on any of these specific models would meet with little success. The approach taken here will be to consider the two general conceptualizations suggested in Comstock (1973) about how a central processor might allocate capacity. Later the data will be evaluated with respect to each one.

A single-channel switching model (in the spirit of Bertelson, 1966; Broadbent, 1958; Kristofferson, 1967a,b; and Welford, 1968) assumes that the central processor can attend to only one task requiring its use at a time and that operations on two tasks must occur successively. A variable-allocation model (Moray, 1967, 1970; Kahneman, 1973) assumes that a person possesses a finite amount of processing capacity which can be allocated to various task operations simultaneously as long as the total capacity required does not exceed the amount available at any given point in time.

Results of Comstock's (1973) experiment posed difficulties for both of these models. Basically, no interaction was found in probe RTs between the difficulty of the probe task and the difficulty of the letter task. The probe tasks were Donders (1969) Type a and Type c reactions, and letter task difficulty was inferred from the amount of interference in probe RTs depending on the temporal position at which they occurred during the letter task. Besides needing more time, Type c reactions also need more processing capacity than Type a reactions (Ells, 1973). The variable allocation model would predict that Type c reactions would reflect more interference from the letter task than would Type a reactions (see Kerr, 1973), since the more capacity being used by the letter task, the less would be left over for the tone task. With a smaller amount of capacity available, a greater delay in probe RTs would be expected the harder the probe task was. Instead, Type c RTs were always about 117 msec. slower than Type a reactions, regardless of the difficulty of the letter task. For the variable allocation model to work, it would seem necessary to support the unlikely assumption that Type c reactions required only more time and not more capacity than Type a reactions.

A single-channel model can handle the lack of interaction between probe task difficulty and probe position. The delay in the probe RT which occurs when processes in the letter task are engaging the single channel should be the same regardless of the difficulty of the probe task. Interference, in this model, simply reflects the amount of time it takes for the channel to be free to switch to the probe task. However, a single-channel model fails to handle another aspect of the data--the very long baseline probe RTs (i.e., RTs to tones presented during the ITI). It is generally reported that when Type a auditory reactions are the sole task for Ss, RTs after practice are as fast as 140-150 msec. Type c reactions may take anywhere from 20 to 200 msec. longer than simple reactions, depending on experimental conditions (see Donders, 1969; James, 1890; Woodworth, 1938; Woodworth & Schlosberg, 1954). In Comstock (1973), however, although the difference between Type c and Type a RTs was consistent with previous findings, the absolute Type a RTs, even during the ITI, were about 500 msec. It seems unlikely that switching to the probe task from the letter task would account for the long baseline probe RTs. Such a long switch would seem to be inconsistent with the findings of a small increase in RTs to probes presented at the first letter relative to probes 100 msec. before the first letter. If longer RTs to probes at the first letter indicate that encoding requires use of the single channel, and if switching time is long, then probes 100 msec. before the first letter should cause even more difficulty because when the first letter comes on, the single channel would still be engaged in switching to the probe task.

Experiment I was designed to further investigate the high baseline probe RTs and the lack of interaction between probe task difficulty and probe position. Control conditions, in which responses were required to tones only or to letters only, were included to provide baseline RT information for the same conditions that exist in the two-task conditions. The difficulty of the probe task was varied by using Donders Type a and Type b reactions (simple and 2-choice) to be more sure that the processing capacity requirements were greater for the 2-choice probe task than for the 1-choice probe task. Processing capacity requirements, or difficulty, of the letter task can be thought of as varying in three ways, first by whether the letters must be responded to or not, second by the time in the task (e.g., the task is more difficult near the second letter than near the first), and third by whether the second letter indicates a same response (easier) or a different response (harder).

The most interesting results for a model of the attentional processes concern the interactions of probe task difficulty and letter task difficulty in RTs to the probes. Most simply, variable allocation models predict that the more difficult the letter task is, the more interference there will be in probe RTs. Single-channel switching models can handle a lack of interaction if it is assumed that one switch to the probe task is all that is needed and if the baseline probe RTs under two-task conditions are approximately as much longer than under probe-alone conditions as would be expected by a single switch from the letter task to the tone task.

EXPERIMENT I

METHOD

Subjects. Sixteen Ss were run individually for 3 1-hr. sessions within a week or less. Seven men and seven women were undergraduate psychology students who received extra course credit for their participation. One man and one woman in professions outside of psychology also served as Ss. Data from 3 additional Ss were not included because the error rates exceeded a pre-established maximum of 22% errors on more than 2 of the 8 trial blocks of one experimental session. All Ss were right-handed and reported normal or corrected-to-normal vision.

Apparatus and stimuli. A Hewlett-Packard 2114B computer was programmed to present all stimulus sequences and to record all responses. The Ss sat at a table in a small sound-damped room. Visual stimuli were displayed on a Hewlett-Packard 1200A X-Y oscilloscope located approximately 4 ft. away. At the beginning of each session the intensity and focus of the display were adjusted by eye so that stimuli had no fuzzy edges and the individual points composing the stimuli were just barely discernible. For nonflickering continuous presentations, the display was refreshed once every 15 msec.

The visual stimuli were upper case letters selected at random from the 20 letters excluding C, J, L, M, N, and V.

Each letter was constructed by illuminating the appropriate points of an array 7 points high and 5 points wide; the vertical visual angle was approximately 30'. The auditory stimuli were 2 tones distinguished by pitch, the high tone approximately a musical seventh above the low tone. Although no sound pressure measurements were made, both tones were approximately equal in loudness and were clearly audible to all Ss.

The Ss responded by depressing 1 of 4 plexiglass keys on a response board. The two right keys were used to respond to the visual letter task. For half of the Ss same responses were made by depressing the key corresponding to the index finger of the right hand and different responses the key corresponding to the second finger. For the other half of the Ss the right hand key assignment was reversed. The 2 left keys were used to respond with the second and index fingers of the left hand to the low and high tones, respectively. Clearly legible labels reading LOW, HIGH, SAME, and DIFF were attached to the appropriate keys.

Primary and probe tasks. The present study employed 2 tasks similar to those used in a previous experiment (Comstock, 1973). In the primary letter-matching task, Ss were required to respond same or different to 2 successively presented visual letters. The sequence and duration of events composing 1 trial of the letter task were as follows: First, a small plus sign came on in the center of the screen as a fixation point and warning signal; it remained for 600 msec. The first letter was then presented for 30 msec. just above and to the right of the warning signal. After another 20 msec., the visual masking stimulus came on in the same position as the first letter. The mask, which was an asterisk 9 points high and 9 points wide, remained on the screen for 550 msec. (see Haber, 1970, for the rationale behind using this form of mask). The second letter came on 1200 msec. after the onset of the first letter (600 msec. after the offset of the mask). It was present for 1000 msec. in a position directly below the first letter. Had the entire visual display (warning signal and both letters) been present at once, it would have subtended approximately 45' of visual angle horizontally and $1^{o}35'$ vertically.

At the end of each trial of the primary task, feedback was displayed for 2 sec. in the upper righthand corner of the screen well away from the stimulus presentation area. For blocks of trials on which responses to the letters were required, the feedback was the <u>same</u> or <u>different</u> reaction time in msec. if <u>S</u> had responded correctly. If <u>S</u> had made an error, the letters "ERR" were displayed instead of the RT. For blocks of trials on which no letter-matching responses were required, a zero was displayed in place of feedback. After the feedback went off, the screen was blank for an intertrial interval (ITI) which varied randomly in length between 2 and 6 sec.

There were 2 versions of the secondary or probe task, which involved responses to the tones. In the 1T task, 1 tone occurred and S was required to make a simple reaction by pressing the appropriate 1 of the 2 lefthand keys. In the 2T task, either a high tone or a low tone could occur and S was required to make a choice reaction. Half of the Ss in the 1T task heard high tones and half heard low tones. Tone probes were presented during half of the trials on the letter task. The probe could occur at any 1 of 8 positions relative to the sequence of events in the primary task. The probe positions were as follows: (1) during the ITI, 1200 msec. prior to the onset of the warning signal, (2) 200 msec. after the onset of the warning signal, (3) 100 msec. prior to the onset of the first letter, (4) simultaneously with the first letter, (5) 300 msec. after the first letter, (6) 600 msec. after the first letter, (7) 900 msec. after the first letter, and (8) simultaneously with the second letter. No RT feedback was displayed for the probe task, but if S made an error, he did not see his RT to the letter task, and "ERR" was displayed in the upper lefthand corner of the screen.

Six treatment conditions differed only in the number of tones presented (1T or 2T) and the tasks on which responses were required (letters only - L, tones only - T, or both - T + L). In all conditions the characteristics of the visual stimuli were the same. Each 32-trial block consisted of 16 <u>same</u> trials (the first and second letters were identical) and 16 <u>different</u> trials. Different random sequences of letter pairs were used for each block of trials for each <u>S</u>. Within the <u>same</u> and <u>different</u> categories, tone probes occurred on half of the trials, once in each of the 8 probe positions. In the 2T conditions, high and low tones were selected at random without assuring an equal number at each pitch. For any treatment block, each trial to be presented was selected randomly without replacement from the set of 32 trials. When an error was made on either task (by pressing the wrong key or by waiting more than 1500 msec. to respond) the trial was replaced in the pool of trials remaining to be presented. A maximum of 9 errors was allowed. If more errors were made, the trial block was terminated and rerun at the end of the session. If more than two trial blocks needed rerunning, the data from that <u>S</u> were not included in the experiment.

<u>Design and procedure</u>. The first day of the experiment was considered an introduction to the tasks. Both the letter task and the tone task were described fully and any questions were answered. Emphasis was placed on speed consistent with accuracy. For the 1T + L and 2T + L conditions, <u>S</u>s were told that the letter task was the main task and that they should give it as much attention as needed for fast and accurate responses. They were told to respond with speed and accuracy to the tones as well, but to try

not to let responses to the tones affect responses to the letters in any way.

Six blocks of trials were run on Day 1: L (with 1 tone irrelevant), L (with 2 tones irrelevant), 2T, 1T + L (2 blocks), and 2T + L. Since pilot work had shown that many Ss initially have trouble seeing the masked first letter, the first block of trials was run with no masking stimulus. For any S who complained about the difficulty in seeing the first letter masked, the fourth block of trials was also run with no mask.

On each of the 2 experimental days, all 3 response conditions were run, but only 1 of the tone conditions. Half of the Ss heard 1 tone on Day 2 and 2 tones on Day 3; for the other half the reverse was true. After 16 practice trials on the T + L condition, 8 blocks of 32 trials were run. Blocks of the T + L condition alternated with blocks of the control conditions (L or T). Half of the Ss began with T + L on Day 2 and with a control condition on Day 3; for the other half the reverse was true. The 6 possible orderings of the control conditions were approximately equally represented across Ss, and no S received the same ordering on both days.

Before the start of each trial block, the conditions of that block were identified by E over an intercom, as well as by a message on the screen accompanied by sample tones. The S initiated each block of trials by pressing any key, which ended the message and started the timing of the first ITI. At the end of each block of trials the average letter-matching RT and the number of errors made on that block of trials were displayed in the upper righthand corner of the screen.

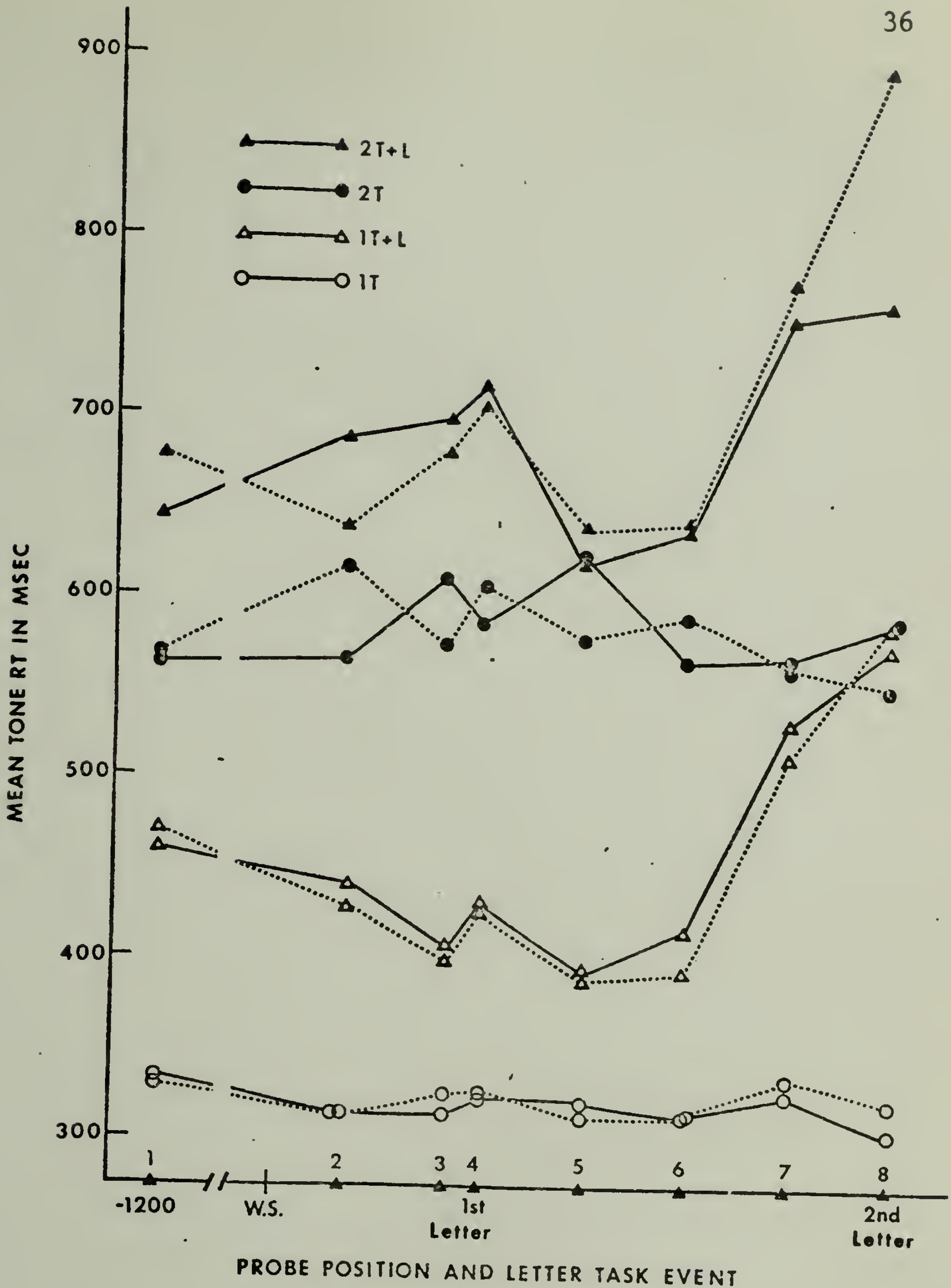
RESULTS

The basic results are of 3 types--RTs on the probe task (tone task), RTs on the letter task, and number of errors. Each of these measures may be considered as a function of the following variables: 1T vs. 2T conditions (called T for number of tones), 1 Task vs. 2 Task conditions (called J for number of jobs required), whether the letter task called for a <u>same</u> or a <u>different</u> response (called K for kind of trial), and the time at which a tone occurred relative to the stimulus events of the letter task (called P for probe position). To each cell of this 2 x 2 x 2 x 8 factorial design, each of the 16 <u>S</u>s contributed 1 score, which was the mean of 4 RTs in the 2 Task conditions and of 2 RTs in the 1 Task conditions. For the 2 Task conditions median RTs for each <u>S</u> were also analyzed; these data showed very little difference from data based on the means, so they will not be discussed further. Mean and mean median probe RTs, letter RTs, and total number of errors are contained in Appendices A-1, A-2, and A-3.

Three between-<u>S</u>s control variables were analyzed for effects in the RT data: which tone (high or low) was heard during the 1T conditions (called I), which fingers were assigned to same and different responses (F), and in which order the 2 experimental days occurred (1T then 2T, or vice versa, called O). None of these variables had significant main effects or interactions with each other in probe RTs or letter RTs. None of the interactions of the control variables with the 4 within-Ss variables was significant in the probe RTs; in the letter RTs, however, 4 of these interactions reached .05 levels of significance: FxT, OxT, IxOxT, and IxOxJxK. Since they were not reflected in any readily interpretable aspects of the data, and since any analysis of variance with 7 factors is likely to turn up some spurious findings, these interactions were considered minor and the control variables were dropped from all further analyses.

Probe RTs. Mean probe RTs for the 4 conditions in which responses to tones were required are graphed in Figure 1. A 4-factor repeated measures analysis of variance including all probe positions indicated highly significant effects of number of tones ($F(1,15)=145.67$, $p < .001$), number of tasks ($F(1,15)=50.89$, $p < .001$), probe position ($F(7,105)=17.02$, $p < .001$), and the interaction of number of tasks with probe position ($F(7,105)=17.63$, $p < .001$). Thus, as Figure 1 clearly shows, RTs were faster in the 1T condition than in the 2T condition; they were faster for

Figure 1. Reaction times on the tone task in Experiment I. Solid lines represent _same_ trials and dotted lines represent _different_ trials. W.S. means warning signal. The time between the W.S. and the 1st Letter was 600 msec. The time between the 1st Letter and the 2nd Letter was 1200 msec. See the text for exact probe times.



