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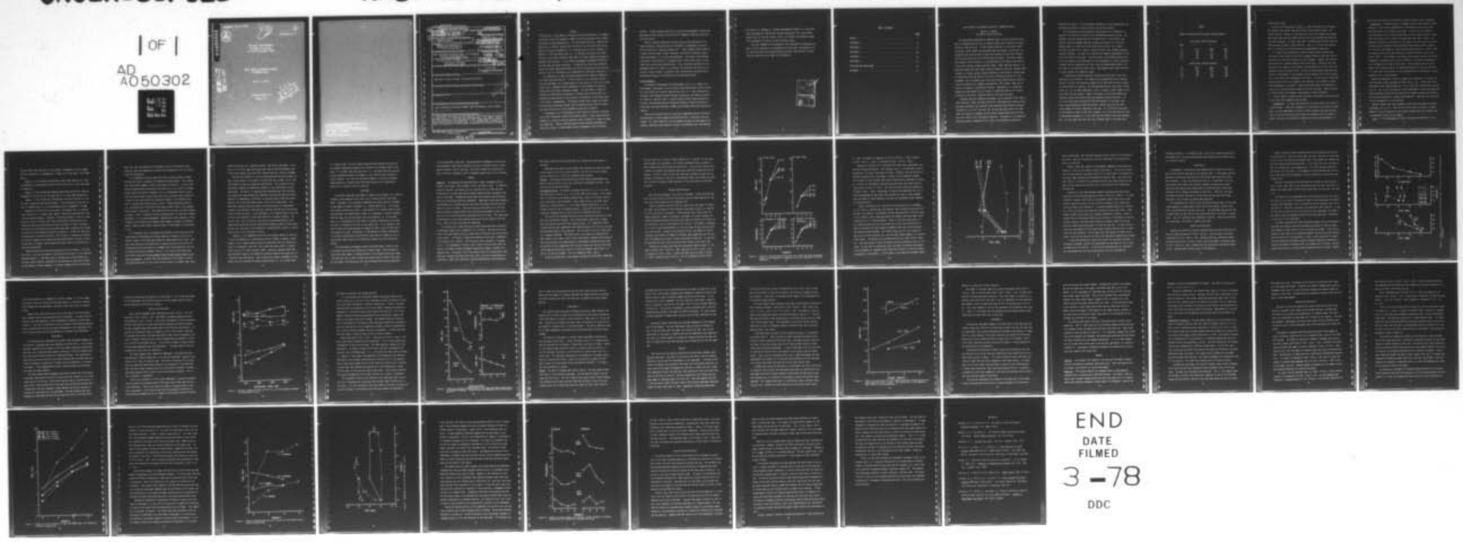

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INPUT, OUTPUT, AND RESPONSE BLOCKING IN IMMEDIATE RECALL

Warren H. Teichner

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Operational definitions of input and output processing times and rates are presented based on a simple model of immediate recall. The temporal measures are then evaluated for the independence of their responsiveness to variables which affect the total processing time. It is concluded that the measures are useful and applicable to a wide variety of theoretical and practical problems.

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Preface

There are a large number of occasions in which the operator of a complex system must receive and remember a number of briefly displayed visual signals and respond to them appropriately. It is well-known that man's capacity for doing this is limited. Whether that limitation is on the input side of his ability to process information, i.e., to receive and to store in memory, or whether it is on the output side, i.e., to retrieve from memory and select actions, is not known although a great deal of current research and theory is devoted to the question. In this report ~~we propose~~ a method is proposed for measuring the input and the output separately. In addition, by using two assumptions beyond the simple input-output model, the rate of processing of each and the source of loss of information can be determined for specified conditions. → (Cont on p1473A

The separation of input and output processing has important immediate and longer range implications. For the latter it is an important step toword the development of an understanding of what goes on in the input and the output, and a consequent better formulation of the information processing system upon which human performance depends. For the former, a method is provided for determining the adequacy of display-control design which can evaluate the contributions to the operator's performance of the display and of the control independently. The method provides both a means for evaluating available and proposed designs and for determining the limits of input and output processing to which equipment design must accomodate.

The methods as so far developed are restricted to situations involving very brief simultaneous signals and discrete actions. Every signal must be a command for a specific discrete reaction, which in effect is a report of what the signal was. Further research should include extending the method to successive stimuli, to more complex output requirements, and to tracking controls. Further research should also include the development of additional measurements which reflect the activities of component processes within the input and output.

Finally, separate attention should be given to the importance of response blocking in the processing of information, a phenomenon associated with an inability to "get the response out." Since response blocking may be a highly critical event in many situations, the ability to measure, understand, and predict it is of critical importance. One aspect of the methods indicated is a definition of a response block in terms which allow it to be identified and described quantitatively. Since available approaches to the phenomenon define it simply as an unusually long reaction time with only arbitrary criteria of what is unusually long, the definition provided by the methodology proposed is considered to be an important advance.

Acknowledgements

We gratefully acknowledge the encouragement of Dr. A. R. Fregly, Program Manager, Directorate of Life Sciences, who monitored this effort for the Air Force Office of Scientific Research and of Mr. R. L. Hann, Research Psychologist, USAF Aerospace Medical Research Laboratory, the technical monitor. Dr. Donald A. Topmiller, Chief, Systems Research Branch, Human Engineering Division, USAF Aerospace Medical Research Laboratory, Wright Patterson Air Force Base, and other personnel of AMRL also provided continuing intellectual support.

The actual research could not have been accomplished without the direct contributions of certain people associated directly or indirectly with the project: Ms. Nancy Hutchcroft ran the subjects through the experimental procedures, analyzed a great quantity of data in preliminary form, and prepared

the figures; Dr. Benjamin A. Fairbank programmed the PDP8/e, Dr. Evelyn Williams programmed the IBM 360 data analyses through APL; Ms. Laura Shaffer entered data into the APL system, and Ms. Julie Goodrich prepared the manuscript through its revisions to this technical report.

I am also indebted to my colleagues in the Department of Psychology for their critical reactions to a presentation of this paper, and especially to Dr. Evelyn Williams who provided endlessly patient, constructive criticism from the inception of the ideas to the manuscript.

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Input, Output, and Response Blocking in Immediate Recall

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The experimental paradigm for immediate recall is one in which the subject is presented with an array of stimulus items, and is required to report as many of them as he can. If the stimulus duration is sufficiently small, the subject cannot report the items when they are present. Accordingly, to respond he must have had them in some kind of memory so that after termination of the display, he could retrieve them and report. One form of memory which appears to be involved is a representation of the sensory data held in a very brief sensory storage (Sperling, 1960). Other than that memory, it is generally agreed that some longer-duration storage is involved. Whether that storage is a single, general purpose immediate or short-term or primary memory transferred from the sensory store (e.g., Atkinson and Shiffrin, 1971; Broadbent, 1971) or whether one or more such stores specialized for specific kinds of encoding (e.g., Baddely and Patterson, 1971; Posner, 1969) are involved is a matter of considerable interest. Regardless, it is generally agreed that some second form of storage is established before such further processes as retrieval, response selection, and execution begin.

Although some very ingenious procedures, such as masking of the sensory store (Sperling, 1963), have been devised to investigate the processes which have been postulated, and although these techniques have produced important information, it is still the case that the data obtained, errors and sometimes the latency of response, do not reflect anything more selective than the total effect of all intervening processes. Inferences to or assumptions about any process independent of any other are untestable no matter how plausible they may be. It is desirable, therefore, to have operationally defined measures which do reflect portions of the total process.

For the measures to have generality they should be as independent as possible of any particular model of the information processing system. Consequently, we shall assume only that following onset of the display, the stimulus items are somehow acquired, encoded, and stored in a final non-sensory memory, a collection of activities which we shall call "input." Similarly, we shall call, "output," whatever follows that storage including response execution. Our goal is to separate the temporal requirements of the input from those of the output. The only aspects of the model really critical to the measures to be developed are the requirement of a final non-sensory memory and the assumption that input stops and output begins when all of the items to be stored have been stored. What happens within input and within output exceeds the fundamental model.

To explain the proposed measures, consider the task used in the first experiment to be presented. The subject was presented with briefly-exposed displays of digits and required to report all of them that he could as quickly and accurately as possible. He reported them one-at-a-time using a single finger on a set of coded pushbuttons. Table 1 presents a small sample of raw data taken from one subject. Shown in the table are the times between the responses made by the subject under two different display conditions. In one, four digits were displayed for 200 milliseconds; in the other eight digits were presented for 400 milliseconds. Within each trial are shown times between the events indicated in the rows. S-1 is the time from onset of the display to onset of the first response; 1-2 is the time from the first to the second response; 2-3 is the time from the second to the third response, etc. For this table only the first four responses made in the eight-item

TABLE 1

Sample of Latencies (Milliseconds) From Experiment 1.

	Four Digits, 200 Milliseconds		
Event	1	2	3
S-1	1787	1498	1988
1-2	500	415	367
2-3	414	454	419
3-4	425	352	407
	Eight Digits, 400 Milliseconds		
S-1	1907	2599	2208
1-2	359	430	314
2-3	405	510	608
3-4	417	426	325

condition are shown.

The most striking aspect of Table 1 is that the time to first response was several times greater than the following inter-response times. The second aspect of interest is that the time to the first response was greater when eight items with the longer duration were to be reported than when only four were presented. It seems clear that S-1 differs qualitatively from the other measures as well as quantitatively. That is, it is not only greater, but it is sensitive to something about the experimental conditions.

It follows from the meaning of input and output above that the time from onset of the display to the first response represents the total time of the input plus the time to output the first response. However, the time following the first response contains none of the input. Similarly, the time from the first response to the second, from the second one to the third, etc. represent successive output times. The mean of those output times which follow the first response is the average time per response (t/r) or the reciprocal of the output rate independent of the input. If that value is subtracted from the time to the first response, the remainder is an estimate of input time independent of the output. Input time should reflect the combined effects of all processes which consume time within the input. Output time and t/r should reflect the temporal requirements of output processes.