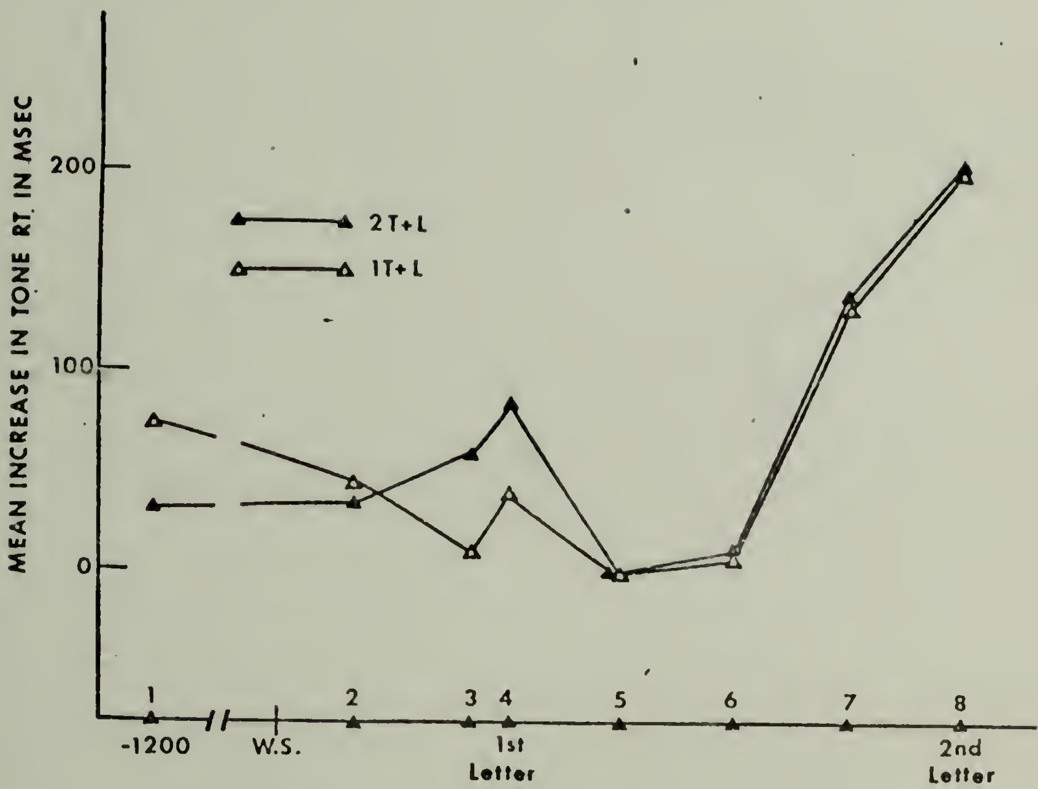
2T+L
2T
1T+L
1T
900
800
700
600
500
400
300
MEAN TONE RT IN MSEC
1
2
3
4
5
6
7
8
-1200
W.S.
1st Letter
2nd Letter
PROBE POSITION AND LETTER TASK EVENT

1 Task than for 2 Task; and the time at which a tone occurred relative to events in the letter task influenced RTs to that tone, but only in the 2 Task conditions, when both the letter task and the tone task needed to be performed. In this overall analysis there was no significant main effect of K (whether the letter response was same or different), and except for the JxP interaction mentioned above, none of the interactions among J, T, P, and K was significant.

In general, the shapes of the probe RT curves for individual Ss were similar to the group curves. One problem, however, was that RTs in the 2T condition tended to be very erratic. Even though the group curve is fairly flat, individual S curves tended to be much less smooth, and one S even showed longer RTs in this control condition than in the 2T + L condition. Since the added variability may have reduced the sensitivity of the overall analysis of variance, the control conditions were not included in the remaining probe RT analyses, which concern the shapes of the probe RT curves as a function of probe position.

In Figure 2 the 1T + L and 2T + L curves are collapsed across same and different trials and replotted with the lowest probe RT on each curve (position 5) equated at zero. This is not meant to indicate that RTs at position 5 should necessarily be taken as the best baseline against which to compare the two curves for amount of interference from events in the letter task. Rather, Figure 2 is meant to facilitate

Figure 2. Increase in reaction time on the tone task of Experiment I. The 2T + L and 1T + L curves have been collapsed across kind of trial (*same* or *different*), and they have been equated at probe position 5.



PROBE POSITION AND LETTER TASK EVENT

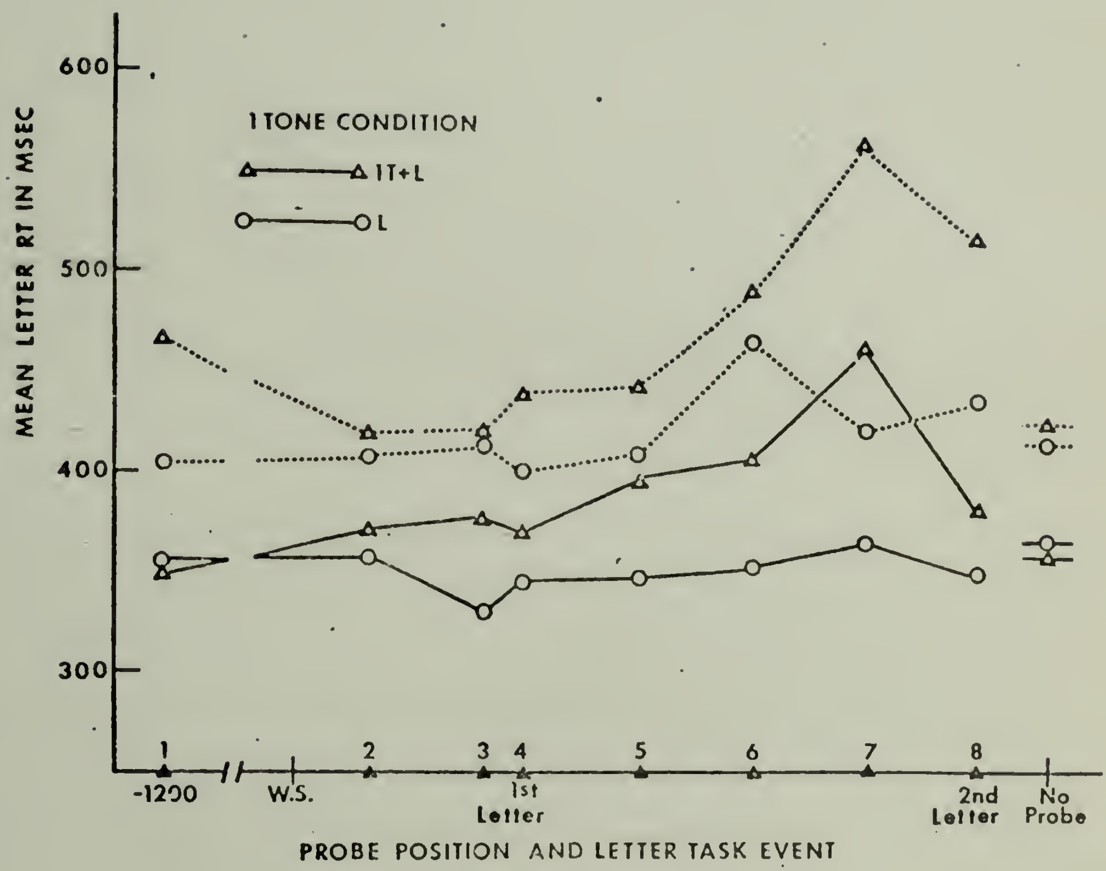
a comparison of the shapes of the curves. The 2 Task curves are similar, and, as was mentioned above, the overall TxP and JxTxP interactions failed to reach significance. However, inspection of Figures 1 and 2 suggests that the 2 Task condition curves do show some interesting differences depending on the difficulty of the tone task.

Analyses of variance were done on 4 adjacent subsets of the probe positions which were separated by changes in direction of the curves. The main effect of number of tones was always significant at the .001 level. In addition, the following may be said about the shapes of the 2 Task curves: While the 1T + L curve drops between positions 1 and 3, the 2T + L curve rises, resulting in a TxP interaction over the first 3 probe positions ($F(2,30)=4.59$, $p < .025$). Both curves rise approximately 25 msec. between positions 3 and 4 ($F(1,15)=4.64$, $p < .05$). Between positions 4 and 5 the 1T + L curve drops 38 msec. and the 2T + L curve drops 84 msec. Both the drop across probe position ($F(1,15)=14.33$, $p < .005$) and the TxP interaction ($F(1,15)=5.00$, $p < .05$) were significant. Thus, RTs on the tone task were inflated by the presentation of the first letter, and this effect was greater for the harder tone task than for the easier tone task.

The analysis of the probe RTs in the last 4 probe positions revealed a great deal of interference from the events associated with the presentation of the second letter. The rise in probe RTs across positions 5 to 8 was 205 msec. on the average ($F(3,45)=45.36$, $p < .001$). As Figure 2 shows, this effect did not interact with the difficulty of the tone task ($F < 1$). Whether the trial was a <u>same</u> or a <u>different</u> letter match (K) had no significant main effect ($F(1,15)=2.19$, $p < .10$). However, K interacted with number of tones ($F(1,15)=20.88$, $p < .001$) and with probe position ($F(3,45)=3.85$, $p < .025$). Figure 1 indicates that these effects are due to the fact that in the 2T + L condition probe RTs on <u>same</u> trials were always faster on the average than probe RTs on <u>different</u> trials, while in the 1T + L condition there was no difference, or a tendency in the reverse direction. The average difference between probe RTs on <u>same</u> and <u>different</u> trials tended to increase as a function of probe position. In Figure 1, the <u>different</u> curves rise more steeply than the <u>same</u> curves near the second letter, an effect which is especially evident in the 2T + L RTs between positions 7 and 8.

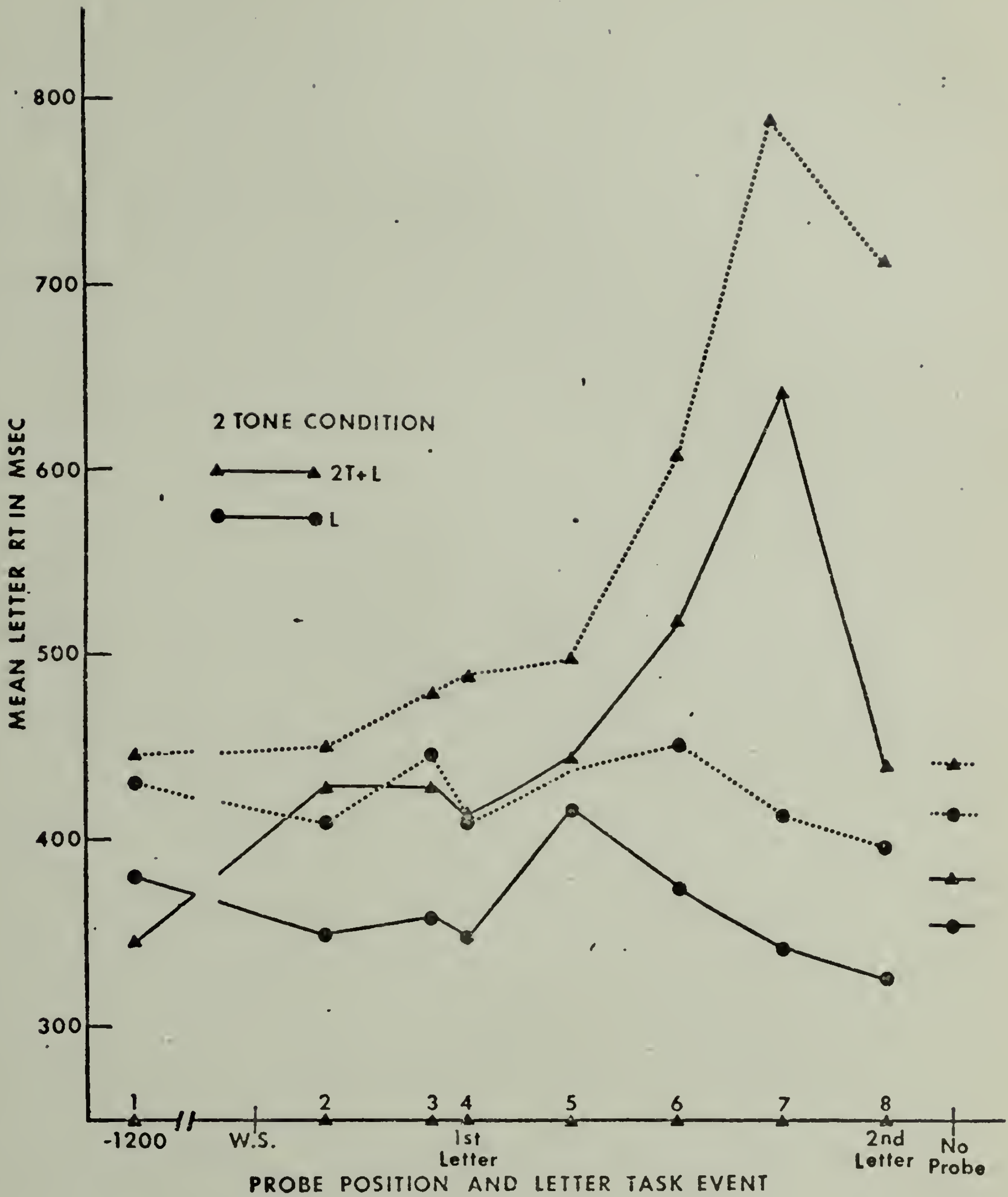
<u>Letter RTs</u>. Figures 3 and 4 show mean RTs on the letter task on 1 tone days and 2 tone days, respectively, as a function of the position during the task at which a tone occurred. The letter RTs marked "No Probe" are the means for all the trials on which no tone occurred. Each <u>S</u> contributed 32 RTs to each of these points in the 2 Task conditions and 16 RTs in the 1 Task conditions, as opposed to 1/8 that number for each of the probed positions. Probe and

Figure 3. Reaction times on the letter task in the 1 Tone Condition of Experiment I. (See Figure 1 for a more detailed key.)



600
500
400
300
MEAN LETTER RT IN MSEC
1 TONE CONDITION
1T+L
L
1
2
3
4
5
6
7
8
-1200
W.S.
1st Letter
2nd Letter
No Probe
PROBE POSITION AND LETTER TASK EVENT

Figure 4. Reaction times on the letter task on the 2 Tone Condition of Experiment I. (See Figure 1 for a more detailed key.)


2 TONE CONDITION
2T+L
L
MEAN LETTER RT IN MSEC
800
700
600
500
400
300
1
2
3
4
5
6
7
8
-1200
W.S.
1st Letter
2nd Letter
No Probe
PROBE POSITION AND LETTER TASK EVENT

No Probe data were analyzed separately. Inspection of the rightmost points in Figure 3 shows that on No Probe trials _same_ responses were about 60 msec. faster than _different_ responses, regardless of the tone or task condition. Adding the 1T task to a block of letter trials did not influence letter RTs on No Probe trials, but adding the 2T task increased both _same_ and _different_ RTs by an average of 26 msec. on these No Probe trials. A 3-factor repeated measures analysis of variance on the No Probe trials alone supported these observations. There were significant effects of kind of trial ($F(1,15)=73.48$, $p < .001$) and a JxT interaction --number of tones with number of tasks ($F(1,15)=7.55$, $p < .025$). None of the other main effects or interactions approached significance.

Letter RTs on Probe trials were substantially influenced when responses to those probes were required (2 Task conditions), but not when tones were irrelevant (1 Task conditions). As can be seen in Figures 3 and 4, the curves for the 1 Task conditions are fairly flat. Systematic inflation of the 2 Task curves over the 1 Task curves resulted in the significance of 11 effects in a 4-factor repeated measures analysis of variance including all probe positions. All 4 main effects (J, T, K, and P) were significant, reflecting the findings that letter RTs under 2 Task Probe conditions were longer than when the letter task was performed alone ($F(1,15)=22.47$, $p < .001$), that on the average letter RTs were longer in the 2T conditions than in the 1T conditions ($F(1,15)=9.68$, $p < .01$), that different responses took longer than same responses ($F(1,15)=89.83$, $p < .001$), and that letter RTs varied with probe position ($F(7,105)=25.22$, $p < .001$). The JxT interaction ($F(1,15)=34.67$), $p < .001$) reflected the greater increase in letter RTs in the 2T + L condition as opposed to the 1T + L condition. The JxK interaction ($F(1,15)=7.56$, $p < .025$) reflected the greater increase in 2 Task condition different RTs than same RTs. In addition, each of these effects tended to increase in size with presentations of tones nearer to the second letter. Thus, the following 5 interactions with probe position were also significant: JxP ($F(7,105)=24.24$, $p < .001$), TxP ($F(7,105)=4.12$, $p < .005$), KxP ($F(7,105)=6.26$, $p < .001$), JxTxP ($F(7,105)=9.23$, $p < .001$), and JxKxP ($F(7,105)=5.00$, $p < .001$). The remaining 4 possible effects, all of which involve interactions of T and K, did not approach significance.

Errors. Combining across all experimental conditions, the error rates were 4.7% for trials on which no tone occurred and 7.8% for trials with a tone. Table 1 shows the percent errors for each condition and probe position. Figure 1 displays the same information for the 2 Task conditions only (for a finer breakdown, see Appendix A-3). Since error rates were low and had a fixed ceiling, no formal error analyses were done. However, as can be seen in Table 1, errors varied depending on experimental condition. Only 6

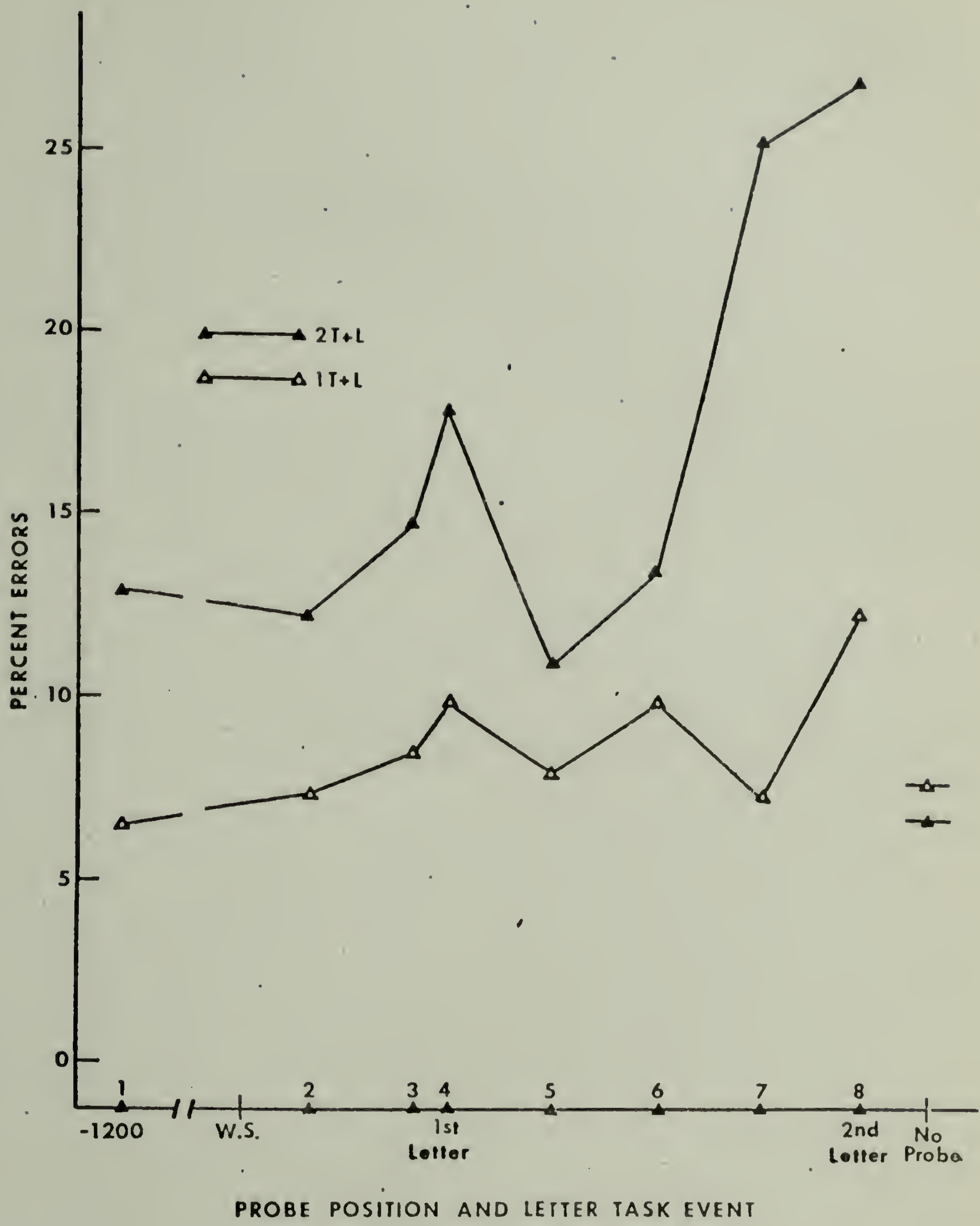
Table 1

Percent Errors in Each Condition of Experiment I as a Function of Probe Position

Condition	Probe Position 1	2	3	4	5	6	7	8	No Probe
Letters Only - 1T	5.9	5.9	7.3	9.9	5.9	11.1	5.9	7.3	5.5
2T	8.6	7.3	4.5	4.5	4.5	8.6	9.9	5.9	8.2
Tones Only - 1T	1.5	1.5	1.5	0.0	1.5	0.0	1.5	1.5	---
2T	5.9	1.5	7.3	3.0	4.5	7.3	8.6	3.0	---
2 Task 1T + L	6.6	7.3	8.6	11.1	7.9	9.9	7.3	12.3	7.7
2T + L	12.9	12.3	14.7	17.9	11.1	13.5	25.6	27.3	6.7

Note: Since error trials were always rerun during the trial block in which they occurred, the percentages tabled here were computed by dividing the number of errors by the constant number of correct trials plus the number of errors, then multiplying by 100.

Figure 5. Percent errors on the 2 Task conditions of Experiment I. The curves have been collapsed across kind of trial (_same_ or _different_) and kind of error (on the letter task or on the tone task).



2T+L
1T+L
PERCENT ERRORS
25
20
15
10
5
0
1
2
3
4
5
6
7
8
-1200
W.S.
1st Letter
2nd Letter
No Probe
PROBE POSITION AND LETTER TASK EVENT

errors were recorded in the 1T condition when only tone responses were required. It was possible to make errors in the most ways in the 2 Task conditions, and the 2T + L condition produced the most errors. Also, of the 15 blocks of trials which were rerun because they contained more than 9 errors in addition to 32 correct trials, 14 were 2T + L condition blocks.

An attempt was made to investigate whether some of the changes in probe RTs and letter RTs could be accounted for by trade-offs of speed and accuracy. Evidence for one such trade-off was found in the No Probe trials. Errors on these trials were all the result of responding same when the letters were different, or vice versa. It was pointed out in the preceding section (see Figure 3) that No Probe letter RTs were about the same for 1T and 2T Letters Only conditions; Table 1 shows that there were fewer errors for 1T than 2T Letters Only conditions. For the 1T condition, letter RTs did not increase from L to 1T + L conditions, but errors went up from 5.5% to 7.7%. Letter RTs did increase for the 2T + L condition, but error rates decreased from 8.2% to 6.7%. These findings suggest that the letter task was always more difficult in the context of 2 tones than 1 tone. In the Letters Only conditions this difference showed up as a higher error rate for the 2T condition. The 1T + L error rate rose in the more difficult 2 Task conditions. However, in the 2T + L condition, the very high error rates on Probe trials (an average of about 17%) necessitated low error rates on No Probe trials in order to stay within the maximum number of errors allowed per trial block. Thus, in the 2T + L condition, increased task difficulty was reflected in letter RTs rather than in error rates.

On Probe Trials, error rates as a function of probe position tended to increase with increases in probe RTs rather than exhibit trade-offs. In the 1 Task conditions error rates were fairly flat. In the 2 Task conditions error rates were highest when tones occurred near the second letter and also tended to show a peak near the presentation of the first letter.

An additional point of interest is that in the conditions for which responses to letters were required, error rates on _same_ trials were on the average higher than error rates on _different_ trials. This means that _Ss_ more often responded _different_ when the letters were actually the same than they responded _same_ when the letters were different. Collapsing across 1T and 2T Letters Only conditions, 69% of the errors on No Probe trials and 55% of the errors on Probe trials were on _same_ trials. In the 2 Task conditions the figures were 62% on No Probe trials and 57% on Probe trials. These results suggest that the reason _same_ responses were faster than _different_ responses was not because of a bias to respond _same_. If that were the case, more _same_ responses would be expected when the letters differed than _different_ responses when the letters were the same. Instead, the opposite was true for these data.

Another way to look at the error data from the T + L conditions is shown in Table 2, where errors on the tone task and errors on the letter task are separated, as are same and different trials. The first 4 and the last 4 probe positions are combined. It can be seen that in 5 of the 6 cells concerned with errors on the letter task, error rates were higher on same trials than on different trials, as was reported above for the averaged results. However, when a tone for the 2T condition occurred within the last 4 probe positions, the error rate on different trials was 15.8%, much larger than the 8.6% error rate on same trials, and much larger than the 4.8% error rate on different trials in the first 4 probe positions. Perhaps the relative same and different error rates can be explained by assuming that Ss usually tended to prepare for a match and to respond more quickly on same trials, but to respond different if they were unsure, thus having lower error rates on different trials. However, when the 2T task occurred near the second letter, Ss may have tended to respond impulsively on the letter task by pressing the same key, the response for which they were most prepared. Making these quick same responses would have inflated the error rate on different trials. It also may explain the fact that tone RTs in the 2T + L condition reflected less interference near the

Table 2

Percent Errors on the Letter Task and on the Tone Task in the 2 Task Conditions of Experiment I as a Function of Kind of Trial and Number of Tones

		Probe Position				No Probe	
		1 - 4		5 - 8			
Type of Error		Same	Diff	Same	Diff	Same	Diff
Letter Errors	1T + L	10.8	4.5	9.5	6.2	9.2	6.1
	2T + L	12.3	4.8	8.6	15.8	8.2	5.2
Tone Errors	1T + L	.4	1.2	3.0	.4		
	2T + L	6.9	6.9	11.4	8.3		

presentation of the second letter on <u>same</u> trials than on <u>different</u> trials.

DISCUSSION

The results will be discussed first in terms of the evidence they yield concerning the use of processing capacity by specific mental processes, and second in terms of the characteristics they suggest of central limited-capacity mechanisms. As was pointed out in the Introduction, at least 4 processes can be identified in the letter task with reference to the sequential visual stimuli presented--preparation, encoding, retention, and responding. Requiring responses to tones during these processes could result in interference between the 2 tasks as evidence of competition for the limited processing capacity available. Interference could take the form of increased RTs or errors on the tone task or on the letter task, and the results pointed out interference effects in all of these measures.

It is immediately apparent that combining the tone task and the letter task resulted in impaired performance on both tasks. Interference in the letter RTs was not expected. The instructions emphasized strongly that the letter task should always have priority. Posner and Boies (1971), using a simple probe task similar to the 1T task here, reported no significant effects of the probe task on performance of the letter task. Posner and Klein (1972) did not report RTs for the letter task. Comstock (1973) found interference in both the letter task and the tone task, but the instructions used in Experiment I here more strongly emphasized that Ss should not let the tone task interfere with speed or accuracy on the letter task. Using the tone task as a subsidiary task to measure spare capacity left over from the letter task is only strictly correct when performance of the letter task remains unimpaired. If both tasks show interference, as was the case in Experiment I, then both tasks must be considered when examining the data for evidence of the use of processing capacity. Inferences are more complicated and difficult to draw.

Because tone RTs and letter RTs were consistently longer in 2 Task conditions than in 1 Task conditions, regardless of probe position, it might be possible to make a case for every process of the letter task interfering with, and being interfered with by, tone responses. However, it would seem more reasonable at this time to say that the division of attention between 2 tasks involves extra processes, such as constantly holding ready the rules for both tasks instead of just one and monitoring for signals in two modalities, and that it is these processes which produce increases in the baselines of the 2 Task curves relative to their 1 Task controls. Thus, the data from Figures 1, 3, and 4 will be interpreted in the following way: (1) The lowest point on each 2 Task tone RT curve (position 5 for these data) will be taken as the fastest possible fully-alerted tone RT for the condition. (2) The difference between that point and the 1 Task control will be assumed to be due to the general division of attention between 2 tasks and whatever constant minimum amounts of capacity are required by the letter task. These baseline changes will be discussed mainly as evidence for the characteristics of limited-capacity mechanisms in dealing with a dual-task situation. (3) Increases in the 2 Task tone RT curves above the lowest point will be discussed mainly as evidence for the use of processing capacity by specific mental processes. (4) Increases in the 2 Task letter RT curves will be taken as specific interference with letter processing as a result of doing the tone task.

Preparation. The first visual event on each trial of the letter task was the onset of the warning signal, which should have initiated the process which Posner and his colleagues (Posner and Wilkinson, 1969; Posner and Boies, 1971) have called alertness or nonspecific preparation. The results of Experiment I provide support for the notion that preparation requires no processing capacity. Consider the 1T + L curve for tone RTs (see Figure 1). If processes occurring during the warning interval required processing capacity, then tones in positions 2 and 3 should have resulted in longer RTs than tones in position 1. In fact, in the 1T + L condition, responses to tones during the warning interval were faster than responses to tones between trials. This finding is consistent with those of Posner and Boies

(1971) and Posner and Klein (1972), who suggested that the process of preparation for the letter task is nonspecific in that it also facilitates fast responses on the tone task.

In the 2T + L condition, however, tone RTs did not drop across positions 1, 2, and 3. Since responses to tones in positions 2 and 3 came after the onset of the first letter, these RTs may have been inflated by processes connected with encoding the first letter rather than with the process of preparation. The only evidence of a decrease in tone RTs in the 2T + L condition as a result of being prepared for the letter task is that tone RTs in positions 5 and 6 are lower than those in position 1; but even this decrease (about 31 msec.) is less than the decrease observed in the 1T + L condition (about 74 msec.).

Many explanations for this difference between the 1T + L and 2T + L conditions are possible. It may be that responses to the tones were facilitated as a kind of side effect of the preparation for the letter task, as Posner and Boies suggest. If the tone RTs were only reflecting preparation for the letter task, then the question remains as to why this "nonspecific preparation" only extended to simple tone responses and not to 2-choice tone responses, a question which can only be addressed with further experimentation. However, another explanation which is consistent with previous findings and with data from this experiment is that preparation was specific for the sources of stimulation expected.

Suppose that the warning signal, in addition to indicating the beginning of a trial on the letter task, also indicated an increased probability that a tone would occur. It is a well-documented finding that increasing the expectation that a signal will occur at a given time decreases its RT (c.f., Hyman, 1953; Klemmer, 1957; Moss, 1969; and Nickerson, 1968). In the control conditions, tone RTs were flat regardless of probe position because Ss ignored the visual events and thus did not use them to predict the occurrence of tones. In the 1T + L condition, RTs to tones in position 1 were longer than in positions 2, 3, or 5 because tones during the intertrial interval were less expected than tones during the trial.

Figures 1 and 2 suggest that the difference between the 1T + L and 2T + L tone RT curves is not that the 2T + L curve did not decrease as much after position 1, but rather that it was already fairly fast relative to the rest of the curve and relative to its control. While the position 1 RT for the 1T + L condition was 133 msec. above the control curve, the 2T + L curve began only 96 msec. above its control curve. It may be that during the intertrial interval in the 2T + L condition Ss remained more prepared to make tone responses than was the case in the 1T + L condition. This speculation was corroborated by the remarks of several Ss who volunteered that between trials on the 1T + L condition they tended to feel bored or to let their minds wander, while between trials on the 2T + L condition they tended to remind themselves of the assignment of keys for high and low tones or to turn their attention to the tone task, on which they had made many errors when tones occurred during the letter task trials. If this interpretation is correct, then it supports the notion that preparation processes required no capacity, and it is reasonable to use the lowest point (position 5) on each 2 Task curve as the fully-alerted baseline against which to measure interference in the tone RTs from other processes of the letter task.

Did presentation of tones during the warning interval disrupt processing on the letter task? In the 1T + L condition, letter RTs in positions 2 and 3 were no longer on the average than letter RTs on No Probe trials. In the 2T + L condition, on the other hand, letter RTs in positions 2 and 3 were approximately 36 msec. longer than letter RTs on No Probe trials. It seems unlikely that these increases were due to a disruption in response processes for the letter task, since responses to tones in these positions were always completed well before responses on the letter task were required. For example, position 3 tone RTs took an average of 690 msec., which meant that the tone responses occurred about 610 msec. prior to the onset of the second letter. Bertelson (1966), in summarizing studies of RTs to 2 successive signals, concluded that in some situations the RT to the second signal was delayed even when that signal came on after the response to the first signal had been initiated. However, the interval after the first response during which a delay to the second was found was almost always less than 150 msec. Therefore, the increases in 2T + L letter RTs found in this experiment are probably due not to the effect of the tone response on the readiness to process or respond to the second letter, but rather to a disruption in processes associated with the first letter, such that when it came time to match the two letters, the information about the first letter was less accurate and thus the matching process took longer. It is not possible to identify exactly whether preparation, encoding, or retention on the letter task was interfered with by the 2 Tone task, since RTs to tones in positions 2 and 3 overlapped with all three processes. However, the most parsimonious explanation would ascribe the effect of an early tone to encoding or retention, processes for which other evidence of interference exists, as the sections below will discuss.

In summary, the data from Experiment I are consistent with the notion that preparation, such as that occurring following a warning that pertinent stimuli are about to be presented, requires no processing capacity.

Encoding. The probe positions most relevant to the discussion of the processing capacity requirements of "reading in" the first letter are positions 3, 4, and 5 --tones occurring 100 msec. before, simultaneously with, and 300 msec. after the onset of the first letter. In both the 1T + L and the 2T + L conditions, presenting a tone simultaneously with the first letter resulted in longer tone RTs than presenting a tone either 100 msec. before or 300 msec. after the first letter. The decrease in tone RTs between positions 4 and 5 was larger for the 2T + L condition than for the 1T + L condition. Error rates also tended to show a peak at the first letter. These results suggest that processes occurring with the presentation of a single letter did require a detectable amount of processing capacity.

As was described in the Introduction, Posner and Boies (1971) estimated that encoding, or the process of extracting enough information from the first letter to make matching it to a second letter maximally efficient, took between 250 and 500 msec. It seems reasonable to accept their definition and estimated duration of encoding for this similar experimental situation. Now, if processing on the tone task were delayed for the entire encoding process, interference of about 250 msec. would be expected in both the 1T + L and the 2T + L conditions. Instead, comparing tones presented simultaneously with the first letter to the lowest point on the 2 Task curves (position 5), the interference was only 38 msec. for the 1T + L condition and 84 msec. for the 2T + L condition. If only the first small portion of the encoding process interfered with the tone tasks, equal interference would be expected for both probe positions

3 and 4, since both overlapped with the beginning of the encoding process. Instead, RTs to tones in position 3 reflected no interference in the 1T + L condition. In the 2T + L condition, position 3 RTs reflected some interference, but it was less than the interference reflected by position 4 RTs.

The pattern of tone RTs is consistent with the explanation that only a small portion of the tone task was interfered with by the process of encoding the first letter. If it is further assumed that encoding in the 2T task required processing capacity for a longer period of time than encoding in the 1T task, then an explanation of the interference at position 3 and the greater overall interference in the 2T task than the 1T task is possible. Suppose that in the 1T task encoding only consisted of a simple detection--hearing any tone was sufficient to initiate a tone response. If this detection required less than 100 msec., then for tones in position 3 the use of processing capacity in detection would be completed before the first letter came on, and the tone RTs would not be lengthened when encoding the letter used capacity. For tones in position 4, competition for available capacity would lengthen tone RTs. In the 2T task it could be supposed that the process of encoding was longer because a discrimination between high and low tones was required. If this encoding process took more than 100 msec., then RTs on the 2T task would be expected to be delayed in both positions 3 and 4, and the delay in position 4 would be expected to be longer than the position 4 delay in the 1T task.

While the words "detection" and "discrimination" in the above explanation are appealing, they are not essential. The only necessary features of an explanation for the greater interference with 2T + L tone RTs than with 1T + L tone RTs are that an early process in the 2T task must have required capacity for a longer time than was the case in the 1T task, and the encoding of the first letter must have interfered less (or not at all) with processes in the middle of the reactions to the tones. Thus, one question which might be asked at this point is whether the increases in tone RTs were the result of the interference of specific processes or just general competition for freely-assignable processing capacity. Using the terms suggested above, it could be argued that encoding a letter required detection plus discrimination, each process having its own pool of capacity (or separate processing mechanism). Requiring a simultaneous discrimination would tax the discriminator's capacity, and requiring a simultaneous detection would tax the detector's capacity. If this were the case, then increasing the discrimination requirements of the letter task would be expected to result in more interference with a tone task which also used the discriminator; but it should not increase the interference with a tone task which only used the detector. On the other hand, if interference were nonspecific, then increasing the difficulty of the encoding connected with the first letter should increase the interference detected by both tone tasks. Experiment II is an attempt to test these notions. The difficulty of the discrimination required for the first letter stimulus is varied by presenting either 1 letter or 2 letters, followed by a mask. The same 1T and 2T tasks were used as subsidiary tasks.