If one wishes to analyze farther than what is provided by input time and t/r as such, two assumptions must be made:

Assumption 1. At least some portion of the input handles the stimuli in a serial manner. Given this assumption it is possible to calculate an input rate. For the experimental situation in which responses are made one-at-a-time, it does not seem necessary to make the assumption that the output is serial since even if everything in memory were removed simultaneously, it would have to be held in still another storage to permit serial responding.

Assumption 2. Everything that is in memory receives some degree of output processing. Part of this consideration is analagous to that on the input side when stimuli on a display are not seen. In that case the number of items displayed is not a correct description of the proximal stimulus. Sometimes this problem can be solved by knowing where the subject looked. No comparable technique is available for the output, but an estimate of what was in memory might be obtained from experiments which compare naming responses to the count of the number of items displayed under conditions in which counting requires much of the same processing as naming (Teichner, Reilly, and Sadler, 1961). In the absence of estimates of the memory content, the second assumption is necessary under certain conditions if the loss in responses is to be assigned to the input or the output. The assumption does not state where in the output or how an item might have been lost, but only that even if it were lost in the output, it was processed there to some degree, and consequently that t/r was affected.

Suppose an experiment in which N_s symbols are displayed, all of which are to be reported, and N_r responses are made, and $N_s = N_r$. In that case since there was no loss, given Assumption 1, t/s is the input time divided by either N_s or N_r. $N_s = N_r$ will be the case in many experiments in which the number of items displayed is small and the questions of interest concern only the accuracy and time required to process the information. Note that since there was no loss, Assumption 2 is not required.

Suppose, though, that fewer responses occured than the number of symbols displayed, i.e., $N_s > N_r$. Was the loss in the input, the output, or both? Whether or not this question can be resolved depends upon the following four circumstances in which it can happen:

Case 1. If the independent variable of interest has affected t/r, but not the input time, the loss is in the output. Assumption 2 is not needed for this conclusion. If Assumption 1 is made, t/s is the input time divided by N_s.

Case 2. If the variable has affected neither input time nor t/r, then on Assumption 2, the output was equal to the input and t/s is the input time divided by N_r.

Case 3. If the variable has affected input time, but not t/r, then on Assumption 2 the loss was in the input and t/s is input time divided by N_r.

Case 4. If the variable has affected both the input time and t/r, the loss was in both the input and the output. Since the amount of the loss in each is indeterminate, t/s is not meaningful even if Assumption 1 is made.

Regardless of which of the four cases of information loss is involved, input time and t/r, or output time, remain as meaningful descriptions of the input and output processes. However, if the input process is really at least partially serial in nature, then input time provides a measure which confounds the underlying processing rate with the number of stimuli processed. This means only that there are restrictions about what inferences can be made from the input time measure given serial processing. It does not imply that the measure has no descriptive value. The situation is analagous to knowing the distance traveled by a vehicle without knowing either its rate of travel or how long it traveled. Both distance and input time still provide useful descriptive quantities.

Measures other than those discussed may also be of interest. For example, let $N_s = N_r$, but the number of the N_r which are correct is less than the maximum possible. If the input rate is affected, but not the output rate, time per correct stimulus processing can be expressed as input time divided by the number of correct responses. A similar argument holds for the output.

Note, too, that such measures as the amount or rate of information transmitted as input and separately as output can be expressed for all but Case 4, given the assumptions.

It is important to keep in mind that input includes storage in memory and that the input is assumed to end before the output begins. This implies that losses within memory, itself, could happen in two ways: (1) they could possibly happen during the period of the input, e.g., as a result of a decay process before the input is complete, or as an interference effect of more than one item of input, and (2) they could result from the output process as a result of the time required for successive outputs or interference with what is stored by the output process, itself. Proper experimental design, e.g., by delaying the initiation of the output, should reveal a post-storage decay process if one exists. Note though that any activity involving response is output. Thus, if rehearsal involves subvocalization or some other response mechanism, it is an output phenomenon. Manipulation of the complexity of the response or the coding of the response might suggest a response interference effect. Both of these effects should be seen, if they happen, as alterations in t/r.

It is important also to recognize that portions of the input and of the output might be determined with further measures, although to do that will require a model of each that goes beyond the simple model we are using. However, that portion of the output due to response execution can actually be estimated directly from measures of movement time, word production time, etc. By subtracting time per movement from t/r, a t/r results which approaches pure output processing on the assumption that no other output process is going on in parallel. We shall make that assumption in this paper, but with the understanding that if one is not willing to make it, movement time, which should be constant for a practiced subject, need not be subtracted. In any case, it is critical when calculating input time to keep the movement time in the output measure since the first response made must include a movement.

What we have proposed is a set of operational definitions the model for which (input-output) is as simple as we have been able to make it, yet flexible enough to allow for theoretical exploitation. The existence of such definitions, however, no matter how rational, is not sufficient for their application. For that it is necessary that the definitions also be useful which means that they provide new information and that the input and output measures be independently responsive to variables which affect the overall measure, total time from display onset to the final response made. This means that sometimes they may depend in different ways on an experimental variable, and sometimes in the same way; sometimes one may vary with the variable, but not the other. In the experiments to be reported below it was the utility of the measures in that sense which was of primary interest. For the most part, but not entirely, variables were manipulated which it was hoped would provide the various relationships between N_s and N_r listed above. We were less interested in the theoretical interpretation of specific results than we were in this question of utility.

Sometimes in the immediate recall task the subject reports an inability to "get the response out," and he may be seen to stammer in making a verbal report, or for a manual report to have his hand hover over the response buttons for an unusually long time. Such a delay has been called a "response block" (e.g., Bills, 1931; Teichner, 1964). Generally response blocks have been defined in terms of an arbitrarily selected cutoff on the upper tail of a reaction time distribution. Such a definition, however, provides no information that the distribution cannot provide without it. As a unique event, it is weak at best. We shall report below that when subjects do hover over the response keyboard and appear to be blocking in an everyday sense of the term, t/r is greater than the input time, i.e., the time required to get all of the information possible into memory is less than the time to output a single response. This kind of relationship appears to satisfy the general understanding of a response block both qualitatively and in quantitative terms, and to provide a critical criterion.

Experiment 1

It has been shown that the number of symbols on the display is a critical variable in the immediate recall task (e.g., Teichner, Reilly, and Sadler, 1961). Experiment 1 was designed to determine how input time and t/r depend on the number of symbols displayed, i.e., display density (D). At the same time display duration was varied. Since duration is a variable that can only operate before the output begins, unless it is extended, it would be expected that the input, but not the output would be affected by it. On the other hand, it is conceivable that the number of response alternatives could interact with D in producing an effect on the output rate. If so, whether or not D will affect the output measure will depend at least in part on the size of the response set used. Accordingly, in the absence of further information, it could be predicted that D would affect input time, but whether or not it would affect output rate for any particular response set could not be predicted.

The experimental arrangement used was one which made it difficult for the subject to acquire and organize the stimulus items. This was done by having the items appear in random positions on the display and to be of such size that only two or three of them could occupy central vision at one time. By this means it was hoped that the input processes would be very sensitive to the experimental conditions. The experimental arrangement and the particular parameters chosen were selected on the basis of extensive prior investigation (Teichner, Christ, and Corso, 1977) which showed that practiced subjects could attain expected levels of immediate memory span in this situation.

Method

Apparatus. The apparatus has been described in detail elsewhere (Christ, Stevens, and Stevens, 1974; Teichner, Christ, and Corso, 1977). To summarize essential features, the subject sat at a console with his right hand positioned below six square gray plastic-capped response buttons arranged in two rows of three each. Through the button caps were projected identifying symbols from single-plane read-outs underneath. Immediately below these buttons, and centered, was a marked position from which the subject started with the onset of a block of trials. After pressing the last button on a trial the subject pressed a seventh button which terminated measurement on that trial and, with a 5.0 millisecond delay presented the next display. The subject was instructed not to press that seventh button until he was ready for the next trial. Only one finger was used for responding.

The display was a square dark glass screen behind which were located 16 single-plane readout units arranged in a 4 x 4 matrix. Each unit could provide 12 different symbols (one-at-a-time) each projected to the same position on the screen. The display, located with midpoint at eye level, subtended a visual angle of 16.7 degrees. Each projected letter subtended 1.8 degrees of arc. The programming of stimuli, and all data collection were under the control of a PDP8/e (Digital Equipment Corporation) computer located in an adjacent room. The subject sat at the console alone in an experimental room which was isolated from other activities, quiet, and with low background illumination. Under these conditions, based on manufacturers specifications, the symbols projected to the screen were 27.1 candela per square meter in luminance.

Recordings were taken of which buttons were pressed, the time from onset of the display to the first button response, from the first to the second, second to third, etc. to the last response button pressed.

Subjects. The subjects were three male and three female undergraduate students at the university, paid a fee of $2.00 per experimental session. Each session required about 50 minutes.

Experimental Design. The symbols used were the digits, 2, 3, 4, 5, 6, and 7. They were used to form Ds of 1, 2, 4, and 8 items on the screen. For Ds other than D-1 the digits were sampled randomly from a source of 12 digits consisting of two each of those indicated. Thus, except for D-1, any digit could appear on a single display 0, 1, or 2 times, thereby requiring 0, 1, or 2 presses of each of the six response buttons. Location of the digits on the screen was randomized on all trials over the 16 possible positions.

The four Ds were combined factorially with four display durations of 100, 200, 400, and 800 milliseconds. The 16 experimental conditions so formed were administered twice over four successive days. In a completely within-subjects design eight combinations were administered on the first test day and the remaining eight on the second day. This was done in 32-trial blocks each at a constant condition. The order of the trial blocks was randomized for each subject, and on Days 3 and 4, which constituted a complete replication of the first two days, new random orders of experimental combinations were used. An exception to the randomization of the trial blocks was that the first condition administered on Day 1 was D-1 at 200 milliseconds, and on Day 2, it was D-1 at 100 milliseconds. This was repeated on Days 3 and 4.