One objection could be raised concerning the interpretation of the source of the interference with responses to tones presented at the first letter. It may be that ordinarily the encoding of visual and auditory information goes on automatically without the use of processing capacity, but that in this experiment, masking the first letter after 50 msec. made accurate perception of the letter very difficult. If some Ss did not see the letter well enough to encode it in the usual way, they may have found it necessary to apply special processes at the onset of the letter in order to sort out the letter information from the masking stimulus. If so, then it may have been those extra processes rather than encoding which lengthened RTs to simultaneous tones. A few Ss did mention that on some trials they simply missed the first letter altogether. In Experiment II an attempt was made to ensure that every S could accurately perceive the first letter stimulus. The shortest length of time prior to the onset of the mask at which nonspeeded performance of the letter task was essentially perfect was estimated for each S for both 1 and 2 letters. It was hoped that this procedure would effectively equate the constraints on the times available for encoding 1 and 2 letters and reduce the likelihood that processes other than encoding would be required. It is of interest to note that in Experiment II for 1 letter, an average exposure duration of 62.5 msec. was needed, which supports the suggestion that the 50 msec. used in Experiment I could have given some Ss difficulty.

Retention. The process of retaining the first letter did not result in longer responses to the tones. On both the 1T + L and 2T + L curves, RTs to tones in positions 5 and 6, which occurred entirely within the retention interval between the 2 letters, were the fastest. This finding disagrees with earlier work of Comstock and of Posner and Boies, in which tone RTs usually began to increase with the offset of the first letter (Posner and Boies, 1971; Posner and Klein, 1972), or with the onset of the first letter if it was masked (Comstock, 1973), and never decreased after the first letter once an increase had occurred. This was true whether the matches were based on the physical identity of the letters or their name identities. It was also true even when RTs occurring after the onset of the second letter were excluded from the analysis, thus suggesting that some process occurring during the retention interval required capacity, perhaps overt rehearsal, maintenance of a visual image, or preparation for the second letter.

One procedural difference between previous letter conditions and Experiment I might possibly account for the lack of interference with tones during the retention interval. While the interstimulus interval in previous studies was almost always 1 second, here it was 1200 msec. It may be that the extra 200 msec. gave Ss some assurance that their responses to tones after the first letter would fit into the interval before the second letter came on. With this explanation, the increases found in previous studies would be interpreted as reflecting a hesitancy on the part of S to respond to the tone because he was monitoring for, or expecting, the second letter, not because retention of the first letter was requiring processing capacity.

On the other hand, inspection of the letter RTs suggests a more satisfying explanation. Unlike previous studies, responses to tones during the retention interval resulted in increased RTs on the letter task. Since tone reactions in positions 5 and 6 began after the offset of the first letter and were complete before the onset of the second, they must have disrupted some process which usually occurred during the retention interval. The disruption was greater for inserted 2T reactions than for inserted 1T reactions. It appears that processing capacity needed for retention interval processes was used instead for fast processing on the tone task. Thus, these data are consistent with interpretations of previous studies in showing that a process following the encoding of the first letter, but preceding the response to the second, required processing capacity. Similarly, it was probably this retention interval process which was disrupted by tones which occurred early in the trial but which were responded to during the retention interval.

The argument presented in the preceding section that encoding interfered more with the 2T task than with the 1T task rested heavily on the comparison of tone RTs in positions 4 and 5 on the 2 Task curves. The validity of this comparison might be questioned in light of the interpretation that tone RTs were fast in position 5 as a result of a trade-off between letter retention processes and tone processes. Letter RTs were more interfered with by the 2T task than the 1T task. On the other hand, 2T + L tone RTs decreased more between positions 4 and 5 than did 1T + L tone RTs. Could these decreases have been the result of a heavier bias away from retention processes and towards the tone task in the 2T + L condition than in the 1T + L condition? Several observations argue against this interpretation. First, using any probe position other than position 3 or 4 (not only using position 5) as a baseline leads to the same conclusion--that the 2T task showed more interference than the 1T task at positions 3 and 4. Second, unless the bias was only effective after the presentation of the first letter, the sharp decline from position 4 to position 5 in the tone RT curves would not be expected. Yet, the letter RT curves began increasing when tones came on at or before the first letter, a time when tone RTs and errors were also increasing, and the bias, if it existed, should have been favoring the letter processes. Thus, the most parsimonious explanation is that RTs to tones in position 5 provided a reasonable estimate of fully-alerted baseline RTs against which to measure interference from processes in the letter task, that encoding did produce more interference with 2T RTs than 1T RTs; and that when responses on the tone task occurred during the retention interval, processing on the letter task was impaired, the degree of impairment depending on the length of time or the processing capacity required by the tone task.

In Experiment II it may be possible to draw some further inferences about the retention interval, since the process of retaining 1 letter to match with 2 letters can be compared with the process of retaining 2 letters to match with 1 letter. If, during the retention interval, processes are needed which are associated with the first letter stimulus, such as memory and rehearsal, then retaining 2 letters might be expected to produce more interference than retaining 1 letter. If processes are needed which are associated with preparation to make one of 2 responses or to receive any second visual stimulus, then the 1 Letter and 2 Letter conditions might be expected to show equal interference. If processes are needed which are associated with the number of possible stimuli which could constitute the second letter stimulus, then retaining 1 letter (which is followed by a pair of letters) might be expected to show more interference than retaining 2 letters.

Responding. The most obvious conclusion that can be drawn from the results of Experiment I is that the processes connected with responding required processing capacity. The greatest amount of interference in both tone RTs and letter RTs occurred when the second letter came on before the response to the tone had been made. Some of the characteristics of this interference will be discussed later with reference to dual task performance. This section will examine the evidence for differences in the processing capacity requirements of same and different responses, and of responses on the 1T and the 2T tasks.

If different responses required more capacity than same responses, more interference would be expected on different trials than on same trials, a finding which was very strong in the 2T + L condition, and only hinted at in the 1T + L condition. In the letter RTs, different responses were more interfered with than same responses, regardless of the tone condition. These results offer support for the notion that responding different takes more capacity than responding same. In addition, the fact that interference was much greater on different trials than on same trials in the 2T + L condition but not in the 1T + L condition can be interpreted to agree with the suggestion made in the discussion of encoding that the 2T task requires processes which the 1T task does not require. It could be that 1T tone responses and _same_ responses used the discrimination mechanism only minimally, while 2T tone responses and _different_ responses used it maximally. The most interference would then be expected when two tasks both required the discrimination mechanism --2T _different_ trials. The 1T task would never use the discrimination mechanism and thus would not produce more interference with _different_ trials than with same trials. However, carrying these speculations very far is unwise. As was pointed out in the Results section, the error rates suggest that a shift in bias could account for the differences in RTs between _same_ and _different_ trials (see Table 2).

Error rates were almost always higher on _same_ trials than on _different_ trials, indicating a bias to respond _different_. At the same time, RTs were faster on _same_ trials than on _different_ trials. It seems likely that _Ss_ were usually prepared to make a match and respond _same_, but that they tended to respond _different_ if there was any doubt about the correct answer. In the 2T + L condition, relative error rates for _same_ and _different_ trials changed when tones occurred near the second letter. Error rates were much lower on _same_ trials than on _different_ trials. This changed bias probably indicates a tendency for _Ss_ to make impulsive _same_ responses when responses were being made to tones at the same time. Impulsive _same_ responses might be thought of as having been made before the usual processes associated with correct letter responses were completed. Thus, tone RTs and letter RTs may have shown less interference on _same_ trials than on _different_ trials because impulsive _same_ responses required less processing capacity, not because correct _same_ responses required less processing capacity. The 1T + L condition showed slight tendencies in the same direction as the 2T + L condition. Although error rates on _same_ trials were always greater than error rates on _different_ trials, comparing the first half of the trial to the last half, there was a tendency for errors on _same_ trials to decrease and for errors on _different_ trials to increase. Thus, impulsive _same_ responses when tones in the 1T + L condition occurred near the second letter may explain the smaller interference with letter RTs on _same_ trials than on _different_ trials.

In summary, the evidence presented is inconclusive with respect to the question of whether _same_ and _different_ responses differ in their processing capacity requirements. Since to the author's knowledge no adequate method exists for assessing the tradeoffs between RT and errors in this kind of situation, it is not clear whether the explanation in terms of a changed bias to respond _same_ is powerful enough to account for the greater interference found on _different_ trials than on _same_ trials. It was hoped that Experiment II would provide more evidence on the processing capacity requirements of different kinds of responses. As in Experiment I, responses fell into two categories (yes the single letter matched one of the letters in the pair or no it did not). Also, in the condition in which 1 letter was followed by a pair of letters, there were different kinds of yes and no responses. Did responding yes to B followed by BB take less capacity than responding yes to B followed by BC or CB? Did responding no take a different amount of capacity when the pair was CC than when it was CD? It is unlikely that response bias explanations will work to explain different amounts of interference with tone RTs within one category of response. Another change in Experiment II was the inclusion of a probe position 100 msec. after the onset of the second letter. It was hoped that tones presented in this position, along with tones presented simultaneously with the second letter, would increase the power to detect differences in processing capacity used on different kinds of trials.

For purposes of this paper, response processes are defined as all the mental operations occurring between a signal to respond and the actual response. In this sense, only response processes can be distinguished in the tone tasks used here. Evidence that responses on the 2T task required more capacity than responses on the 1T task has been presented in preceding sections. Tone RTs only showed greater interference with the 2T task than with the 1T task during the encoding of the first letter. On the other hand, whenever tones called for responses during trials on the letter task, letter RTs showed greater interference from the 2T task than from the 1T task. In addition, both interpretations of the difference in interference on _same_ and _different_ trials imply that the 2T task required more capacity than the 1T task. The effect that _different_ responses resulted in more interference than _same_ responses was much greater in the 2T + L condition than in the 1T + L condition. The response bias shift from favoring _different_ responses to favoring _same_ responses was much stronger in the 2T + L condition than in the 1T + L condition. These results are difficult to explain except by saying that the 2T task did require more processing capacity than the 1T task.

Dual task performance. The preceding sections have discussed the interference between the tone tasks and the letter task as evidence for the use of processing capacity by the specific processes of encoding, retention, and responding. This section will discuss how the limited capacity might be allocated when _S_ is attempting to perform two tasks, both of which require capacity.

The simplest notions of single-channel switching and variable allocation each fail to account for the results of Experiment I for the same sorts of reasons that they failed to account for the results of Comstock (1973). As was mentioned in the Introduction, the variable allocation notion assumes that a finite amount of capacity is available at any one time, and that it is shared among processes which need it.

The more capacity one task needs, the more it should be interfered with and the more interference it should cause with a concurrent task also using capacity. Thus, this variable allocation notion always predicts interactions in both tone RTs and letter RTs between the difficulty of the tone task (1T vs. 2T) and the amount of capacity being used in the letter task (probe position).

On the other hand, a single-channel switching notion predicts that interference in one task should be a function of the length of time that the channel is engaged with another task before a switch can be made. Interference in tone RTs in the 1T + L and 2T + L conditions should be the same, reflecting only the length of time for which the letter task required the channel. Delays in letter RTs should reflect the difficulty of the tone task, since the single channel would be engaged for a longer period of time with the 2T task than with the 1T task. Thus, this single-channel switching notion predicts interactions in letter RTs, but no interactions in tone RTs, as a function of tone task difficulty and probe position.

Letter RTs cannot be used to distinguish between the single-channel switching and the variable allocation notions, since the obtained interaction between tone task difficulty and letter task difficulty would be predicted by both. Tone RTs did not fully support either notion. Variable allocation was suggested by the fact that more interference from the encoding of the first letter was detected in the 2T + L condition than in the 1T + L condition. There was also a suggestion that different trials resulted in more interference than same trials in the 2T + L condition but not in the 1T + L condition. On the other hand, RTs to tones presented in positions 5 through 8 did not show greater interference as task difficulty increased, suggesting a switching notion. The 1T + L and 2T + L tone RT curves were almost exactly parallel when tones were presented near the second letter and the two curves were detecting the most interference from the letter task. Also, the overall increase in tone RTs between the T control conditions and the T + L conditions was no greater for the 2T conditions than for the 1T conditions; if anything, there was a smaller increase for the harder task.

What modifications can be made in the two notions of the allocation of capacity to enable them to account for the tone RT data? Consider variable allocation. One assumption of this view is that two concurrent tasks must share the available capacity. However, one reasonable modification which has occasionally been suggested (see Kahneman, 1973; Connor, 1972) is that processes which sometimes occur in parallel, sharing capacity, might become serial processes when the combined task demands exceed the amount of capacity available. This is essentially saying that the pool turns into a single channel; capacity is allocated in an all-or-none fashion, first to whatever tasks have priority. Combining variable allocation and single-channel switching in this way can account for the tone RT data. Parallel curves when tones came on near the second letter would be expected because response processes in the letter task would be making heavy demands for capacity, and the variable allocator would operate like a single channel.

Variable allocation notions would not be needed at all if the greater increase from encoding in 2T + L tone RTs than in 1T + L tone RTs could be explained with a single-channel switching notion. Before discussing how each notion handles the interference found in the first part of the trial, an important point from the previous discussion of encoding needs to be recalled. If both the 1T and the 2T tasks required a uniform amount of capacity throughout their entire reaction times, then both notions of allocation would predict that interference in position 3 would be greater than or equal to the interference in position 4, since processing on both tasks would overlap completely with the process of encoding the first letter. To explain the relative amounts of interference in the 1T + L and 2T + L conditions at positions 3 and 4 it would seem necessary to assume that encoding a tone in the 2T task required capacity for a longer period of time (over 100 msec.) than encoding a tone in the 1T task, and that processes between the encoding of the tone and the response to it required very little capacity.

Letter RTs provide another piece of evidence consistent with the view that there is a time between the initial encoding of a stimulus and the response to it when the capacity requirements are low and when processes on two tasks can go on simultaneously more efficiently than they could go on individually. In both the 1T + L and the 2T + L conditions, when tones were presented simultaneously with the second letter, responses to the tones took longer on the average than responses to the letters. Thus, RTs on the two tasks overlapped for the entire duration of the letter RT. If both tasks usually required full use of the channel for the entire duration of the RT, then the sum of the interference detected in the letter task and the tone task should equal the length of the overlap time. This would be the case, for example, if all tone processes were delayed until the letter response was made. Clearly, the total interference was much less than the length of time the two tasks overlapped. For example, in the 1T + L condition, tone responses were 595 msec. (204 msec. above position 5) and letter responses were 381 msec. on <u>same</u> trials and 516 msec. on <u>different</u> trials (22 and 92 msec. above the No Probe values). The total interference of 226 and 296 msec. was much less than the total overlap time of 381 and 516 msec. As crude as these calculations are, they suggest that about 155 or 220 msec. were saved by doing the two tasks simultaneously. Similar calculations for the 2T + L condition resulted in similar estimates of time saved--241 and 171 msec. When tones occurred in position 7, 300 msec. prior to the second letter, there was no savings in overlap of the two tasks. The sum of the interference in tone RTs and letter RTs tended to be about the same as the length of time for which the two tasks overlapped. The estimates of time saved on same and different trials, calculated as above, were -11 and -50 msec. for the 1T + L condition and +63 and -22 msec. for the 2T + L condition.

All of these results suggest that after the encoding of a tone there is a period of time on the order of 200 msec. during which letter task processes can be performed without interference. It is intriguing to speculate about the nature of this "effortless processing." Perhaps this is the nonattentive encoding or memory access discussed by Posner and Boies (1971) and Keele (1972, 1973). If so, then the interference detected here from the initial encoding of simple visual or auditory stimuli may reflect something related to the very crude extraction of raw information sufficient for the nonattentive memory access process to operate accurately.

Returning to the variable allocation and single-channel switching notions, the indications that the initial processing of the 2T task took longer than that of the 1T tasks still leaves it easier for the variable allocation notion to account for the interference from encoding. As has been stated before, according to the variable allocation notion, the 2T + L condition reflected more interference because encoding the tone and encoding the letter shared capacity and the 2T task required more total capacity than the 1T task. According to the single-channel switching notion, in the 1T + L condition, tones in position 2 would have been done using the channel before the letter came on and encoding the letter would have been done using the channel before the response to the tone required the channel again. Only retention processes on the letter task would then be disrupted. In the 2T + L condition, tones in position 3 would not have been done using the channel before the letter came on. Thus, tone RTs would have been delayed while the channel was used to encode the letter or slowed because the tone response was based on less accurate tone information. These explanations, if somewhat strained, will account for position 3 tone RTs. However, tones in position 4 still should have shown the same delay from the encoding of the letter in the 2T + L condition as in the 1T + L condition. In order for the single-channel switching notion to account for the greater interference in the 2T + L condition, it would seem necessary to assume that when the channel can switch to the tone task is a function of that tone task and not of the processing on the letter task. One suggestion discussed in the section on encoding is that interference is the result of specific processing mechanisms such as a detector and a discriminator. Then the letter encoding, which requires both detection and discrimination, would interfere with another task only when that other task demanded the same mechanism at the same time. This would actually seem to be a fairly drastic change in the single-channel switching notion, since it is tantamount to assuming that there are two separate channels, one for detection and one for discrimination. The idea seems related to Smith's (1969) finding that performance on a discrimination task was influenced by the number of alternatives in a subsidiary task, while performance on a detection task was not. It seems that two discriminations interfered, while discrimination and detection did not. The previous discussion of encoding suggested that Experiment II might further test the notion of separate mechanisms by increasing the load on the discriminator. The two-mechanism idea would predict that doing so would increase the interference detected in the 2T task but leave the same interference in the 1T task.

One final aspect of the data, which both notions of the allocation of capacity have trouble handling, is the differences in tone RTs in the T + L conditions compared to their T controls. According to the simplest variable allocation notions, if the difference is due to processes which require processing capacity, then that increase should be larger for the 2T task than for the 1T task. Instead, the increase for the 2T task is the same as (or smaller than) the increase for the 1T task. According to the single-channel switching notion, the increases should reflect the length of time needed to switch the channel from the letter task to the tone task. In Experiment I, if tone RTs at position 5 are used, the estimated switching times would be 74 msec. and 28 msec. for 1T and 2T, respectively. If tone RTs at position 1 are used, the estimates would be 133 msec. and 96 msec. Varied as these estimates are, they may not be so far removed from Kristofferson's (1967b; Schmidt and Kristofferson, 1963) estimates of switching time, which have varied from 40 msec. to 100 msec. Switching times so long, however, make it very difficult for single-channel switching notion to handle the interference from encoding the first letter. For example, take 2T + L tone RTs. When a tone came on in position 3 the channel would switch from the letter task to the tone task to begin encoding the tone, switch to the letter channel to encode the letter, and switch back to the tone channel to finish encoding the tone and respond to it. When a tone came on in position 4, the channel would merely have to encode the letter and then switch to encode and respond to the tone. It is difficult to see how tone RTs in position 3 could be faster than tone RTs in position 4, when the former would require three switches and the latter only one.

Any number of post-hoc explanations could account for the baseline differences between T and T + L conditions, while leaving the variable allocation and single-channel switching notions to handle the specific interference within the T + L curves. For example, it might be speculated that baseline differences reflect a kind of motor preparation unrelated to central processing. This kind of preparation would be expected to be strongest in the 1T condition when responses were required from only 1 finger. Adding 2 letter fingers in the 1T + L condition would be expected to decrease the motor preparation for any one response. Going from 2 to 4 possible responses in the 2T conditions might be expected to have less of an effect on motor preparation than going from 1 to 3 possible responses in the 1T conditions. This agrees with the tendency for the baseline increase to be less in the 2T conditions than in the 1T conditions.

Interpretation of the results of Experiment I would obviously be easier if all of the interference detected were in one measure. Ss were carefully instructed to consider the letter task their primary task and to let the tone task suffer if anything did, yet performance on the letter task was also systematically worse under 2 Task than 1 Task conditions. It may be that Ss, who seemed to be trying to follow instructions, were simply unable to perform the letter task without interference. However, the instructions may have been ambiguous. Another problem may have been that having to distinguish 2 separate tone tasks and only 1 letter task may have tended to emphasize the tone task. In Experiment II it was hoped that the inclusion of 2 letter tasks and the use of a payoff scheme to help disambiguate the instructions would concentrate the interference effects more in the tone RTs.

EXPERIMENT II

METHOD

Subjects. Eight men and eight women were run individually for 5 1-hr. sessions within 10 days or less. Data from 1 additional male S were not included because a combination of procedural errors by the experimenter, and high error rates and anticipatory responding by S made the results very difficult to interpret. Ss were recruited with bulletin-board advertisements and were paid $9.00, plus a possible bonus (described in the Procedure section below) of as much as $2.00. All Ss reported normal or corrected-to-normal vision; 12 were right-handed, 3 were left-handed, and 1 was ambidextrous.

Apparatus and stimuli. All apparatus was identical to that described for Experiment I, except for the following minor modifications: (1) Ss sat approximately 3 feet from the oscilloscope screen; this was slightly closer than in Experiment I, in which several Ss complained about the small size of the letters. (2) The plexiglass keys on the right, used for the letter task, were labeled YES and NO instead of SAME and DIFF. As in Experiment I, half of the Ss used the key corresponding to their index finger for yes responses and to their middle finger for no responses, and the other half used the reverse key assignment.

The letter stimuli were of the same screen size as in

Experiment I, but because of the shorter viewing distance, each letter subtended approximately 40' of visual angle vertically. To avoid having some letter pairs form words, only the 20 consonants were used in Experiment II. The high and low tones were the same ones used in Experiment I.

Primary and probe tasks. The primary letter task differed in several ways from the letter task in Experiment I. Instead of 2 letters, S saw 3 letters on each trial. In the 1 Letter condition (1L), a single letter was followed after 1200 msec. by a pair of letters, and in the 2 Letter condition (2L), a pair of letters was followed by a single letter. In both cases, S's task was to respond yes if the single letter was a member of the pair and no if it was not. The 1L and 2L conditions were never mixed in a block of trials, and except for the initial practice day, they were never both included in the same session of the experiment.

In the 1L condition there were 5 classes of letter pairs for the second stimulus. If X and Y represent any 2 non-matching consonants, and if the first stimulus was B, then the second stimulus could have been BB, BX, or XB for a yes response, or XX or XY for a no response. Among trials to which correct responses were made in each trial block, the number of yes trials equalled the number of no trials, and the number of pairs of identical letters equalled the number of mixed pairs.

In the 2L condition there were 3 classes of single letters for the second stimulus. If the first stimulus was BC, then the second could have been B or C for a _yes_ response, or any non-matching consonant such as X for a _no_ response. None of the first stimuli were identical letter pairs. As in the 1L condition, the number of _yes_ trials equalled the number of _no_ trials.

The sequence and timing of events in the letter tasks were the same as in Experiment I except for the onset time of the masking stimulus. At the end of each _S_'s practice day, estimates were made of the delay of the mask following the first letter stimulus at which he could correctly match it with the second stimulus 90% of the time. The task used was the same _yes_-_no_ letter task described above, except that no tones occurred and no reaction times were shown. The instructions described the estimation procedure, and _S_ was told to respond as accurately as possible without trying to be fast. Any RTs over 1800 msec. would have been discarded from the estimation data, but in fact none that long occurred.

The estimation procedure used was a version of the adaptive procedure PEST (Taylor and Creelman, 1967). Briefly, from a starting value of 110 msec., the mask onset time was decreased or increased in steps, the direction and size of which depended on _S_'s accuracy on previous trials. The mask onset time remained the same until the observed proportion correct exceeded by more than 1 the proportion correct which would be expected if in fact the mask onset time were set for 90% correct. With each reversal in the direction of the changes, the size of the step was halved. The starting step size was 32 msec. When a step size of 4 msec. was called for, the procedure was terminated. Thus, normally 4 reversals of direction were made as the step size decreased from 32 to 16 to 8 to 4 msec.

One estimate was made for the 1L condition and another for the 2L condition. The data for mask onset times longer than the 90% level were then examined, and the first time (evenly divisible by 5) at which it was likely that S could correctly match the first stimulus 100% of the time was determined separately for the 1L and 2L conditions. These mask onset times were used on the 4 experimental days. If an S complained that he could not see the first stimulus at the mask onset time used during the warmup block, and if he made more than 6 errors for 24 correct trials, then the mask onset time was increased by 5 msec. and another warmup block was run. If necessary, this procedure was repeated until S's error rate decreased and he reported that he could see the first letter stimulus better. For the 1L condition the mask onset times ranged from 40 msec. to 80 msec. (mean 62.5 msec.) and for the 2L condition they ranged from 50 to 95 msec. (mean 75 msec.). Each S's 2L mask onset time was longer than or equal to his 1L mask onset time. Regardless of the mask onset time, the mask went off 600 msec. prior to the presentation of the second stimulus.

The 2 versions of the tone task were similar to the tone tasks in Experiment I, except for 2 changes. (1) Instead of occurring on half of the trials of the letter task, tones occurred on 2/3 of the trials. (2) The last 3 probe positions were more spread out than in Experiment I, so that tones in the last probe position occurred after the onset of the second letter stimulus. The probe positions for Experiment II were (1) during the ITI, 1200 msec. prior to the onset of the warning signal, (2) 200 msec. after the onset of the warning signal, (3) 100 msec. prior to the onset of the first letter stimulus, (4) simultaneously with the first letter stimulus, (5) 300 msec. after the first letter stimulus, (6) 750 msec. after the first letter stimulus, (7) simultaneously with the second letter stimulus, and (8) 100 msec. after the onset of the second letter stimulus.

There were 12 possible treatment conditions, depending on the tone condition (1T or 2T), the letter condition (1L or 2L), and the tasks on which responses were required (letters only, tones only, or both T + L). Each block of 48 trials consisted of 24 _yes_ trials and 24 _no_ trials. As in Experiment I, different random sequences of letter stimuli were used for each _S_ on each day. Within the _yes_ and _no_ categories, tone probes occurred on 16 trials, twice for each probe position. In the 1L condition, half the trials had identical letter pairs for the second stimulus and half had mixed pairs. In the 2L condition, half of the yes responses were to second stimuli matching the first letter of the first stimulus, and half were to second stimuli matching the second letter of the first stimulus. In the 2T conditions, high and low tones were selected at random. As in Experiment I, trials were selected at random without replacement from the set of 48 trials, and error trials were replaced in the pool of trials remaining to be presented. However, in Experiment II no maximum number of errors was set and no trial blocks were rerun due to excessive error rates.

Design and procedure. The instructions given on the first day of Experiment II were similar to those used in Experiment I. The various versions of the letter tasks and tone tasks were introduced by a full description and a block of 24 trials. Emphasis was placed on speed and accuracy, especially on the letter task, which Ss were told was always the main task. They were told that if they ever felt as if performance on one task had to suffer, to let it be the tone task.

Each S had the same sequence of conditions on Day 1: (1) 1L (with 1 tone irrelevant), (2) 1T + 1L, (3) 2T (with the 2 letter task irrelevant), (4) 1T + 2L, (5) 2T + 2L. These first 5 blocks were run with a mask onset time of 150 msec. Then estimates of the mask onset times for the 2L and the 1L conditions were made. These blocks were as great as 147 or as little as 31 trials long, depending on the final threshold from the starting value. After each 32 trials, the message REST came on the screen; S could continue whenever he desired by pressing any key.

As in Experiment I, on each of the 4 experimental days, the stimulus conditions remained the same (1T or 2T, and 1L or 2L conditions), but all 3 response conditions were run (letters only, tones only, or both tasks). A Latin square was selected to order the days on which each of the 4 stimulus conditions was presented. Across all Ss, each condition followed each other condition the same number of times.

Within each experimental day there were 24 warmup trials of the T + L condition, followed by 6 experimental blocks of 48 trials each. Three blocks of the T + L condition alternated with 3 blocks of control conditions, either T, L, T; or L, T, and L. At the end of the experiment, each S had provided 3 blocks of trials for each of the 4 T + L conditions and 3 blocks of trials for each of the 4 control conditions.

At the beginning of the first experimental day (Day 2), Ss were told that in addition to the $9.00, bonuses for those who performed especially well would be given according to the following procedure: Each of the 16 Ss would be given a score consisting of the sum of the rank orders of his speed on the letter task multiplied by 5, the rank order of his error rate multiplied by 3, and the rank order of his speed on the tone task multiplied by 2. In addition, 10 points would be added for each letter condition for which the letter RT when responses to tones also had to be made was within 50 msec. of the letter RT when only responses to the letters had to be made. Five points would be subtracted for every block of 48 trials with more than 10 errors. The top 4 people on this scale would receive a bonus of $2.00, the next 4 $1.25, the next 4 $.75, and the last 4 no bonus. It was emphasized that these bonuses were meant to reward Ss for being consistently fast and accurate, especially on the letter task.

RESULTS

Treatment of the results of Experiment II closely paralleled that of Experiment I. RTs on the tone task, RTs on the letter task, and number of errors were each considered as a function of the following variables: 1T vs. 2T conditions (called T for number of tones), 1L vs. 2L conditions (called L for number of letters), whether the letter task called for a yes or a no response (called K for kind of trial), and the time at which a tone occurred relative to the stimulus events of the letter task (called P for probe position).

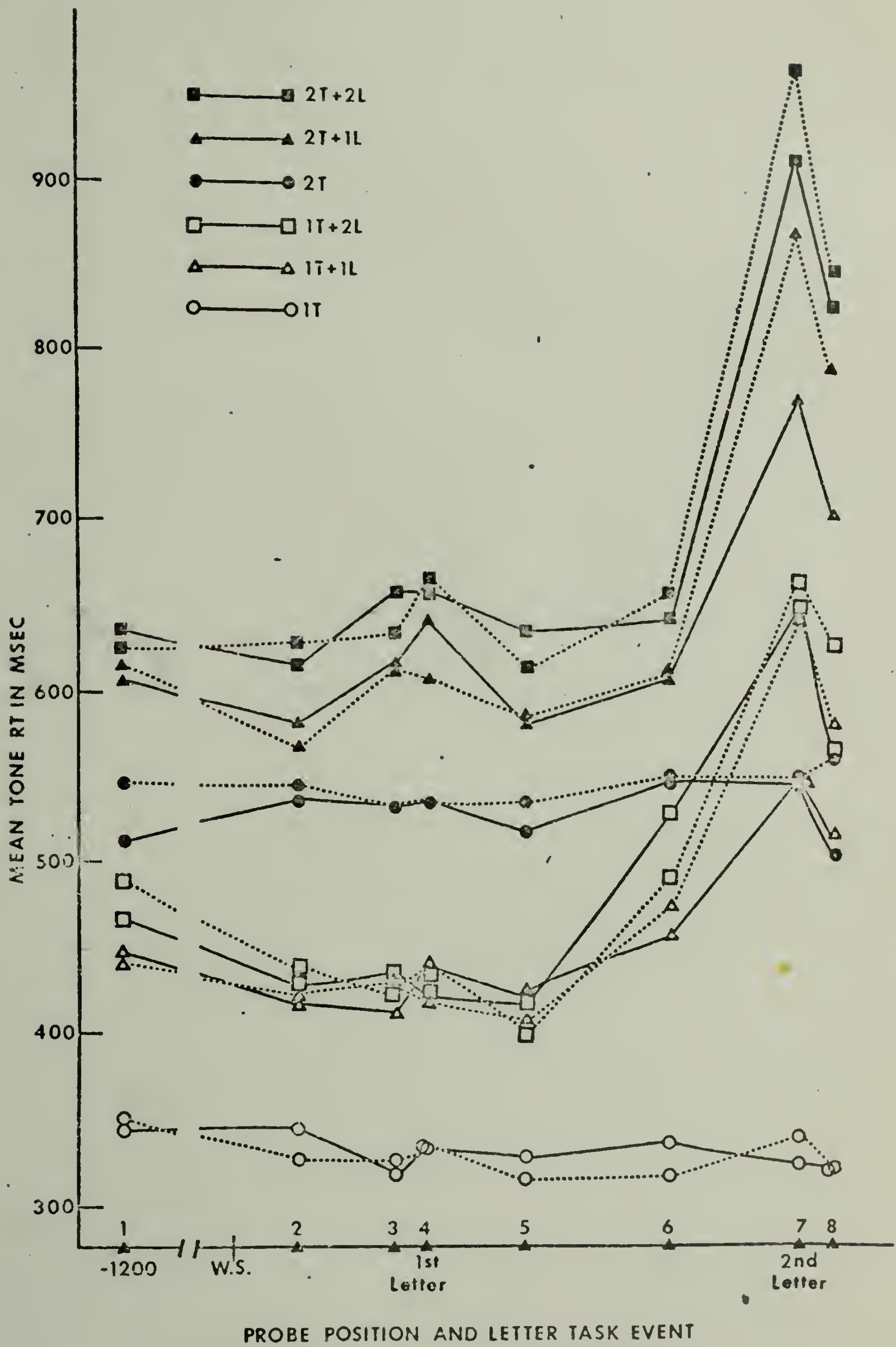
In experiment I, when responses to tones were not required, RTs on the letter task were not influenced by the number of tones occurring in the irrelevant tone task (see Figures 3 and 4). Therefore, in Experiment II the T and L control conditions were not separated according to the level of the irrelevant L or T task. When Ss were responding only to tones, stimuli for either the 1L task or the 2L task may have been occurring simultaneously, and when Ss were responding only to letters, either 1 or 2 tones may have been sounded. When tone control conditions were included in the analyses of tone RTs, they appeared as an additional level of the L variable (T + no letter task, T + 1L, T + 2L). Similarly, in the analyses of letter RTs, letter control conditions appeared as an additional level of the T variable (no tone task + L, 1T + L, 2T + L). Both letter RTs and tone RTs could be viewed as 3x2x2x8 factorial designs. To each cell of the design, each of the 16 Ss contributed 1 score, which was always the mean of 6 RTs. In the initial analyses, the K variable was further subdivided into the kind of yes or no response required. This resulted in 3 kinds of yes trials and 2 kinds of no trials for the 1L conditions, and in 2 kinds of yes trials and 1 kind of no trial for the 2L conditions.

Mean probe RTs, mean letter RTs, and total number of errors, collapsed across Ss, are contained in Appendices B-1, B-2, B-3, B-4, and B-5.

Probe RTs. The initial analyses found that probe RTs on yes trials did not differ significantly depending on the kind of yes trial (in the 1L conditions, $F(2,30)=1.75$, $p > .10$; in the 2L conditions, $F < 1$.) Similarly, probe RTs on *no* trials did not differ significantly depending on the kind of *no* trial (in the 1L conditions, F(1,15=1.97, p > .10; in the 2L conditions there was only 1 kind of *no* trial.) None of the interactions of kind of *yes* or *no* trial with the other variables (T and P) reached significance. The above effects were also not significant when only RTs to probes in positions 5 through 8 were included in the analyses. Therefore, in the figures and in the remaining analyses of probe RTs, all *yes* trials were combined and all *no* trials were combined within each condition.

Mean probe RTs for the 6 conditions in which responses to tones were made are shown in Figure 6. A 4-factor repeated measures analysis of variance which included the control conditions and all 8 probe positions revealed 10 significant effects. All 4 main effects (L, T, K, and P) were significant, reflecting the following findings: Tone RTs were fastest in the T conditions, next fastest in the T + 1L conditions, and slowest in the T + 2L conditions (F(2,30)= 87.07, p < .001). Tone RTs were faster in the 1T conditions than in the 2T conditions (F(1,15)=242.29, p < .001). *Yes* trials gave faster tone RTs on the average than *no* trials (F(1,15)=18.64, p < .001). Probe position also influenced tone RTs (F(7,105)=57.44, p < .001). Of the 11 possible interactions, 6 were significant. The effects of number of letters, number of tones, and kind of trial each interacted with probe position (LxP, F(14,210)=31.67, p < .001; TxP,

Figure 6. Reaction times on the tone task in Experiment II. Solid lines represent *yes* trials and dotted lines represent *no* trials. See the text for exact probe times.