On the day before Day 1 each subject received four differently randomized

32-trial blocks at D-1 with a display duration of 1.0 second. At this time, and throughout all experiments, the subjects understood that the order of their reports would not be used to score errors. This practice day was used to teach the subjects the response code and to familiarize them with the procedures. Similarly, the first two test days were intended to reduce the importance of learning of the task to the measures taken, and thereby allow the last two days to provide clearer measures of input and output as practiced processes.

Results and Discussion

Only the data from Days 3 and 4 will be reported. It may be noted, however, that the trends of the two replications did not differ materially, and that some learning data will be presented later.

Figure 1 presents the total time, the input time, the number of responses made, and the number of those responses which were correct as a function of D with duration as a parameter. Taken together they indicate that the temporal measures, number of responses, and number of correct responses increased systematically with D and that the effects of duration were mainly at D-8, much less so at D-4, and absent at D-1 and D-2. The number of responses at D-1 and D-2 were maximum whereas at the two larger Ds they were generally less than maximum. Except for one inversion at D-8, the number of correct responses approximated the number of responses made suggesting that the subjects had emphasized accuracy in their orientation to the task. It may also be seen that the total time was qualitatively similar to the input time.

Analyses of variance confirmed the observations made on Figure 1: for total time D(F 3/15 = 189.74 $p < .001$), duration (F 3/15 = 6.52 $p < .01$), D x Duration (F 9.45 = 4.81 $p < .001$); for input time D (F 2/10 = 132.58 $p < .001$), duration (F3/15 = 20.51 $p < .01$) D x Duration (F 6/30 = 26.81

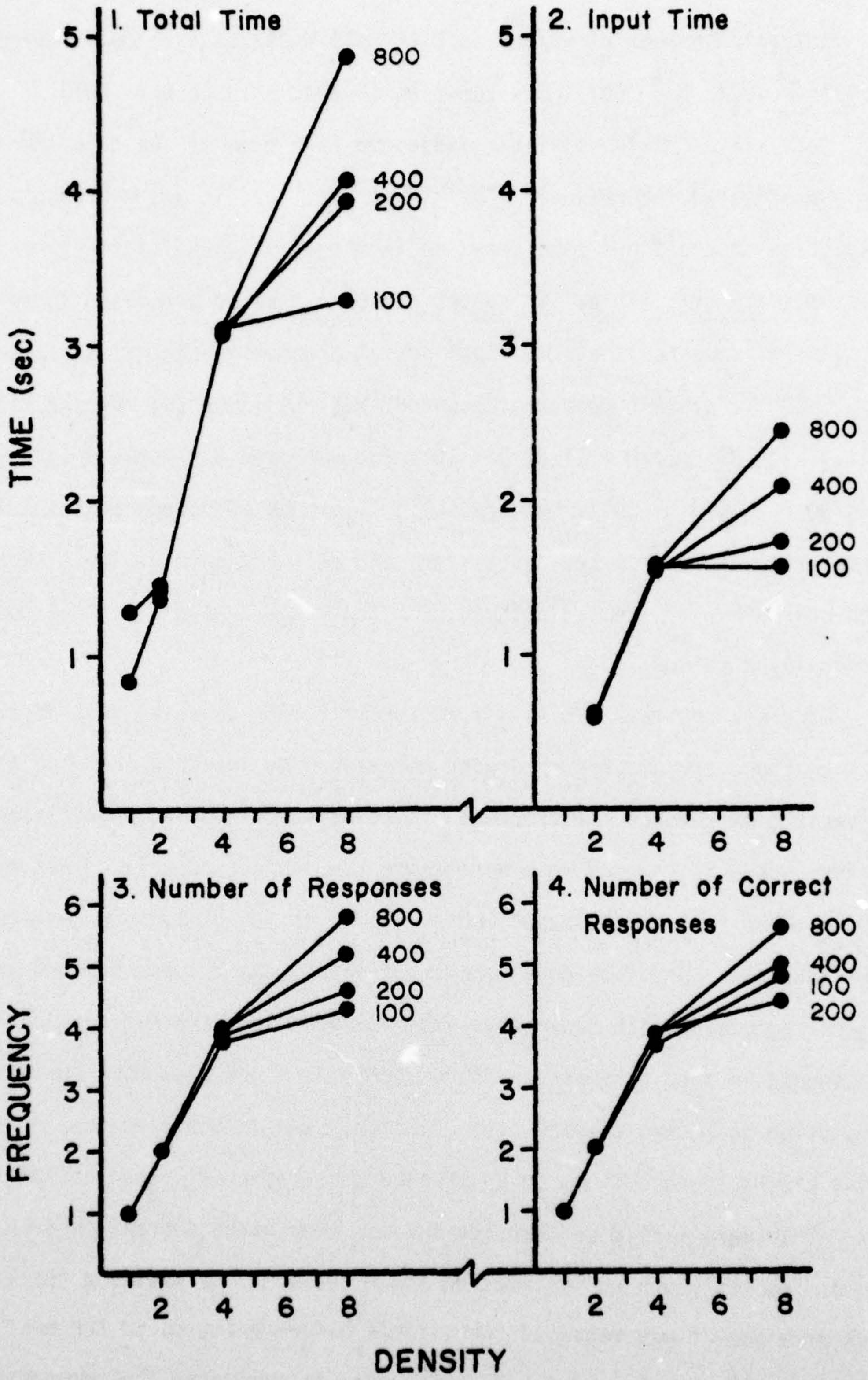

Figure 1. Effects of display density and duration on total and input processing times, on the frequency of responses, and on the frequency of correct responses.

$p < .001$); for number of responses D ($F\ 3/15 = 253.61\ p < .001$), duration ($F\ 3/15 = 18.22\ p < .001$), D x Duration ($F\ 9/45 = 15.50\ p < .001$).

Analysis of variance of t/r indicated that none of the experimental conditions affected the measure. The situation, then, is as described in Case 3. Inspection of the input time shown in Figure 1 indicates that the measure increased systematically as the number of stimuli to be processed increased. On this basis we shall assume input serial processing and calculate t/s using N_r. Analysis of that measure indicated that the input rate varied significantly with D ($F\ 2/10 = 11.33\ p < .01$) and with the D x Duration interaction ($F\ 6/30 = 3.44\ p < .001$). Accordingly, it may be concluded that the loss in items processed was on the input side, and that the rate of input depended upon the number of items displayed, and that that dependency itself depended on display duration.

Figure 2 presents t/s as a function of D with duration as a parameter. It also shows t/r plotted once with movement time included and once with the movement time removed. The movement time was obtained from a different group of four subjects, two of whom were among the subjects described above, after completion of all of the experiments. While it would have been better to have obtained those data on a concurrent basis, the values obtained are in general agreement with other keypress movement times that we have obtained and should be good estimates. The subjects were run over four successive days using no actual display, but using the same random sequences of selected trial blocks. The buttons to be pressed would have all been correct responses. They were marked so that the subject knew which buttons to press in advance. He was given no instruction about the order of pressing the buttons. Each arrangement was repeated three times before going on to the next button arrangement in the sequence. By this means it was hoped that movement speeds

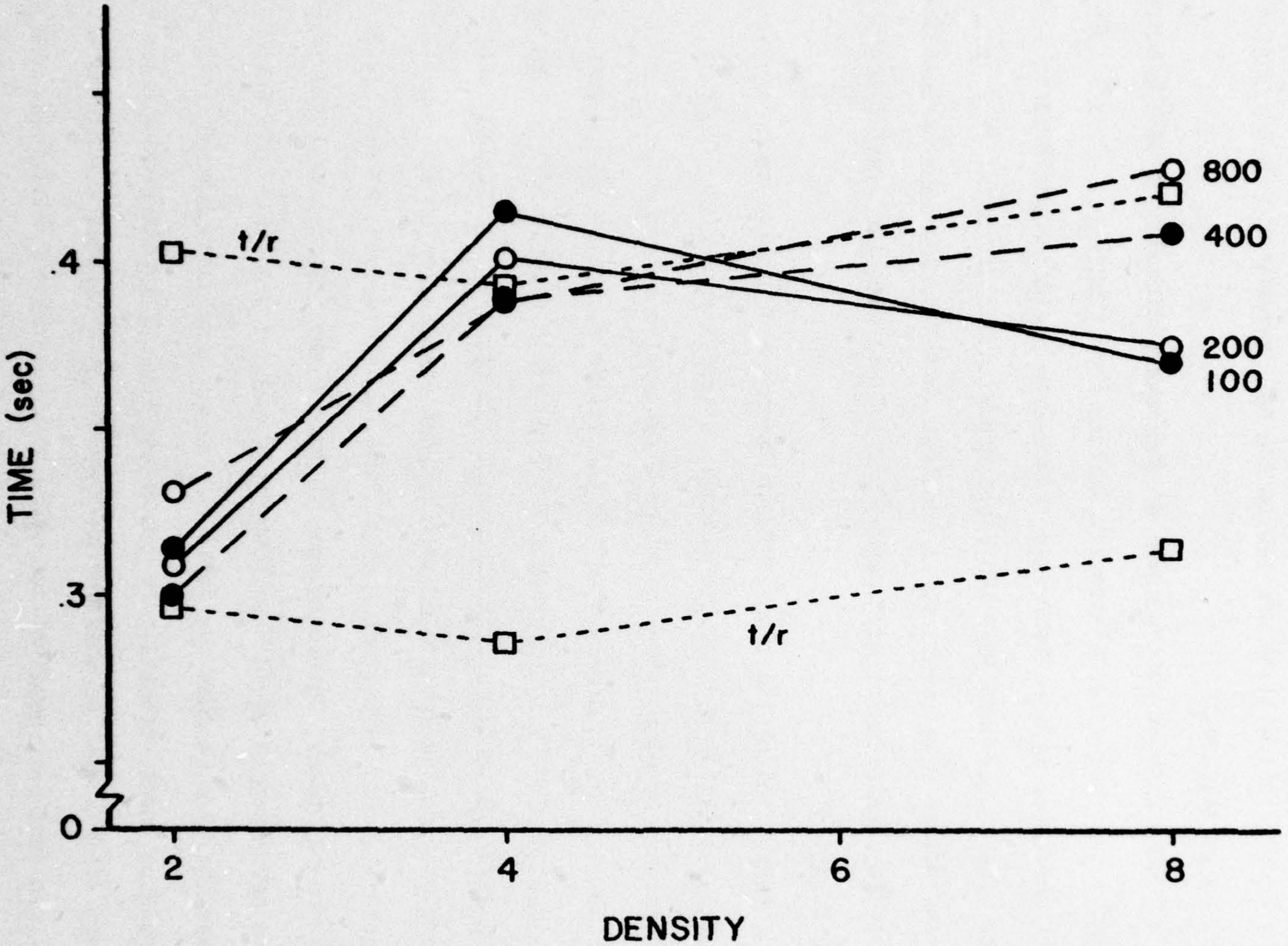

Figure 2. Effects of display density and duration on the processing time per stimulus and on the processing time per response. The upper t/r is the time per response including movement time; the lower t/r is the remainder after subraction of time per movement.

would be maximized. Only the data obtained on Days 3 and 4 of this procedure were used. They will be applied to the next experiments to be reported as well as to this one.