2T+2L
2T+1L
2T
1T+2L
1T+1L
1T
900
800
700
600
500
400
300
MEAN TONE RT IN MSEC
1
2
3
4
5
6
7
8
-1200
W.S.
1st Letter
2nd Letter
PROBE POSITION AND LETTER TASK EVENT

$F(7,105)=7.27$, $p < .001$; KxP, $F(7,105)=9.28$, $p < .001$). Thus, as can be seen in Figure 6, tone RTs tended to rise near the second letter more in the 2L conditions than in the 1L conditions, more in the 2T conditions than in the 1T conditions, and more on _no_ trials than on _yes_ trials.

A significant LxK interaction ($F(2,30)=3.59$, $p < .05$) suggested that on the average the difference between tone RTs on _yes_ and _no_ trials was greater in the 1L conditions than in the 2L conditions or the control conditions. This effect tended to vary with probe position, as is indicated by the LxKxP interaction ($F(14,210)=2.75$, $p < .005$). Inspection of Figure 6 suggests that the LxK interaction occurred primarily in probe positions near the second letter.

The LxT interaction was not significant ($F(2,30)=1.32$, $p > .10$), since the overall differences among the T, T + 1L, and T + 2L conditions were about the same for the 1T and the 2T conditions. However, there was a significant LxTxP interaction ($F(14,210)=3.23$, $p < .001$), which primarily reflected the finding that the difference between the 2 Task (T + L) conditions and the control (T) condition tended to be smaller in the early probe positions and larger in the later probe positions for the 2T conditions than for the 1T conditions. The interpretation of the significance of the LxTxP interaction as due to differences between control and 2 Task conditions rather than differences betwwen the 2 Task conditions themselves was supported by an analysis of variance using tone RTs in the 2 Task conditions alone. Here the LxTxP interaction was not significant ($F(7,105)=1.78$, $p > .10$). It should be noted, however, that all other effects which were significant in the analysis which included the control conditions were also highly significant in the analysis of the 2 Task conditions alone. Neither of these analyses showed significant effects of LxT, TxK, LxTxK, TxKxP, or LxTxKxP.

In summary, the above results show that in the 2 Task conditions tone RTs tended to increase with number of tones (T), number of letters in the first letter stimulus (L), and, particularly in the 1L condition, on <u>no</u> trials more than on <u>yes</u> trials (K and 1xK). In addition, there was a main effect of probe position (P) which interacted with each of the other significant effects.

To further investigate the effects of probe position, analyses of variance were done on tone RTs in the 2 Task (T + L) conditions for 4 adjacent sets of probe positions: positions 1 and 2; positions 2, 3, and 4; positions 4 and 5; and positions 5, 6, 6, and 8. In each of these analyses, the main effect of T was significant at the .001 level. In positions 1 and 2, significant effects of L ($F(1,15)= 12.63$, $p < .005$) and P ($F(1,15)=14.53$, $p < .005$) reflected the longer tone RTs in the T + 2L conditions than in the T + 1L conditions and the drop of 28 msec. in tone RTs from position 1 to position 2. The suggestion of an interaction LxTxP did not reach significance ($F(1,15)=3.80$, $p < .10$).

Probe RTs in positions 2, 3, and 4 were longer on the average for T + 2L conditions than T + 1L conditions ($F(1,15)=6.13$, $p < .05$). The main effect of probe position was not significant ($F(2,30)=2.02$, $p > .10$). However, there was a TxP interaction ($F(2,30)=3.84$, $p < .05$), which reflected a rise of 46 msec. in tone RTs between positions 2 and 4 in the 2T + L conditions as compared with a rise of only 7 msec. in the 1T + L conditions. Thus, in Experiment II, the presentation of the first letter stimulus resulted in inflated tone RTs only in the harder tone task. Number of letters in the first letter stimulus did not affect the rise in tone RTs between positions 2 and 4 (LxP, $F < 1$).

The main effect of L did not reach significance for tone RTs in positions 4 and 5 ($F(1,15)=3.71$, $p < .10$). However, a significant LxT interaction ($F(1,15)=4.69$, $p < .05$) reflected the tendency for the difference between 1L and 2L tone RTs to be greater in the 2T + L conditions than in the 1T + L conditions. Tone RTs dropped approximately 28 msec. between positions 4 and 5 ($F(1,15)=6.20$, $p = .025$). Two interactions suggested by the results shown in Figure 6 failed to reach significance: TxP ($F(1,15)=3.41$, $p < .10$) and LxKxP ($F(1,15)=3.70$, $p < .10$).

By far the largest increases in tone RTs occurred near the presentation of the second letter. Considering all 4 T + L conditions together, the mean increase from position 5 to position 7 was 240 msec. Eight of the 10 effects found significant in the overall analysis were also found significant in the analysis of 2 Task tone RTs in the last 4 probe positions (positions 5 through 8): L, $F(1,15)= 32.83$, $p < .001$; T, $F(1,15)=162.11$, $p < .001$; K, $F(1,15)= 13.81$, $p < .005$; P, $F(3,45)=90.83$, $p < .001$; LxP, $F(3,45)= 8.34$, $p < .001$; TxP, $F(3,45)=9.73$, $p < .001$; KxP, $F(3,45)= 12.34$, $p < .001$; and LxK, $F(1,15)=10.91$, $p < .005$. Not significant here were LxTxP, $F(3,45)=1.63$, $p > .10$; and LxKxP, $F(3,45)=1.48$, $p > .10$. The interpretation of these results is the same as that previously stated for the overall analysis. In short, tone RTs were longer in 2L conditions, in 2T conditions, and on no trials. Also, tone RTs were longer near the second letter, and this effect interacted with each of the other main effects. The LxK interaction reflected the greater difference between yes and no trials in the 1L conditions than in the 2L conditions. In two further analyses of tone RTs in positions 5 through 8, it was found that the kind of trial was significant in the T + 1L conditions ($F(1,15)=10.97$, $p < .005$), but not in the 2T + 2L conditions ($F(1,15)=2.15$, $p > .10$).

Letter RTs. In the initial analyses of the letter RTs, the different kinds of _yes_ and _no_ trials were kept separate (see Appendix B-2 for these values.) For Probe trials, each of the 16 _Ss_ contributed 6 _yes_ and 6 _no_ letter RTs to each cell of the 3x2x8 design obtained by crossing the T, L, and P variables. The number of scores for particular kinds of _yes_ and _no_ trials (the K variable) depended on the number of kinds of trials into which those 6 RTs were divided. Thus, in the 1L conditions (if the first letter were a B), each _S_'s score was the mean of 3 RTs in each of the BB, XY, and XX kinds of trials, 1 or 2 RTs in the XB kind of trial, and 2 or 1 RTs in the BX kind of trial. In the 2L conditions (if the first letters were BC), each _S_'s score was the mean of 3 RTs in each of the B and C kinds of trials, and 6 RTs in the X kind of trial. For the No Probe trials in both the 1L and the 2L conditions, the proportions of RTs contributing to each kind of _yes_ and _no_ trial remained the same as stated above for Probe trials, but there were 4 times as many RTs contributing to each mean.

The best place to assess the effects of different kinds of _yes_ and _no_ trials on letter RTs is on the No Probe trials, where specific interference from tone RTs was absent. In the 1L (control) condition, mean RTs for the 3 kinds of _yes_ and 2 kinds of _no_ trials were as follows: BB--341, XB--382, BX--382, and XY--433, XX--405. Including the 1L, 1T + 1L, and 2T + 1L No Probe conditions in a 2-factor repeated measures analysis of variance revealed significant effects of kind of trial ($F(4,60)=26.62$, $p < .001$) and condition ($F(2,30)=5.68$, $p < .01$). The interaction was not significant ($F < 1$). In the 2 Task conditions, 1L letter RTs tended to be increased by a constant, 6 msec. in the 1T + 1L condition and 23 msec. in the 2T + 1L condition. Yes responses tended to be faster than no responses. Further analyses within the kind of response revealed significant differences among kinds of yes trials ($F(2,30)=19.23$, $p < .001$) and kinds of no trials ($F(1,15)=35.17$, $p < .001$).

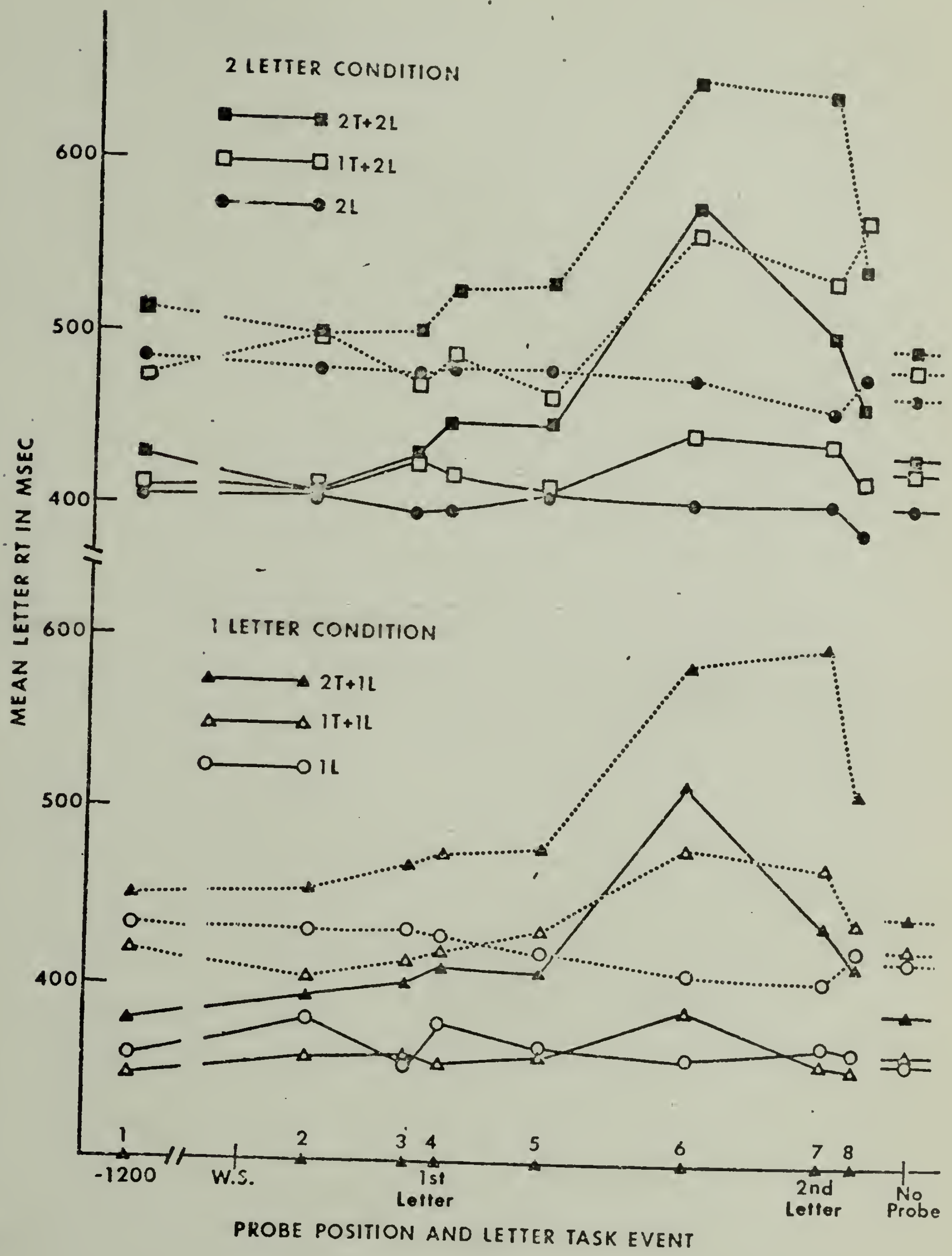
In the 2L condition on No Probe trials, mean RTs for the 2 kinds of yes trials and the no trials were as follows: B--400, C--419, X--474. As was done above in the analysis of the 1L letter RTs, the 1 Task and 2 Task No Probe RTs were included in a 2-factor repeated measures analysis of variance. Only the effect of kind of trial reached significance ($F(2,30)=11.94$, $p < .001$). Increases in the 1T + 2L condition averaged 20 msec. and in the 2T + 2L condition 26 msec., but the effect of condition ($F(2,30)=1.19$, $p > .10$) and its interaction with K ($F < 1$) failed to reach significance. As in the 1L condition, yes responses were faster than no responses; but in the 2L condition the 2 kinds of yes trials did not significantly differ ($F < 1$).

To summarize, letter RTs on No Probe trials were longer for no responses than for yes responses. In addition, in the 1L conditions the kind of yes or no trial made a difference and RTs tended to be longer in the 2 Task conditions. There were no interactions.

As in Experiment I, letter RTs on Probe trials in Experiment II showed a great deal of interference when responses to tones were also required. To assess this interference, 2 Task letter RTs on Probe trials were briefly considered as a function of the kind of yes and kind of no trial. The results were similar to the results reported above for No Probe trials, in that the main effect of K was significant within both yes and no trials in the 1L conditions but not in the 2L conditions. However, none of the interactions of K with probe position or number of tones approached significance. Therefore, in the figures and analyses to follow, all yes trials were combined and all no trials were combined within each condition. Since 1L and 2L conditions then both had 2 levels of the K variable, interference in letter RTs from the tone task could be compared across all conditions.

Mean RTs on the letter task are displayed in Figure 7. The lower panel contains yes and no letter RTs in the 3 1L conditions, and the upper panel contains yes and no letter RTs in the 3 2L conditions. A 4-factor repeated measures analysis of variance, including L, 1T + L, and 2T + L conditions, yielded 3 significant effects. The L main effect

Figure 7. Reaction times on the letter task in the 1 letter and 2 letter conditions of Experiment II.


2 LETTER CONDITION
2T+2L
1T+2L
2L
1 LETTER CONDITION
2T+1L
1T+1L
1L
MEAN LETTER RT IN MSEC
600
500
400
600
500
400
1
2
3
4
5
6
7
8
-1200
W.S.
1st Letter
2nd Letter
No Probe
PROBE POSITION AND LETTER TASK EVENT

($F(1,15)=38.22$, $p < .001$) pointed out that RTs in the 2L conditions were on the average about 60 msec. longer than RTs in the 1L conditions. As can be seen by comparing the 2 panels in Figure 7, the patterns of results were almost identical in the 1L and the 2L conditions. Accordingly, none of the interactions which included L as a factor were significant. Letter RTs varied with probe position, ($F(7,105)=19.00$, $p < .001$), tending to be longest in positions 6 and 7. On the average, RTs were longest in the 2T + L conditions, next longest in the 1T + L conditions, and fastest in the control (L) conditions ($F(2,30)=24.17$, $p < .001$). _No_ responses took longer than _yes_ responses ($F(1,15)=75.11$, $p < .001$). The 4 possible interactions of these P, T, and K effects were also significant. The TxP interaction ($F(14,210)=13.10$, $p < .001$) reflected the greater increases in RTs across probe positions in the 2T + L conditions than in the 1T + L conditions. The KxP interaction ($F(7,105)=3.53$, $p < .005$) reflected the increases in the difference between _yes_ and _no_ trials at certain probe positions. The last 2 interactions, TxK ($F(2,30)=3.89$, $p < .05$) and TxKxP ($F(14,210)=3.63$, $p < .001$), primarily reflected the fact that the difference between _yes_ and _no_ responses tended to be larger in the 2 Task conditions (2T + L and 1T + L) than in the control conditions (L), especially when tones occurred after the presentation of the first letter.

In an analysis including only the 2 Task letter RTs, T and K did not interact (TxK, $F < 1$; TxKxP, $F(7,105)=2.01$, $p < .10$). All of the other effects mentioned above for the analysis including the control conditions were significant at the .001 level in the analysis of the 2 Task letter RTs.

In short, letter RTs on 2 Task Probe trials were heavily influenced by the difficulty of the tone task, and the time at which it occurred (T, P, and TxP). The two variables of the letter task, L and K, each had main effects; but the only interaction involving them was KxP, which reflected the greater interference with no trials than with yes trials after the first letter.

Errors. As in Experiment I, no formal analyses of the errors were done. The error data were examined primarily as a rough check on the results of the analyses of tone RTs and letter RTs. In particular, large increases in error rates where no changes in RTs occurred would suggest that processing capacity limitations existed which were not reflected in RTs. Also, if error rates decreased where RTs increased, or vice versa, the results might be interpreted as a change in the speed-accuracy trade-off rather than interference due to processing capacity limitations.

Combining across all probe positions and kinds of trials, the error rates in Experiment II tended to increase with overall tone RTs and letter RTs. Errors were fewest in the control conditions: 4.9% for 1L, 8.0% for 2L, 1.0% for 1T, and 1.9% for 2T. Error rates were higher in the 2 Task conditions: 7.0% for 1T + 1L, 9.3% for 1T + 2L, 10.5% for 2T + 1L, and 13.1% for 2T + 2L. Yes trials tended to have error rates about 30% higher than no trials, with no obvious differences across conditions. The mean percent errors for the 2 Task conditions on No Probe trials were 7.3% on yes trials and 5.6% on no trials. On Probe trials, these values were 11.7% and 8.9%.

The percent errors in each condition, collapsed across kind of trial, appear in Table 3, and the information from the 2 Task conditions is also plotted in Figure 8. (For more detailed error data, see Appendix B-5).