Figure 2 shows that removal of the movement component of the output produced a t/r that was consistently smaller than the t/s. It may also be seen that the input measure increased from D-2 to D-4 after which it increased further with longer durations and decreased with smaller ones. The result suggests that as D increases for a constant duration, the input processing time given to each stimulus may increase to a limit with the limit depending on the duration.

Inspection of the times between responses indicated that they varied relatively little and unsystematically within a trial (cf. Table 1). In other situations, however, there might be a systematic output effect due to some variable operating directly on the successive responses with a trend that could be hidden by the average t/r. A possible example might be an interference effect associated with successive recodings of the stored items. Other examples might be associated with response inhibition or fatigue. Along a related line an investigator might have an interest in introducing a stimulus between responses, but would want to have an estimate of what the average time per response would have been if he had not done that. In these various cases the time between the first and second responses provides that t/r which should be least affected. To the extent that that measure estimates the average, it may also be used for on-line or for otherwise estimating the average.

To test that possibility, using trial blocks for individual subjects, a 95 percent confidence interval was established for each mean t/r for all output measures at D-4 and D-8. In the 144 such instances over all four days, the time between the first and second button never once exceeded the confidence intervals. In different terms, a plot of t/r based only upon the time between the first and second buttons would have been very similar to the t/r values of Figure 2.

Experiment 2

In Experiment 1 the densities were administered in blocks of 32 trials each of which had the same density and exposure time. If the subject had not been able to anticipate the density of the display would the results have been different? It could be hypothesized that t/r in Experiment 1 was constant because the subject knew how many responses he would have to make, whereas had the density been unpredictable he would have had to make some different kind of response adjustment on each trial. Similarly, the input rate might have been different if the Ds could not have been anticipated. Experiment 2 was intended to examine these questions.

This experiment was similar to the previous one except that all four densities appeared in random orders within the 32-trial blocks, and only durations of 100 and 200 milliseconds were used. The experiment required two sets of eight blocks per day, four at one duration and four at the other in random order. Thus, all conditions were completed in one day. They were replicated on a second day. The same six subjects were used.

Results and Discussion

Analyses of variance of the data indicated that the only significant effects on total time were D ($F\ 3/15 = 107.30\ p < .001$) and the D x Duration interaction ($F\ 3/15 = 5.02\ p < .05$). Density also had a significant effect on input time ($F\ 2/10 = 51.90\ p < .001$), and on the number of responses made ($F\ 3/15 = 125.77\ p < .001$). Nothing that was varied had a significant effect on t/r. Duration had no effect on any of the measures.

Figure 3 shows the results obtained with various measures each plotted as a function of D. The first panel shows the total time and the input time. In this figure, and henceforth, movement time (.107 seconds) was removed from the total time and the output measures. In the figure the input time may be seen to increase with D, but decreasingly. As in the previous experiment, the results fall into Case 3. On Assumption 2 we may conclude that the loss was in the input, and on Assumption 1 we may calculate t/s using input time divided by N_r.

Analysis of variance of the calculated t/s yielded no significant effects. Given, then, that t/s was constant and the loss was in the input, it appears that some stimuli either did not reach input, or they were lost within it.

The results of this experiment and of the previous one fell into Case 3. The values of t/s and t/r from each are shown in the second panel of Figure 3. The data from Experiment 1 are only those at the two durations also used in Experiment 2. Both sets of measures are pooled over those durations. It may be seen that t/s did not vary at all with D in this experiment, but that it was greater than the comparable values of the last experiment. Conversely, t/r was less in this experiment.

A possible explanation of the differences between the two experiments is that when the subjects could not anticipate the number of items to appear, they adopted a single level of t/s as a processing strategy. Since t/s was larger at every point in the second experiment, the processing rate adopted was less than any of the Experiment 1 rates, a very conservative strategy. This would explain the slightly smaller response frequency of Experiment 2 since at the smaller processing rate, the probability of missing a stimulus item on the display (or on the sensory memory?) would be greater. Whether

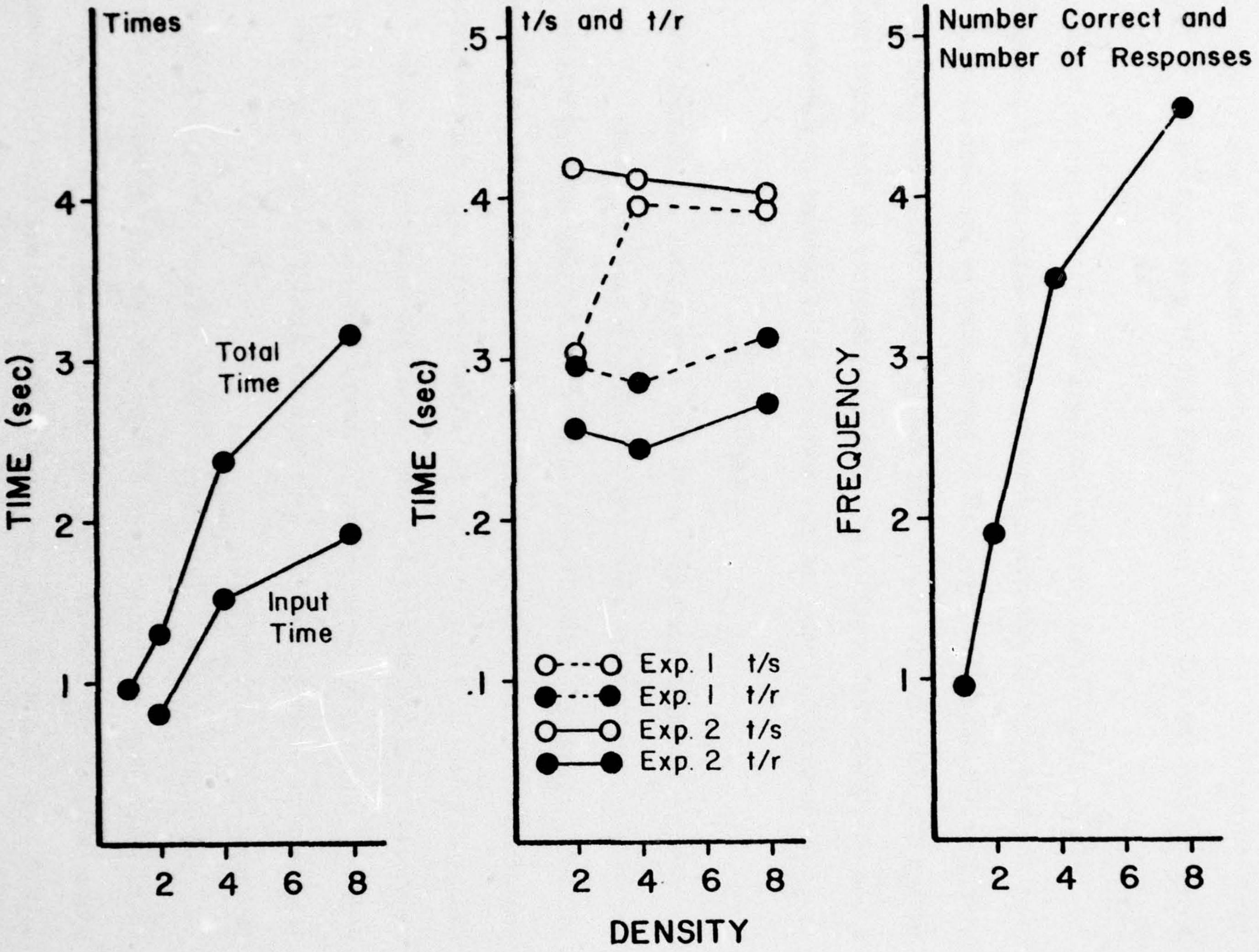

Figure 3. Effects of display density on total and input time, t/s and t/r, and response frequency and correctness.

or not the explanation is fundamentally correct, however, is of less immediate interest than the finding that the input measure is sensitive to differences between the two experiments, and that it does lend itself to interpretation.

Figure 3 also shows that t/r was less in this than in the first experiment, probably due to continued practice by the subjects. If practice had an effect on the input measures, it was overwhelmed by whatever else was determining it. This too is significant for an evaluation of the proposed measures since, assuming that practice did affect performance in this experiment relative to the previous one, the two measures still behaved very differently.

Experiment 3

In the previous two experiments the stimuli were positioned randomly on the display, a procedure which was intended to load the input. If the stimuli had been organized on the display so that the subject knew exactly where they would be, and if they had been grouped in some way, it might be expected that the input would be aided relative to random positioning. Such organization might also have had an effect on the output assuming that the aided input provided an encoding or organization in memory that was beneficial to retrieval from memory. These hypotheses were used to provide another way to examine the input and output measures.

The same random stimulus sequences were used as before, but the stimulus items were placed within an array of two rows and four columns (2 x 4) in the center area of the display. Only D-8 was used so that all positions were always filled. Exposure durations of 100, 200, 300, and 400 milliseconds were blocked within 24-trial sequences, eight sequences per day for two days to provide four replications of the experiment. The same subjects were used. Between this experiment and the last one they were used in pilot work which essentially reproduced the conditions of Experiment 1. As a result they began in this experiment with extensive practice with the random location display and no experience with the matrix display.

Results and Discussion

Total time was dependent upon replications ($F\ 3/15 = 6.53\ p < .01$) and duration ($F\ 3/15 = 8.64\ p < .01$). The number of responses made varied only with duration ($F\ 3/15 = 17.66\ p < .001$) as did the number of correct responses. Neither input time nor t/r were significantly affected by duration although the data suggested input time trends within two of the four replications. Accepting the statistical analysis, however, as far as the variable, duration, is concerned the results are those described by Case 2 and on Assumption 2 the loss in responses relative to the stimuli presented may be assigned to the input; t/s may be calculated using N_r. The results are shown in Figure 4 which also provides comparable data from Experiment 1. The data shown for this experiment were pooled over all replicates.

The figure suggests that compared to Experiment 1 the processing rates obtained were slightly greater and, as in the first experiment, they were constant for all levels of exposure time. The effect of grouping of the stimuli would be expected to permit each stimulus to be processed in less time than when they were randomly located since less time would be expended in finding and moving between stimuli visually (and on the sensory storage?). This result, therefore, is reasonable.

If the t/s is reduced as it was in this experiment, it would be expected that the subject could process more of the eight stimuli than under the previous conditions. Figure 4 also shows the number of responses made in this and in Experiment 1, and it may be seen that the expectation was borne out. The differences between the two are largest at the smallest exposure time and

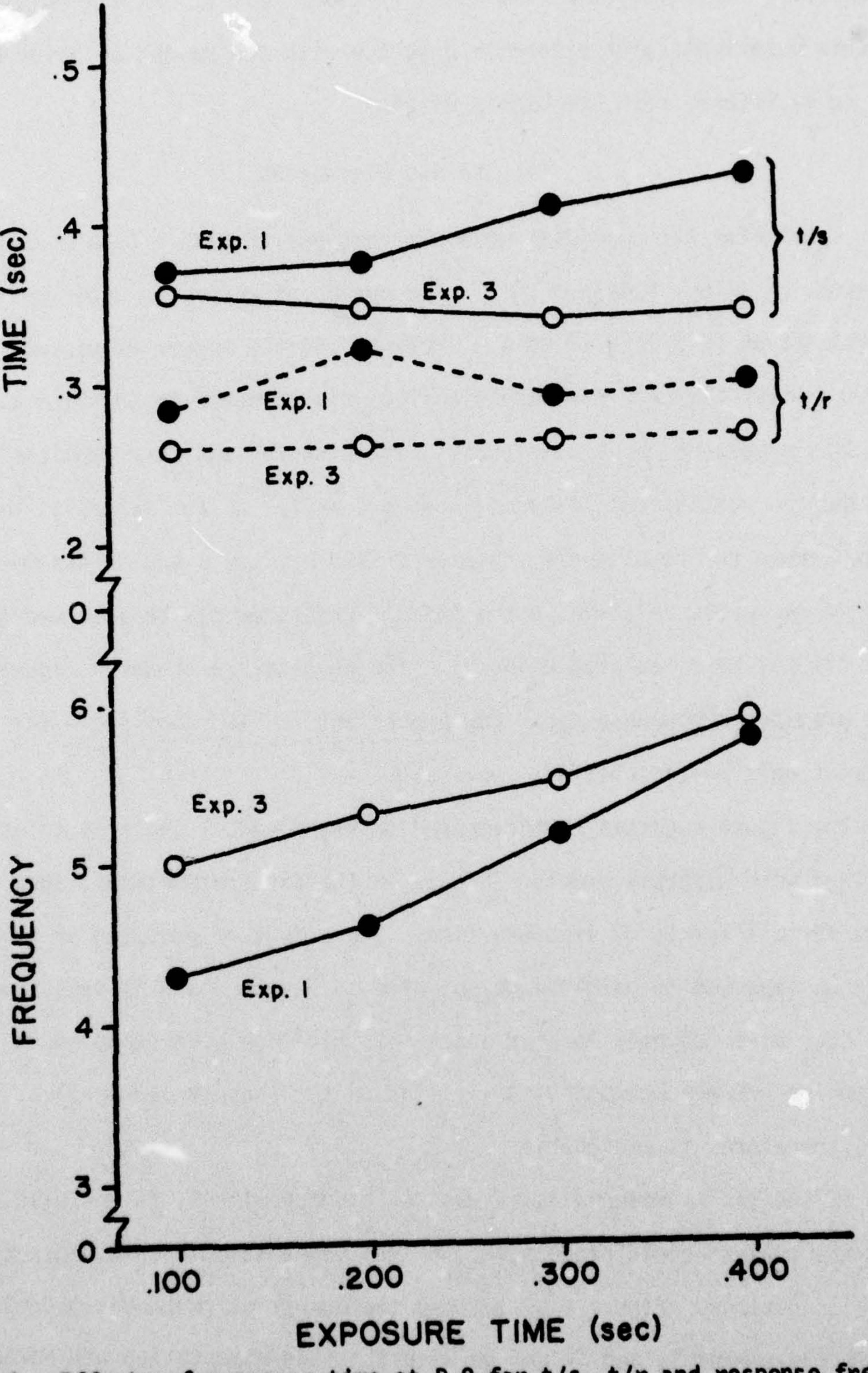

Figure 4. Effects of exposure time at D-8 for t/s, t/r and response frequency for Experiments 1 and 3.

and tend to converge by the longest duration.

It is conceivable that the greater number of responses made and the smaller values of t/s and t/r in this experiment reflect the effects of practice rather than the effects of stimulus organization. Figure 5 considers these questions by presenting a plot of the temporal measures and number of responses as a function of replications pooled over durations. All of the temporal measures decreased systematically with replications, whereas the number of responses made did not change. The temporal measures indicate a loss in performance at the outset of the experiment compared to Experiment 1, but also show that the loss was generally overcome and that the performance level finally attained exceeded the earlier experiment. It seems then that the gains shown in Figure 4 were not due to practice effects.

Both input time ($F\ 3/15 = 5.20\ p < .05$) and t/r ($F\ 3/15 = 5.69\ p < .01$) were significantly affected by the replications. This is Case 4 above, and consequently t/s was not calculated. The other measures, however, are very informative. As shown in Figure 5 both input time and t/r decreased with practice, but in different ways, i.e., t/r linearly and input time non-linearly. Whereas t/r and output time appeared to be unaffected by the change in the nature of the display, and continued to improve from its last measured bases, input time started with an initial large loss from which it recovered. It seems then that changing the organization of the display had a strong initial effect on the input and none on the output. Since display organization would be expected to be an input variable, this result is reasonable.

Of considerable value was the finding in this experiment that locus of the loss in responses due to exposure time (another input variable) was in the input. It is even valuable to have been unable to localize the source of loss with respect to replications since the data suggest new experiments.

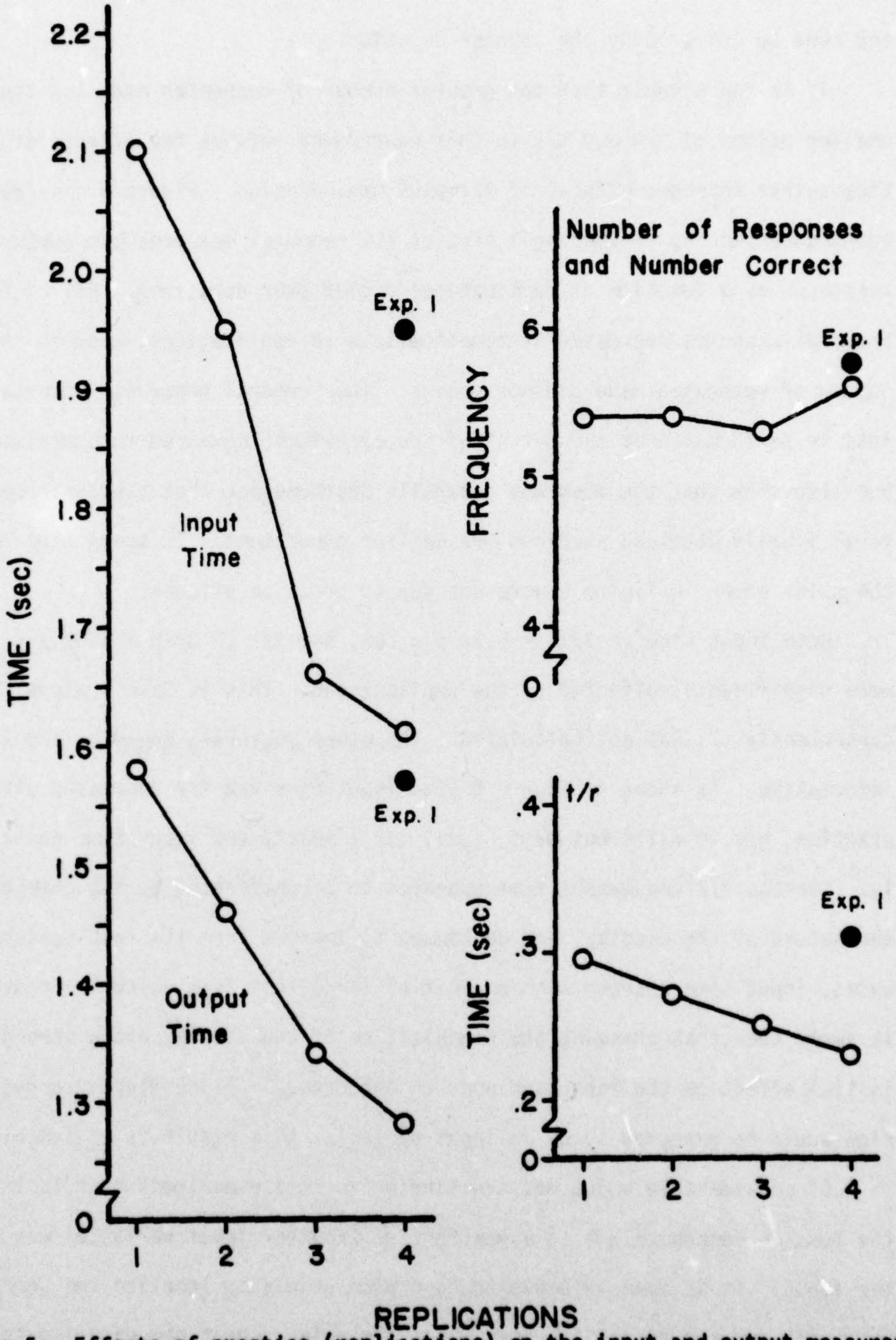

Figure 5. Effects of practice (replications) on the input and output measures and on response frequency. Single points are comparable values from Experiment I.