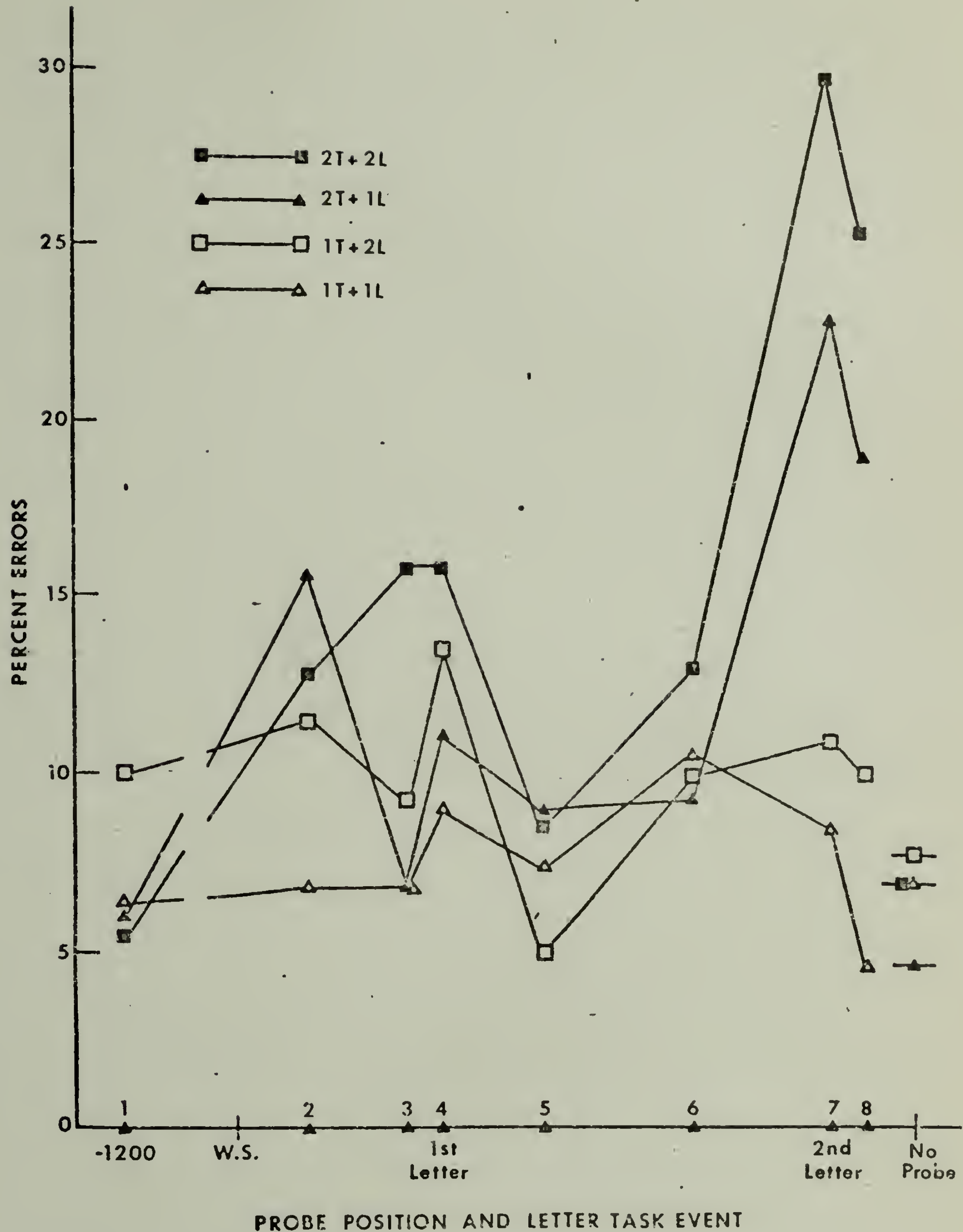
Tone RTs (see Figure 6) and the error rates shown in Figure 8 tended to vary with probe position in similar ways, rather than show trade-offs of speed and accuracy. One striking feature of the error data is that in every 2 Task condition, error rates were higher at position 4 than at position 5. In 3 conditions the error rates increased from position 3 to position 4, the exception being the 2T + 2L condition, in which error rates were high at both positions 3 and 4. The highest error rates at the first letter occurred in the T + 2L conditions, suggesting the possibility that encoding 2 letters required more processing capacity than encoding 1 letter, even though tone RTs reflected the same

Table 3

Percent Errors in Each condition of Experiment II as a Function of Probe Position

Condition	Probe Position 1	2	3	4	5	6	7	8	No Probe
Letters Only - 1L	2.5	7.3	5.4	4.5	3.5	4.0	5.4	6.8	4.7
2L	8.6	5.4	7.7	5.9	6.8	9.9	9.4	6.8	8.7
Tones Only - 1T	2.5	1.0	1.0	1.5	0.0	0.0	1.0	.5	---
2T	4.5	2.5	1.5	1.0	3.5	3.5	2.0	3.0	---
2 Task 1T + 1L	6.3	6.8	6.8	9.0	7.3	10.7	8.6	4.5	6.8
1T + 2L	9.9	11.5	9.4	13.5	5.0	9.9	11.1	9.9	7.8
2T + 1L	5.9	15.7	6.8	11.1	9.0	9.4	23.2	19.3	4.7
2T + 2L	5.4	12.7	15.8	15.8	8.6	13.1	30.2	20.7	6.8

Figure 8. Percent errors on the 2 Task conditions of Experiment II. The curves have been collapsed across kind of trial (yes or no) and kind of error (on the letter task or on the tone task.)


2T+2L
2T+1L
1T+2L
1T+1L
PERCENT ERRORS
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
-1200
W.S.
1st
Letter
2nd
Letter
No
Probe
PROBE POSITION AND LETTER TASK EVENT

amounts of interference. The tendency for errors to increase at position 4 in both of the 1T + L conditions is the only evidence that interference from the first letter occurred in those conditions; tone RTs in the 1T + L conditions did not rise at the first letter. Inflated error rates at position 2 are not inconsistent with this interpretation, since response processes for tones presented in position 2 could easily have been occurring at the time the first letter came on.

The increased error rates at positions 7 and 8 in the 2T + L conditions primarily reflected the increase in errors on the tone task in those conditions (see Appendix B-5). Error rates on the letter task remained fairly constant across positions 6 and 7. Thus, increases in tone RTs and letter RTs cannot be explained as reflecting a stricter criterion of accuracy.

DISCUSSION

The changes in procedure between Experiment I and Experiment II did not produce large changes in the pattern of results. Many of the interpretations of effects found in Experiment I also held for the results of Experiment II. Therefore, this discussion will frequently refer to arguments made in the previous discussion of Experiment I. Preparation, encoding, retention, responding, and dual task performance will each be considered in turn. Emphasis will be given to differences between the 2 experiments and to interpretations consistent with both sets of results.

One purpose of the payoffs and the additional letter task conditions employed in Experiment II was to attempt to concentrate interference effects in the tone task, thus making clearer its status as a subsidiary measuring task. These attempts were not entirely successful. Although more significant effects were present in tone RTs and fewer in letter RTs, each task was obviously influenced by the presence of the other. Thus, interference in both tasks must be considered as evidence for the use of processing capacity. As in Experiment I, for each 2 Task condition, interference in the tone task was defined as an incerase in tone RT above the position 5 value. In the letter task, interference was defined as an increase in letter RT above the No Probe value.

Preparation. There was no evidence in Experiment II for the use of capacity by the process of preparation initiated by the presentation of the warning signal. Tone RTs decreased between positions 1 and 2 in all 2 Task conditions except 2T + 2L, in which tone RTs remained fairly flat.

One possible difficulty with this interpretation arises from the fact that increased error rates accompanied the decreased tone RTs. If a trade-off of speed and accuracy were operating to produce faster tone RTs with preparation, then the increase in errors would be expected to be an increase in errors on the tone task. Instead, the increase was entirely in errors on the letter task (see Appendix B-5). As was mentioned in the presentation of the error results above, it is likely that response processes for tones presented in position 2 overlapped with the presentation of the first letter, interfering with accurate encoding, and resulting in more errors on the letter task.

In Experiment I it was noted that the difference in tone RTs between position 1 and the baseline tone RT (position 5 on the 2 Task curves) was smaller in the 2T conditions than in the 1T conditions. A similar tendency was observed in Experiment II. The decrease in 2T + L conditions was 15 msec. and the decrease in 1T + L conditions was 50 msec. As in Experiment I, the simplest explanation is that during the intertrial interval in the 2T + L conditions, Ss remained more prepared to make tone responses than was the case in the 1T + L conditions.

One difference between Experiments I and II occurred in letter RTs when tones were presented during preparation (positions 2 and 3). In the 2T + L condition of Experiment I, requiring responses to tones presented in these positions resulted in longer letter RTs. This result was not found in the 1T + L conditions of Experiment I, nor was it found in Experiment II. Although letter RTs in the 2T + L conditions were longer than in the 1T + L conditions, both were very close to their corresponding No Probe values. Letter RTs in the 1T + L conditions averaged 8 msec. less than the No Probe RTs, and letter RTs in the 2T + L conditions averaged 3 msec. more than the No Probe RTs. Thus, in Experiment II Ss were successful in keeping tones presented early in the trial from interfering with the speed of the later letter responses.

In short, most of the evidence from both Experiment I and Experiment II supports the notion that the process of preparation requires no processing capacity. Responses to tones presented during preparation were facilitated rather than showing interference. Processing on the tone task did not disrupt letter responses in ways which would indicate interference with preparation. The two instances in which interference was detected when tones occurred early in the trial (Experiment I letter RTs in the 2T + L condition, Experiment II error rates) were most easily interpreted as the result of interference from encoding or retention, not preparation.

Encoding. The results of Experiment II are consistent with those of Experiment I in finding a small amount of interference from encoding, suggesting again that the process of encoding required some processing capacity. In tone RTs, if interference is taken as the difference between RTs in positions 4 and 5, Experiment I detected interference of

38 msec. in the 1T + L condition and 84 msec. in the 2T + L condition. These values were only 17 msec. and 39 msec. in Experiment II, and the difference (the TxP interaction of tone RTs in positions 4 and 5) was not significant. Inspecting the results in Figure 6, however, suggests that 17 msec. overestimated the interference in the 1T + L conditions, where no significant rises in tone RTs occurred prior to position 6. In the 2T + L conditions, tone RTs rose 46 msec. between positions 2 and 4. Thus, although tone RTs in the 1T + L conditions in Experiment II showed little if any interference from the process of encoding, the results were consistent with those of Experiment I in that the interference which occurred in the 2T + L conditions was larger than that which occurred in the 1T + L conditions. The use of processing capacity by encoding was also implicated in both experiments by the sharp peaks in error rates which occurred in all 2 Task conditions when tones were presented simultaneously with the first letter.

In the Discussion of Experiment I, an hypothesis was developed to handle the findings concerning interference with responses to tones presented near the first letter. Basically, it was suggested that encoding interfered with only a portion of the early processing on the tone tasks; that those vulnerable processes took longer in the 2T task than the 1T task; and that there was essentially a "free time," or a time after encoding on the tone task when very little capacity was being used for the tone task, and when encoding on the letter task could proceed without causing interference. Three findings led to this hypothesis. The first was that, compared to Posner and Boies' (1971) estimate of the duration of encoding, interference here was smaller than would be expected if the total process of encoding required capacity which was also needed for the tone task. Second, tone RTs were lower in position 3 than position 4, which would not be expected if the process of encoding simply took a fixed period of time or proportion of capacity away from the tone tasks. Third, in both positions 3 and 4 interference was greater in the 2T + L condition than in the 1T + L condition, suggesting that encoding on the letter task interfered for a longer period of time with the 2T task than with the 1T task. It is of interest to note again here that the main features of these three findings were replicated in Experiment II.

The inclusion of two letter tasks in Experiment II was an attempt to investigate the above hypothesis. It was suggested that one explanation for the 2T task requiring processing capacity for a longer period of time might be that the 2T task and the letter task involved processes of detection and processes of discrimination, while the 1T task involved only detection. If interference between 2 tasks were specific to the detection or discrimination required, then increasing the difficulty of the letter discrimination would be expected to increase the interference with tone RTs in the 2T + L condition but not in the 1T + L condition. On the other hand, tone RTs in both the 1T + L condition and the 2T + L condition would be expected to show increased interference if interference were not specific to the particular processes involved.

To increase the difficulty of discrimination in the letter tasks and leave the difficulty of detection unchanged, Experiment II employed the 1L and 2L tasks. This manipulation was unsuccessful in producing differences related to interference from encoding. Tone RTs tended to be longer overall in the T + 2L conditions than in the T + 1L conditions, but this effect did not vary with probe position. The increase in tone RTs at the first letter stimulus did not depend on whether 1 or 2 letters needed to be encoded. Letter RTs showed the same patterns of interference in the 1L and 2L conditions. The only hint that the 2L task may have needed more capacity than the 1L task came from the error data, in which more errors were made on the 2L task than the 1L task in positions 3 and 4.

Many explanations for this failure might be suggested, but none can be favored without adding new data or post hoc assumptions. For example, it may be that the 1L and 2L conditions were equal in discriminability and use of processing capacity. The procedure of measuring a mask onset interval for each S in each letter condition may have essentially equated them for discriminability. It could also be that the process of discrimination on the 2L task did take longer than on the 1L task, but that when discrimination was shared, the 2T task always completed its discrimination during a portion of the letter discrimination devoted to the first letter; discrimination of the second letter would then have occurred during the "free time" in the tone response. Perhaps a greater increase in the discrimination requirements of the tone task would be needed to detect an increase in the discrimination requirements of the letter task.

Despite the failure of Experiment II to add new information concerning the processing capacity requirements of encoding, its results were consistent with those of Experiment I: encoding produced interference. The best hypothesis is still that the 2T task could detect more of that interference because initial processing prior to a "free time" in the 2T task took longer than initial processing in the 1T task.

Retention. Evidence for the use of capacity by processes occurring during the retention interval in these experiments was meager. In both Experiment I and Experiment II, responses to tones in position 5 were as fast or faster than responses to tones in any other position. Error rates also tended to be low. Since position 5 tone responses began and ended within the retention interval, it would seem that retention processes did not interfere with the tone task. However, some interference occurred in the other direction. Letter RTs in all T + L conditions of Experiment I and in the 2T + L conditions of Experiment II were longer on trials on which tones occurred in position 5 (and position 4) than they were on No Probe trials. The magnitude of this interference was small: in Experiment I about 29 msec. in the 1T + L condition and 60 msec. in the 2T + L condition, and in Experiment II -9 msec. in the 1T + L conditions and 26 msec. in the 2T + L conditions. These data are consistent with the view that a small amount of processing capacity needed for retention interval processes was used instead to optimize performance on the tone task.

As was the case with encoding, the retention interval did not show any differential effects of the two letter tasks employed in Experiment II. Again, although tone RTs in position 5 tended to be higher in the 2T + 2L condition than in the 2T + 1L condition, the same difference was found at all probe positions. Letter RTs in the T + 2L conditions might have been expected to show more interference from the performance of a tone response during retention than letter RTs in the T + 1L conditions, but this was not the case.

Error rates also did not show a difference between the two letter conditions. Thus, no further information was obtained pertaining to the questions asked in the Discussion of Experiment I about the nature of retention interval processes. In fact, interference with retention varied with the difficulty of the tone task, not the letter task. The most parsimonious explanation is that the tone tasks interfered slightly with some process which was the same for both letter tasks, such as the preparation to make one of two letter responses.

Responding. The largest requirement for processing capacity in both Experiment I and Experiment II came from processes connected with responding. Whenever two speeded responses were being required at the same time (that is, in positions 6 through 8, when responses on the tone task occurred after the second letter stimulus had been presented), strong interference effects occurred in at least one of the three performance measures. As was done in Experiment I, the discussion of this interference will be divided among two sections. The characteristics related to the processing capacity required by different kinds of responses will be discussed in this section, and the characteristics particularly related to dual task performance will be discussed in the next section.

The results of Experiment I were inconclusive with respect to the question of whether different responses, which required more time, also required more processing capacity than _same_ responses. It was possible to explain the difference in interference as the result of a tendency to make impulsive _same_ responses on the letter task when tones came on near the second letter. Experiment II sought additional information on the processing capacity requirements of different kinds of responses. The two letter tasks, besides differing in the number of letters in the first letter stimulus, also differed in the number of letters in the second letter stimulus and in the kinds of responses required. There were two physical responses (_yes_ the single letter matched one of the pair or _no_ it didn't). There were also different kinds of _yes_ and _no_ responses, which were predicted to have different RTs and thus possibly require different amounts of processing capacity. As was described in the Discussion of Experiment I, differences in interference within one category of physical response would not likely arise from a biased tendency to make impulsive responses.

The predicted differences in kinds of letter responses did occur in letter RTs in Experiment II. As the Results section pointed out, on No Probe trials in the 1L (control) condition, letter RTs were about 57 msec. faster on _yes_ trials than on _no_ trials, and about 35 msec. faster when the second letter stimulus consisted of 2 identical letters than when it consisted of 2 different letters. In the 2L condition, letter RTs were also faster on yes trials than on no trials (64 msec.). However, the 19 msec. difference between kinds of yes trials was not significant.

In neither the 1L conditions nor the 2L conditions did kind of trial within the yes or no categories have more than an additive effect. Letter RTs fluctuated as a function of probe position and difficulty of the tone task, but the relationships among kinds of yes trials or kinds of no trials remained approximately the same throughout. Probe RTs showed no effects related to kind of yes trial or kind of no trial. These results indicate that reliable differences in the length of time required for a response did not necessarily imply differences in the amount of processing capacity required. In the 1L condition, responding either yes or no to 2 identical letters was faster than to 2 different letters, but there was no evidence that it took less processing capacity.

To determine whether no responses required more capacity than yes responses, the data were collapsed across particular kinds of yes and no trials. Consider trials on which responses were made both to tones and to letters. A great deal of interference was detected in letter RTs and tone RTs. Interference in tone RTs near the second letter stimulus was greater on no trials than on yes trials only in the T + 1L conditions, not in the T + 2L conditions. As Figure 6 shows, yes responses in the T + 1L conditions resulted in markedly less interference in positions 7 and 8 than did no responses, and than did both yes and no responses in the T + 2L conditions. Difficulty of the tone task did not influence this effect--there were no interactions of T with L or K. These results suggest that the processing capacity requirements of letter responses were related to the mental processes used in arriving at a response choice rather than to whether the choice was yes or no. In the 1L conditions, Ss searched a set of 2 visual letters to check for a match with a single letter in memory, while in the 2L conditions, Ss searched a set of 2 letters in memory to check for a match with a single visual letter. No direct evidence was found concerning the reason that yes responses in the first process required less capacity, and many explanations are possible. For example, it might be speculated that the process of searching required capacity. Perhaps in searching a visual array, the search process was self-terminated upon finding a match, thus requiring less search and less capacity. On the other hand, searching an array in memory may have been an exhaustive search (see Sternberg, 1969).

Although yes and no responses produced a different pattern of interference with tone RTs depending on the letter condition, they reflected the same pattern of interference in letter RTs regardless of the letter condition. The only effect with which K interacted was probe position.