That is, they raise the possibility for this task, which involves familiar items, that the number of responses made does not depend on practice, whereas the time to process the stimuli and the time to complete the output process both do.

Experiment 4

The partial report experiment developed by Sperling (1960) presents the subject with a display of items and on termination of the display provides an instruction (probe) to report a specific portion, rather than all, of the display. Typically, the subject can report items in response to a probe that he was unable to provide as part of the whole report. The gain is generally seen as an output phenomenon associated with selective retrieval from the sensory storage.

Two factors in the whole vs. partial report experiment could possibly have important input effects. First, the probe, itself, is a stimulus which must be processed and, presumably, stored before retrieval can begin. Secondly, the subject might encode the stimuli or organize them for storage (a form of encoding) differently in anticipation of a whole report than for a partial one. The experiment reported was not intended as a thorough investigation of these possibilities. Rather the possibilities suggest fruitful ways in which the input-output distinction might be examined. This experiment was exploratory in nature.

Method. The same six subjects were used as before. The same ordered arrays were used as in the previous experiment. On each day the subject received eight 32-trial blocks. For two of these he was always given a probe stimulus that required him to report the two items that had been in one of the four columns (D-2); two of them required him to report the four items in one or the other row (D-4); two of them required that he report a single cell of the matrix (D-1), and two more sequences were presented in which all three of the partial report Ds were intermixed randomly within the trial block. In the varied partial report sequences, 10 trials required a two-item or column report, 10 required a four-item or row report, and 12 trials required reporting a single cell. Of each pair of sequences, one was presented with a 100 millisecond exposure duration, the other with 200 milliseconds. All eight sequences were presented in random order, and Day 2 was an exact replication of Day 1.

The partial report instruction was provided immediately at the termination of the display. For four-item reports that was done by lighting all four of the positions above the upper row or below the lower row; for two-item reports it was done by lighting the position immediately above _and_ below the cells; for single reports it was done by lighting the position above the cell for reporting an item from the upper row or below the cell for the lower row.

Results

The results for the constant probe and the varied probe sequences were analyzed separately. Not much will be said of the latter since the subjects apparently did not meet the requirements of the experiment. From some verbal reports afterwards it was apparent that under the varied probe conditions, at least some of the subjects attempted to store only a single row (four items). Then regardless of what the probe was, they reported all that they could from that row for both D-2 and D-4. This was supported by the finding that the mean number of responses made in D-2 was 2.35. That some subjects did this is not surprising (after the fact) since in the previous experiment they were unable to report more than 4-5 items. Apparently, adding the probe under varied probe conditions placed an overwhelming load on them. Note, though, that from the point of view of the subject, the tactic was probably an optimal strategy. In any case, the problem did not appear to be associated with the constant probe condition.

For the constant probe conditions, the probe D significantly affected all three temporal measures: Total Time (F 2/10 = 93.20 $p < .001$), Input Time (F 1/5 = 9.01 $p < .05$), t/r (F 1/5 = 7.82 $p < .05$). The number of responses made on the average was always less than the probe D, even at D-1. That may have been the result of the varied nature of the probe stimulus and the large size of the stimulus items. The experiment did not yield typical results, therefore, but for our immediate purpose of examining the input and output measures that is not crucial.

Since both input time and t/r were affected by probe D, t/s cannot be calculated (Case 4). Input time and t/r may be examined and they are presented in Figure 6 along with the total time. The upper portion of the figure shows t/r and the average value of t/r from the whole report of eight items from the previous experiment. It may be seen that at D-2 t/r was less for the partial report, but at the higher D it was greater than the whole report. Input time also increased with D, but a comparison between the two experiments with respect to this measure cannot be made since this one measured latency from probe onset and the last one from display onset.

Although the results do not permit us to determine the locus of the loss of response, they do permit the conclusion that under the conditions of the experiment the partial report procedure affects both the input and the output systematically as a function of the number of partially reported items demanded. This suggests that more is involved than simple retrieval from a sensory store. Whether the result would be verified using a more typical

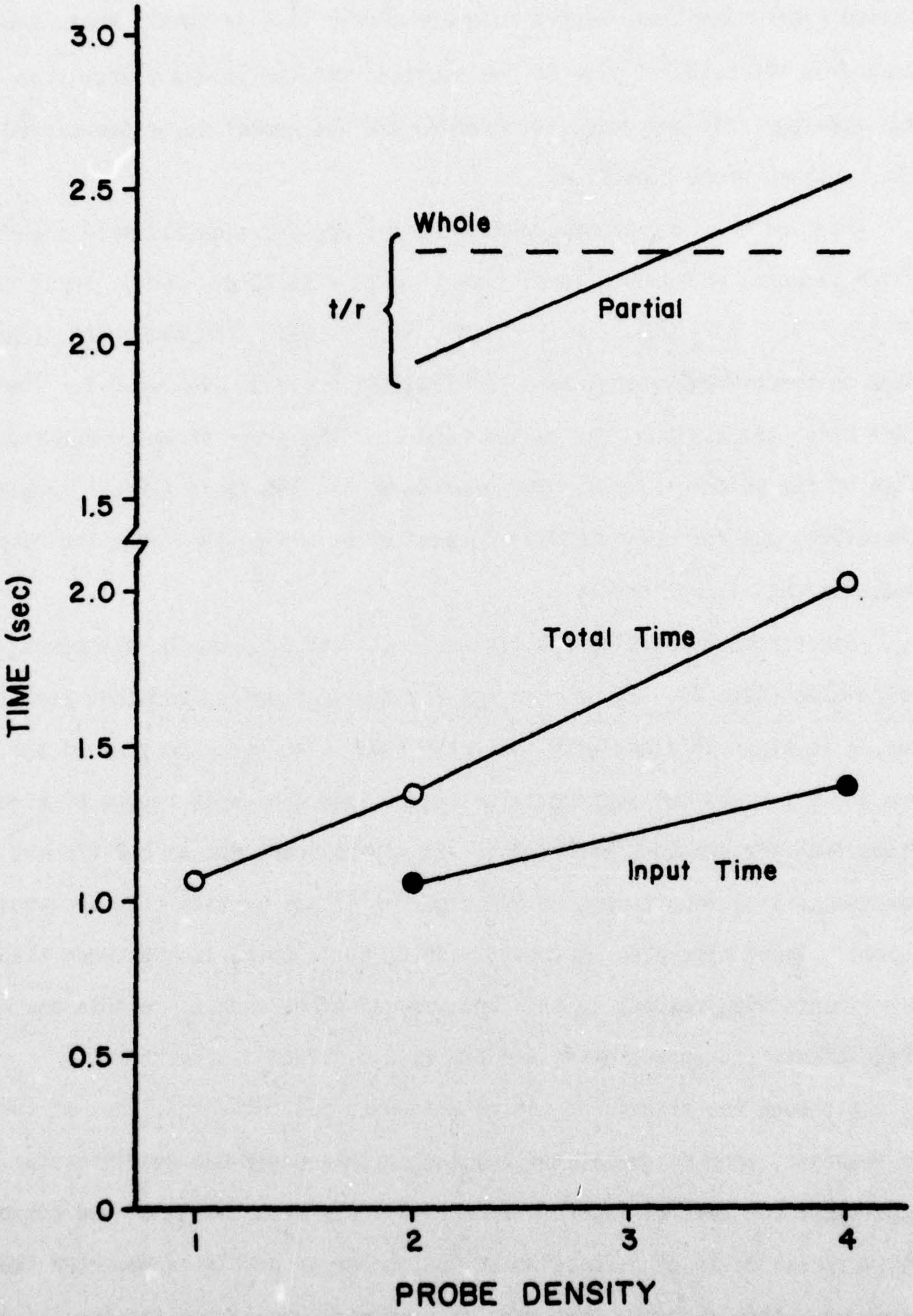

Figure 6. Effects of probe density on the temporal measures associated with constant condition partial reports. The dashed line is the comparable whole report t/r from Experiment 3.

display is a matter for further research.

The number of responses made also varied with exposure time (F 3/15 = 17.66 $p < .001$) as did the total time (F 3/15 = 8.64 $p < .01$). Neither input time nor t/r were affected by duration. Thus, with respect to duration as a variable, the results fall into Case 2, and, on Assumption 2 we conclude that with respect to this variable the locus of loss of responses was in the input. This result appears to reflect the usefulness of the measures very nicely, since it is consistent with the expectation that stimulus exposure time should have its main effect only on the input.

Experiment 5

The previous experiments tended to load the input in the sense that the stimulus items were difficult to acquire due to their size and, for the first two experiments, due to their unpredictable location on the display. If input time is a useful measure of the input processes, the acquisition difficulty should have had an increasing effect on input time as D increased. That it did do that, especially without affecting the output, is strong support for the applicability of the measures.

Considering the problem of stimulus acquisition differently, the size and location of the stimuli may have essentially forced acquisition to be at least partly serial in nature. If so, the increase of input time with D reflects at least that one serial component in the input process. In Experiment 5 all of the stimuli were available to central vision simultaneously. If under these conditions, input time should increase with D, it would be reasonable to infer that something in the input was processed serially other than the stimulus-receptor acquisition.

The previous experiments also tended to allow that part of the output process concerned with the selection of button responses to be minimized since the buttons were always labeled. Although with practice the subjects may not have made use of the labels, the labels were there as an aid if needed. In this experiment all conditions were carried out first with and then without labels available. Two critical questions then, were whether removing the labels would induce a change in the t/r function of D, and whether removing the labels would affect the input. If the input were found to be affected, it would imply that by the time the items were stored in memory they were encoded in anticipation of the output process, whereas if the input were not affected it would imply that all of the preparation for response was performed in the output.

The previous experiments also used a relatively small stimulus and response set. That is, there were only six different response buttons and only six different stimuli although each could occur more than once. Under those conditions D was not found to affect t/r. It is possible, though, that as the size of the response set increases, the uncertainty associated with the stimulus should interact with the response uncertainty. If so, at some response set size larger than the one used in the previous experiments, t/r should be related to D. Experiment 5 attempted to examine this speculation by using a nine-item response and stimulus set.

Method

Subjects. A new group of ten subjects, five male and five female students from the introductory psychology course were used. Their participation was an optional contribution to a course requirement.

Apparatus. The stimulus material was presented with a slide projector equipped with an electronically controlled shutter. The stimuli, black on white, were arranged randomly within the cells (not seen) of a 3 x 3 matrix which when projected subtended a visual angle of 1.59 degrees. Each of the alphabetic letters used subtended 0.38 degrees. The letters used were capital A, C, E, H, K, N, R, S, X.

Instead of pushbuttons, the response panel used a 3 x 3 matrix of pennies which served as contact points. Starting initially from a tenth penny to the right of the matrix, the subject tapped the appropriate penny with a stylus. After his last response, when he was ready for the next slide, he tapped the tenth penny which resulted in the opening of the shutter, and presentation of a new slide which had already moved into position. Measurements of time and error, and control of the apparatus were accomplished with the PDP8/e computer.

Experimental Procedures. The experimental design was a within-subjects factorial of stimulus duration (200, 300, 400 milliseconds) and D (2, 3, 4, 5). Each of the 12 combinations was represented in a block of 24 trials in which the stimulus items were selected randomly from the stimulus set on each trial. Each letter could appear no more than once on a slide. Each subject received the 12 combinations of D and duration in a different random order which was completed within one experimental session. One the following day the subjects received the combinations in different random orders. On the first day a label containing the letter code item of each penny was attached to the panel immediately above each penny. The subjects were informed that the labels would be removed after that day. The letter arrangement was randomized across all nine pennies. The labels were removed prior to the Day 2 session.

Following the experiment, the group of subjects used to obtain movement times described above were employed to obtain movement times on this apparatus. The same basic procedures were employed. That is, the subjects were run through a variety of the same trial sequences as used in the experiment proper with the pennies labeled so that they knew before the starting signal which pennies to tap. The opening of the shutter provided the start signal as in the experiment proper. As before the subjects repeated each button arrangement three times in a row within each sequence and repeated these procedures for four days. Estimated time per movement was based on the last two days of these measurements.

Results and Discussion

The data of one of the subjects was found to have errors due to data handling; therefore, that subject was discarded from most considerations. The errors did not affect the determination of response blocks, and therefore, the presentation of those data will include all ten subjects. The time per movement, .308 seconds, was three times longer for this apparatus than the previous one, a result presumably due to the requirement for aiming the stylus.

The number of responses made was essentially equal to the number of stimuli presented, except at D-5, at all exposure times, and at D-4 for 200 milliseconds. The effects of duration on number of responses was actually very small though significant ($F\ 2/16 = 4.52\ p < .05$). Duration also significantly affected the number of correct responses ($F\ 2/16 = 12.18\ p < .001$); they were less than the number of responses made, but highly correlated with them. The Duration x D interaction also significantly affected both measures (e.g., for number of responses $F\ 6/48 = 2.70\ p < .05$), and, of course the number of responses made depended upon D ($F\ 3/24 = 187.03\ p < .001$) as well as the number of errors. Neither number of responses nor the number correct were affected whatsoever by removing the labels.

The total time was dependent upon D ($F\ 3/24 = 110.81\ p < .001$), and the Duration x D interaction ($F\ 6/48 = 3.36\ p < .01$). It also depended upon labeled vs. unlabeled pennies ($F\ 1/8 = 18.85\ p < .01$) and the interaction of that condition with D (F 3/24 = 7.60 p < .001). Thus, the total processing time depended upon the labeling of the response set, but the frequency of responses and their correctness did not.

The t/r depended upon D (F 3/24 = 9.21 p < .001) and Labeled vs. Unlabeled (F 1/8 = 14.40 p < .01). Input time was affected by the same two main effects: D (F 3/24 = 48.85 p < .001), Labeled vs. Unlabeled (F 1/8 = 7.73 p < .05).

Since t/r was not constant with D, output time must not have been linearly related to D. Figure 7 presents the output times, corrected for movement times, for the labeled and unlabeled conditions as well as the corresponding input times. The data were pooled over all three exposure times. The figure shows that for the labeled conditions the output time was less at D-2 and D-3 than the input time, but that it increased more rapidly so that by D-4 it was at least as long as the input time and by D-5 it was longer. Both curves are essentially linear through D-4.

The effects of removing the labels on input time was to add a constant time to the input processing. The effect of removing the labels on the output time was a marked increase in that time. The overall effect was an even more rapidly increasing output time curve than for the labeled condition so that as D increased, the difference between the two D functions increased. The largest difference between the output curves, shown at D-5, was 1.5 seconds; the comparable difference between input time curves was .354 seconds. Both differences are important in magnitude, but it is clear that removing the labels had its largest effect on the output.

As noted above, the number of responses made were equal to D at the two longer exposure times with the exception of D-5, which approached but did not reach N = 5. Thus, even though both input time and t/r were affected by D

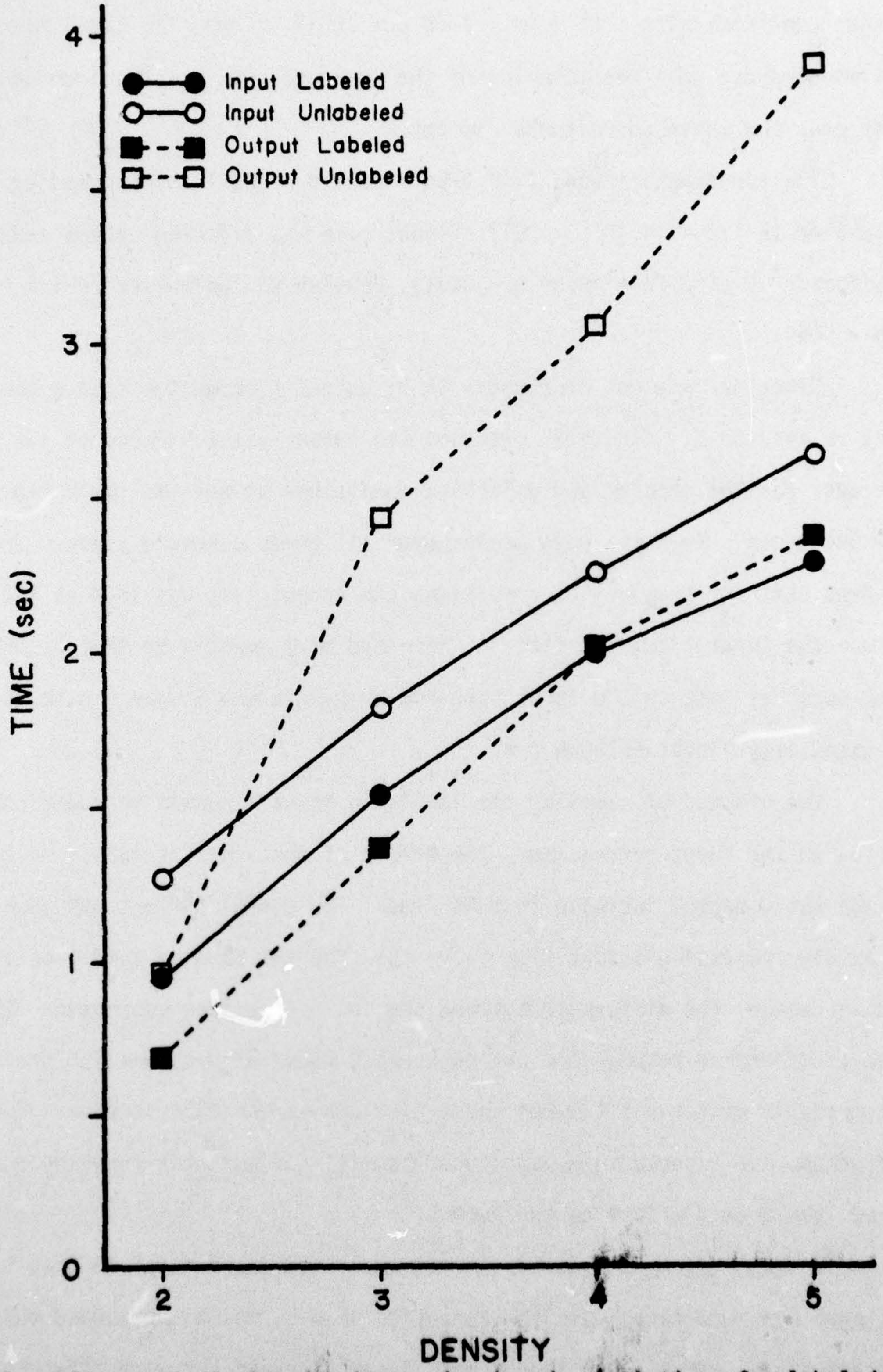

Figure 7. Effects of display density on input and output times for labeled and unlabeled response sets.