No responses showed more interference than *yes* responses, especially from tones presented at the second letter stimulus (position 7). Since interference effects were the same in both letter conditions, it would seem likely that they reflected a disruption of processes which were the same in both letter conditions, such as selection of the response or readiness to execute it. Other evidence consistent with this suggestion was reported earlier in the section on retention, where longer letter RTs were interpreted in the same way.

The section below on dual task performance will consider the reasons that differential interference from the kind of trial and the difficulty of the letter task may have been found in one performance measure and not another. For this section, the two important findings are, first, *yes* responses reflected and produced less interference than *no* responses. Second, besides relating to the physical responses made, processing capacity needs were related to the processes involved in arriving at those responses--only in the T + 1L conditions did *yes* responses produce significantly less interference than *no* responses. There were no apparent trade-offs with error rates. These results suggest that the ambiguous results in the tone RTs in Experiment I are best interpreted as reflecting a small difference, if any, in interference from *same* and *different* responses. The finding that this pattern of interference was not the same in tone RTs for both the 1T + L and 2T + L conditions would then be attributed to the tendency for impulsive same responses to occur in the 2T + L condition. Carrying the speculation a step further, it is possible that if these impulsive same responses could have been removed from the 2T + L condition of Experiment I, the mean tone RTs on same trials would have been increased. In that case, a TxP interaction in probe positions near the second letter would be found, analogous to the finding in Experiment II.

The capacity requirements of the 2T task were greater than those of the 1T task. Letter RTs always showed more interference from the harder tone task. In tone RTs, more interference from processes in the letter task was reflected in the 2T + L conditions than in the 1T + L conditions. This was the case at the first letter in Experiment I and at both letter stimuli in Experiment II. Error rates also tended to be higher in conditions involving the 2T task. It was not the purpose of the experiments presented here to determine the specific processes in the 2T task which required more capacity. However, previous sections have mentioned results which suggest that processes near the beginning of the reaction to a tone and processes near the actual response were both more susceptible to interference in the 2T task than in the 1T task. It thus seems likely that encoding and responding both contributed to the greater processing demands of the 2T task.

Dual task performance. In Experiment I, several objections were raised against the simple single-channel and variable allocation models for the allocation of capacity among two tasks. The same objections hold in Experiment II. Rather than reiterate these objections, this section will consider the constraints on alternative conceptualizations which arise from the results of Experiment I and Experiment II.

Whenever a block of trials involved responses on both the tone task and the letter task, performance on both tasks was impaired. The specific characteristics of this impairment have been discussed in the preceding sections. Several general characteristics of the patterns of interference have emerged. For example, an expectation that processing on one task might be required interfered with efficient performance of the other task. The fastest tone RTs in the T + L conditions were longer than tone RTs in the T control conditions. Similarly, letter RTs tended to be longer in the T + L conditions, even on No Probe trials when no tone actually occurred. Other characteristics of these baseline differences were the following: They were much smaller in the primary letter task than in the subsidiary tone task. In the letter task, they were smaller in Experiment II, in which payoffs and instructions more clearly emphasized the letter task. They were not affected by the difficulty of the task being measured, but did tend to be larger the more difficult the "expected" task was. As the Discussion of Experiment I pointed out, these baseline differences do not seem to reflect interactions in one common pool of capacity or a single channel. Instead, they suggest that a kind of executive process kept track of priorities and expectations for each block of trials. It is not clear exactly what operations would have been performed by this executive, but possibilities are that it controlled motor preparation or the "availability" of the various rules and responses which might have been required.

A second striking characteristic of the patterns of interference in T + L conditions is that RTs were not only influenced by what was expected to occur; they were also influenced by what was specifically occurring. This, of course, was relfected in the effects of probe position, which were used to infer the specific demands for capacity from various processes in the letter task. In Experiment I, probe position was occasionally used to refer to the "difficulty" of the mental processes occurring at that position in the letter task. It now appears more accurate to consider probe position simply as an indicator of the time at which tones came on, and thus as a clue to which processes in the tone task were likely to have overlapped with which processes in the letter task.

What can be said in general about the variables which influenced the amount of specific interference detected in letter RTs and in tone RTs? In other words, what variables interacted with probe position in the T + L conditions? The difficulty of a task, in addition to influencing the baseline differences found in a concurrent task, also influenced the specific interference found in the concurrent task and determined the vulnerability of the first task to interference from the concurrent task. Thus, the more difficult tone task (2T) tended to raise baseline letter RTs more, to cause more specific interference with letter RTs, and to reflect more interference from the letter task, than did the 1T task. Similarly, the difficulty of the letter task (kind of trial) influenced the amount of interference found in tone RTs near the second letter, and also influenced the amount of interference the letter RTs reflected from the tone task. The 2 letter tasks (1L and 2L) did not reflect different amounts of interference, but they did influence the amounts of interference found in tone RTs near the second letter.

On the basis of these general findings, it might be speculated that difficulty of the letter task and difficulty of the tone task both influenced how much of a central pool of processing capacity was being demanded at one time. Arguing against this speculation, however, is the observation that none of the interactions involving difficulty of the tone task (T) and difficulty of the letter task (K and L) were significant. This was the case for tone RTs as well as letter RTs, and was the case in Experiment II, even though all the interactions of K and L with each other, and with probe position, were significant. (The one exception, the TxK interaction in positions near the second letter in the tone RTs of Experiment I, could easily be discounted on the basis of error rates as the result of impulsive <u>same</u> responses.) Several discussions of variable allocation models presented in previous sections have pointed out that 2 processes drawing from the same pool of processing capacity at the same time would be expected to have interactive effects on RTs. The lack of interaction here was strong, so the notion of the variable allocation of a common pool of capacity is again without support.

A model of dual task performance must also be consistent with the evidence that speeded responses did not require uniform amounts of processing capacity throughout. The evidence from tone RTs near the first letter was presented in the Encoding section above. Other evidence comes from probe positions near the second letter, when tone RTs and letter RTs overlapped. In Experiment I it was found that when tones came on simultaneously with the second letter, the sum of the amounts of interference detected in the letter RTs and in the tone RTs was 155 to 241 msec. less than would be expected if each reaction required all of S's capacity throughout and he had simply rapidly switched back and forth between tasks. When tones occurred 300 msec. prior to the second letter, the sum of the interference was about the same as the length of time for which the 2 tasks overlapped. Thus, it appeared that response processes on the tone task were occurring at the same time as initial processing on the letter task, and no advantage of doing both at once was observed.

In Experiment II a very similar pattern of results was obtained. Tone RTs and letter RTs overlapped in positions 6, 7, and 8. In the 1T + L conditions, RTs to tones in position 6 occurred on the average within about 80 msec. after the onset of the second letter stimulus. This small amount of overlap, rather than resulting in an advantage, actually increased the total amount of interference above what would have occurred if the 2 tasks had been done serially. The increase was greater on no trials than on yes trials (105 msec. vs. 55 msec.). Apparently, with the 1T task in position 6, either tone responses so near the second letter stimulus disrupted initial processing of the second letter, or tone responses were sometimes delayed to allow some processing of the letter to occur before the tone response was completed. Total interference in the 2T + L conditions, in which the overlap between tone RTs in position 6 and letter RTs was between 161 and 212 msec., was almost exactly what would be expected from serial processing on the 2 tasks. Thus, for tones 450 msec. (Experiment II, position 6) and 300 msec. (Experiment I, position 7) before the second letter, there was no advantage from overlapping RTs on the letter task and the tone task.

When tones were presented simultaneously with, and 100 msec. after, the second letter stimulus, there were savings in RTs of between 133 and 233 msec. These savings tended to be about 30 msec. greater on yes trials than on no trials only in the T + 1L conditions, reflecting the previously mentioned difference in interference between yes and no trials. On the average, savings were only 25 msec. less when tones occurred 100 msec. after the second letter than when they occurred with the second letter. Taken together, these findings offer further support for the notion that RTs on both the tone task and the letter task used the most processing capacity immediately after the onset of the stimulus and near the execution of the response. In the middle there appears to have been a "free time" during which it was possible for capacity to be allocated to processes on another task without reducing efficiency on the first task.

No information is available in the experiments reported here to specify what processes in a task were occurring during its "free time." One possibility mentioned in the Discussion of Experiment I is nonattentive memory access (Posner and Boies, 1971; Keele, 1972, 1973). Interference detected immediately after the onset of the stimulus might then represent the extraction of enough raw information for accurate accessing of memory. If this explanation were the case, it might be possible in further experimentation to selectively increase the length of time needed for memory access and show comparable increases in the advantage of performing 2 tasks concurrently.

Another observation which places constraints on the types of models which can account for dual task performance is that some processes seem to have been more insistent in their needs for processing capacity than others. For example, when tones were presented such that their responses occurred during the retention interval, letter RTs tended to be lengthened, even though no specific overlap between the 2 responses occurred. It seems that the processes during the retention interval which allowed for efficient performance of the letter task were disrupted by the tone task. This interference was one-sided, however, since tone RTs did not seem to be disrupted by the retention processes. It was concluded, therefore, that retention did require processing capacity, but that for some reason, rather than causing interference in tone RTs, it was especially vulnerable to being disrupted.

CONCLUSION

Two broad questions guided the research reported here --what were the relative amounts of processing capacity required by the mental processes involved in a simple letter-matching task, and how might a central attention mechanism have operated to allocate limited capacity among the tasks at hand? Preceding sections have amply described the specific patterns of interference which led to the conclusions that preparation required no capacity, that encoding and retention required small amounts of capacity, and that responding required the largest amounts of capacity. However, it may be that the most important contribution of this research is not these specific capacity requirements, but rather the finding of severe limitations with single-channel switching and variable allocation conceptualizations of the operation of central attention mechanisms.

It is not possible to specify a fully-adequate model of the allocation of processing capacity based on the results of the two experiments reported here. The preceding section has outlined some of the constraints within which such a model must operate. At this time it appears that a single-channel mechanism can handle most of the patterns of interference found in the results of these experiments if the following features are incorporated: 1) an executive process to control task priorities and the availability of various rules and responses, 2) a specification of what portions of each speeded response required use of the channel, and during what portions processes were occurring which did not require use of the channel; and 3) a notion to account for the greater vulnerability of some processes than others to interference from a concurrent task.

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Appendix A-1

Mean and Mean Median Reaction Times on the Tone Task in Experiment I

		Probe Position							
Mean									
Condition	Kind of Trial	1	2	3	4	5	6	7	8
1T	S	333	315	315	323	321	315	326	306
	D	331	313	326	326	313	313	335	322
1T + L	S	460	441	407	432	389	415	534	588
	D	469	430	400	425	393	393	516	602
2T	S	562	566	612	587	625	567	571	590
	D	569	615	574	608	579	592	567	553
2T + L	S	644	689	699	719	620	639	760	771
	D	678	639	682	708	640	644	782	904
Mean Median									
1T + L	S	429	429	395	412	390	412	519	564
	D	456	411	394	410	389	386	509	586
2T + L	S	624	674	691	708	625	613	737	759
	D	660	627	656	686	625	640	728	892

Appendix A-2

Mean and Mean Median Reaction Times

on the Letter Task in Experiment I

Condition	Kind of Trial	Probe Position 1	2	3	4	5	6	7	8	No Probe
Mean										
L(1T)	S	356	357	330	346	348	353	366	349	365
	D	405	408	413	401	409	466	422	437	415
1T + L	S	348	371	377	370	397	407	461	381	359
	D	464	419	421	440	443	490	565	516	424
L(2T)	S	381	350	360	349	420	378	344	328	357
	D	431	411	448	409	440	453	416	399	418
2T + L	S	347	431	431	416	447	517	649	442	382
	D	446	452	482	491	500	609	797	715	445
Mean Median										
1T + L	S	339	355	348	362	365	395	454	367	339
	D	428	407	412	431	430	456	536	499	407
2T + L	S	346	402	410	405	440	495	656	423	356
	D	420	431	461	472	481	590	784	702	429

Appendix A-3

Total Number of Errors in Experiment I

		Probe Position								
Errors on Letter Task										
Condi- tion	Kind of Trial	1	2	3	4	5	6	7	8	No Probe
L(1T)	S	1	2	1	5	0	4	3	3	22
	D	3	2	4	2	4	4	1	2	8
1T + L	S	4	6	10	11	7	6	4	10	52
	D	4	2	2	4	2	6	3	6	33
L(2T)	S	3	5	2	3	1	4	3	3	30
	D	3	0	1	0	2	2	5	1	16
2T + L	S	6	12	8	10	2	4	10	8	46
	D	0	3	5	5	12	9	15	12	28
Errors on Tone Task										
1T	S	1	0	1	0	0	0	0	0	
	D	0	1	0	0	1	0	1	1	
1T + L	S	0	1	0	0	2	2	3	1	
	D	1	1	0	1	0	0	0	1	
2T	S	2	1	3	2	1	2	3	1	
	D	2	0	2	0	2	3	3	1	
2T + L	S	6	1	4	8	1	5	10	17	
	D	7	2	5	5	1	2	9	11	

Appendix B-1

Reaction Times on the Tone Task in Experiment II

Condition	Kind of Trial	Probe Position 1	2	3	4	5	6	7	8
1T	Y	344	344	319	334	328	337	324	321
	N	350	327	326	333	315	317	340	322
1T + 1L	BB	437	415	427	422	414	459	522	520
	XB	493	402	412	458	414	449	579	529
	BX	424	432	389	436	433	488	569	489
	XY	430	440	444	403	412	489	660	604
	XX	454	405	415	433	404	463	631	560
1T + 2L	B	473	436	451	418	423	535	638	567
	C	461	424	419	424	411	523	662	569
	X	489	438	429	437	402	492	668	629
2T	Y	513	539	534	538	520	550	548	508
	N	547	545	534	537	536	552	549	575
2T + 1L	BB	610	580	624	615	585	637	752	687
	XB	604	577	663	651	601	574	802	718
	BX	618	592	561	702	554	585	755	713
	XY	626	585	596	606	592	615	875	795
	XX	607	551	632	611	582	609	875	785
2T + 2L	B	644	623	669	645	619	639	895	810
	C	626	611	651	676	654	651	947	847
	X	625	628	635	668	616	662	977	850

Appendix B-2

Mean Reaction Times on the Letter Task in Experiment II

Condition	Kind of Trial	1	2	3	4	5	6	7	8	No Probe
1L	BB	331	358	337	338	342	337	345	352	341
	XB	402	421	388	454	402	384	407	376	382
	BX	377	407	366	405	387	382	368	390	382
	XY	450	441	444	451	422	419	415	441	433
	XX	419	424	421	408	420	402	399	409	405
1T + 1L	BB	325	338	338	325	330	372	344	333	337
	XB	377	366	405	385	392	408	380	410	391
	BX	368	403	356	383	387	390	362	353	394
	XY	439	408	431	437	444	503	470	463	443
	XX	401	403	399	404	422	463	476	417	408
2T + 1L	BB	343	376	387	370	372	509	406	375	363
	XB	429	424	413	428	458	516	478	450	419
	BX	395	410	404	482	425	533	473	447	413
	XY	452	480	476	501	511	614	627	521	453
	XX	451	432	465	453	452	567	578	512	437
2L	B	399	404	416	406	411	406	411	410	400
	C	413	410	382	395	412	411	406	380	419
	X	484	482	480	483	483	480	465	484	474
1T + 2L	B	411	396	442	429	414	448	456	432	430
	C	412	427	413	415	413	451	434	415	432
	X	476	500	476	490	470	566	540	577	491
2T + 2L	B	417	391	425	424	446	574	495	454	436
	C	443	426	441	477	458	594	524	482	435
	X	513	501	504	527	534	657	652	545	501

Appendix B-3

Mean Reaction Times on the Tone Task in Experiment II. Entries have been collapsed across kind of *yes* or *no* trial.

Condition	Kind of Trial	Probe Position 1	2	3	4	5	6	7	8
1T	Y	344	344	319	334	328	337	324	321
	N	350	327	326	333	315	317	340	322
1T + 1L	Y	448	416	413	437	419	459	551	514
	N	442	423	429	418	408	476	645	582
1T + 2L	Y	467	430	435	421	417	529	650	568
	N	489	438	429	437	402	492	668	629
2T	Y	513	539	534	538	520	550	548	508
	N	547	545	534	537	536	552	549	575
2T + 1L	Y	607	582	617	641	584	611	776	704
	N	616	568	614	609	587	612	875	790
2T + 2L	Y	635	617	660	660	636	645	921	829
	N	625	628	635	668	616	662	977	850

Appendix B-4

Mean Reaction Times on the Letter Task in Experiment II. Entries have been collapsed across kind of _yes_ or _no_ trial.

Condition	Kind of Trial	Probe Position 1	2	3	4	5	6	7	8	No Probe
1L	Y	359	382	358	379	367	361	369	367	362
	N	434	432	433	429	421	410	407	425	419
1T + 1L	Y	348	360	360	357	361	389	359	357	365
	N	420	406	415	420	433	483	473	440	425
2T + 1L	Y	379	395	403	413	409	518	439	415	389
	N	451	456	471	477	481	590	602	516	445
2L	Y	406	407	399	401	411	408	409	395	409
	N	484	482	480	483	483	480	465	484	474
1T + 2L	Y	411	412	428	422	413	449	445	423	431
	N	476	500	476	490	470	566	540	577	491
2T + 2L	Y	430	408	433	451	452	584	510	468	436
	N	513	501	504	527	534	657	652	545	501

Appendix B-5

Total Number of Errors in Experiment II

Errors on Letter Task

Condition	1	2	3	4	5	6	7	8	No Probe
1L	5	15	11	9	7	8	11	14	38
1T + 1L	13	11	13	16	14	20	15	8	49
2T + 1L	10	34	12	17	12	15	19	16	38
2L	18	11	16	12	14	21	20	14	73
1T + 2L	17	24	19	28	8	19	19	16	65
2T + 2L	8	27	26	30	12	23	26	18	56

Errors on Tone Task

1T	5	2	2	3	0	0	2	1
1T + 1L	0	3	1	3	1	3	3	1
1T + 2L	4	1	1	2	2	2	5	5
2T	9	5	3	2	7	7	4	6
2T + 1L	2	4	2	7	7	5	39	30
2T + 2L	3	1	10	6	6	6	57	32