(Case 4), for those conditions where there was no loss in response we may determine t/s using the value of D. The result of doing that, pooled over the two longer durations, is shown in Figure 8 along with t/r. The figure shows that the differences between measures resulting from removal of the labels was essentially like those of the input and output times. Removing the labels decreased both rates; the largest effect was on the output rate. The two t/s curves appear to have very slight trends in opposite directions, but those trends were not significant statistically indicating that they should be viewed as flat lines. The differences between the lines were significant (F 1/8 = 9.00 $p < .05$). Also, as might be expected from the effects on input time, the interaction of exposure time and D was significant (F 6/48 = 2.51 $p < .05$).

Figure 8 also appears to suggest that the two t/r curves follow the same general relationship, but with different constants. If so, for both input and output the effect of removing the labels was to alter the rate of each form of processing. There is no implication of a change in the nature of the processing. Thus, these results appear to indicate that the processing rates of the previous experiments depended upon the availability of the labels, but that the behaviors of the input and output processes were not qualitatively different from what they would have been if the labels had not been there.

Although the conditions of Experiment 5 differed in several ways from those of Experiment 1, it may still be instructive to compare the differences in rates for the latter with the labeled portion of the former. That comparison is available in Figure 9. The figure shows that the general level of processing in Experiment 5 was lower than in Experiment 1, a result which could be due to the greater amount of practice given in Experiment 1, or to the greater stimulus and response uncertainty of Experiment 5, or to both.

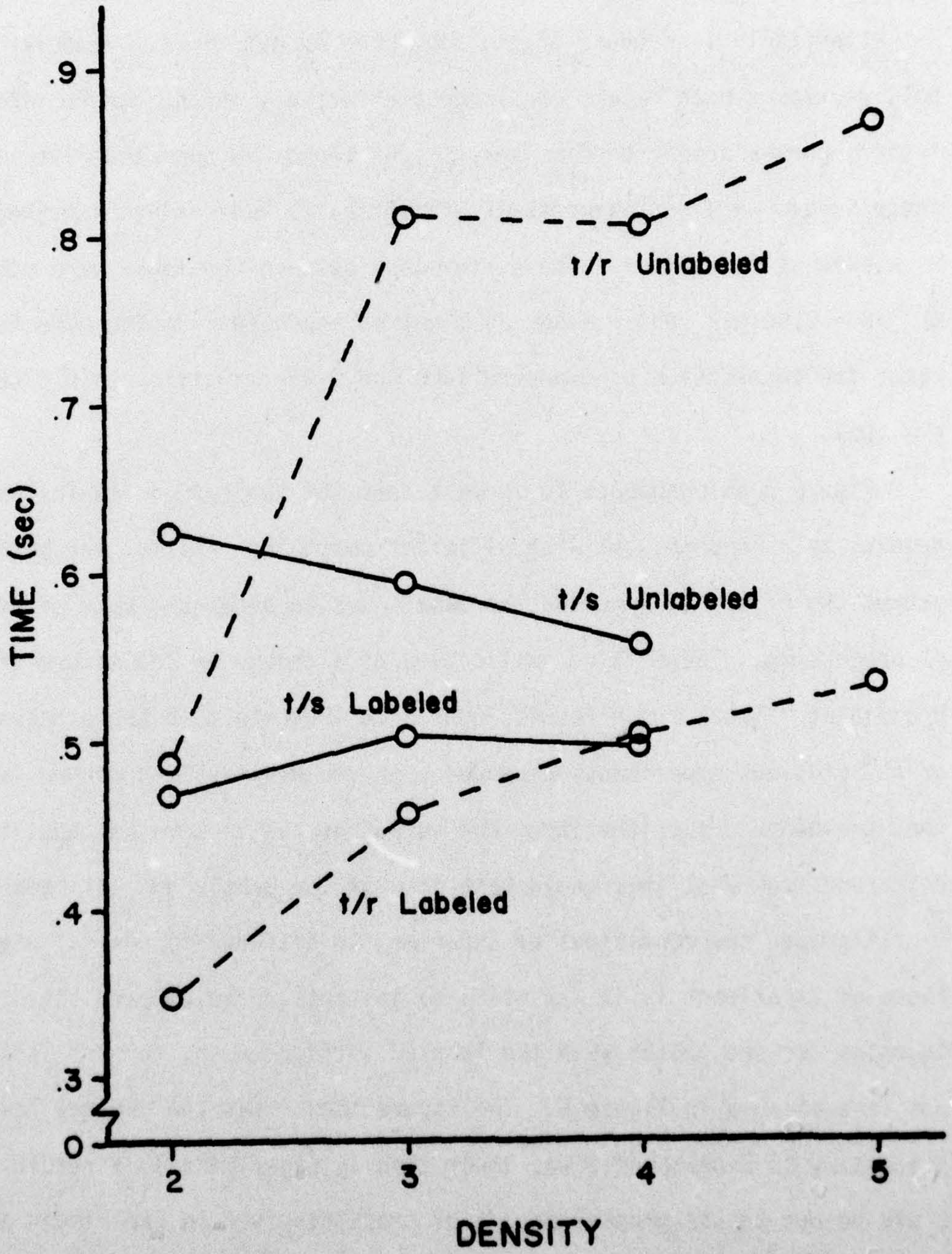

Figure 8. Effects of display density on t/r and t/s for the labeled and unlabeled response sets.

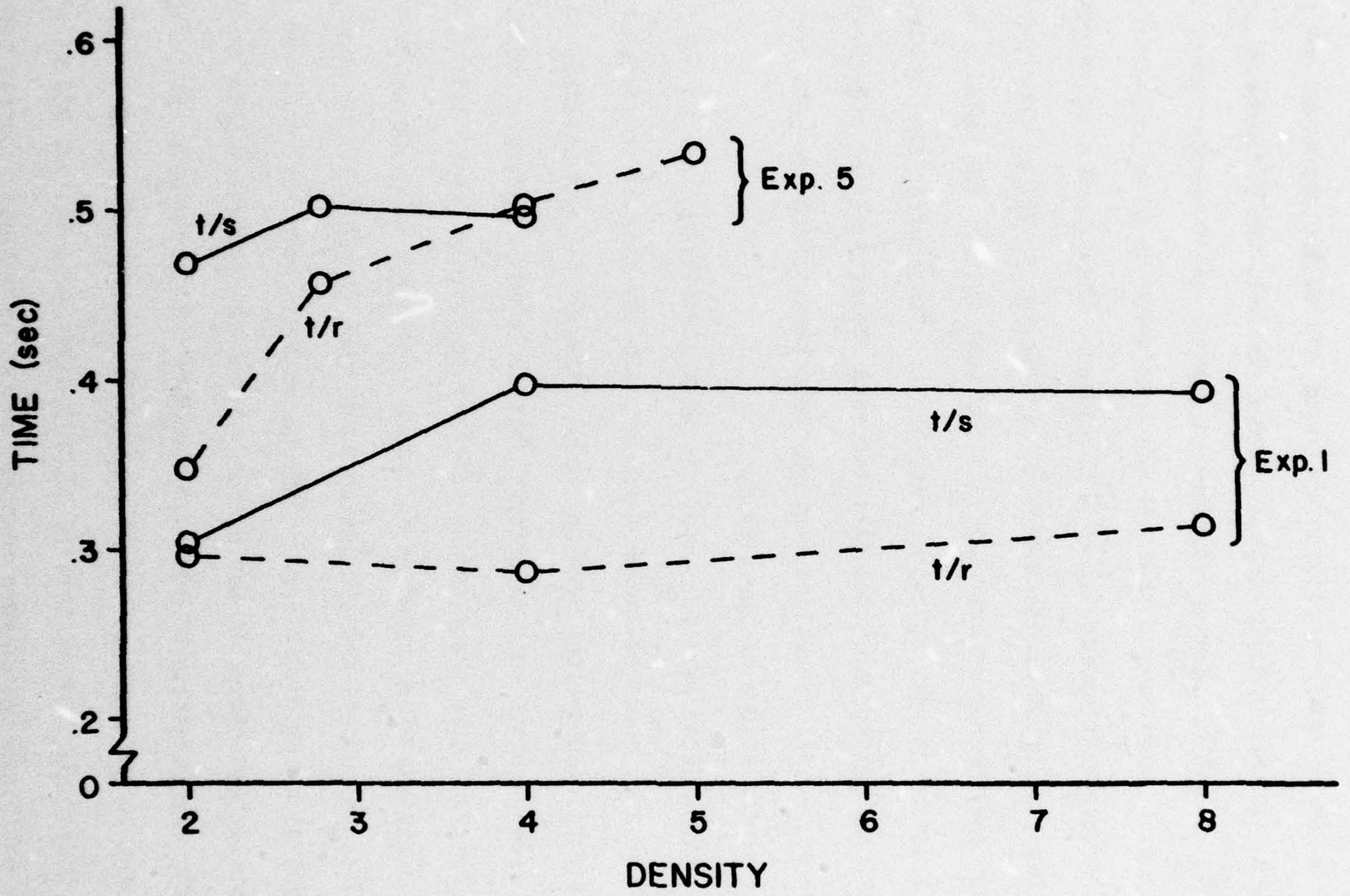

Figure 9. Comparable t/s and t/r from Experiments 1 and 5.

Aside from that, the results of the two experiments differ in that in Experiment 5 the differences between the input and output decreased and then reversed, whereas in Experiment 1, except for D-1, the differences were constant. A second important difference between the two experiments is the finding in Experiment 1 that t/r was unaffected by D, whereas in Experiment 5 it increased systematically as D increased. The figure also suggests that the two t/s curves are essentially the same for as far as they can be compared; they both rise from D-2 to a constant value. The results in both cases was an increasing input time with D. Considering the results of this experiment, it appears that that increase reflects serial processing over and above any serial processing that may have been forced upon the other experiments by the nature of the display.

The subjects were not under constant surveillance during the experiment, although they could be viewed through a one-way mirror, so systematic gross behavioral observations were not made. However, it was observed in pilot work leading up to this experiment that sometimes subjects would have their hand hovering over the response matrix indecisively for relatively long times. Such occasions often resulted in a much longer t/r than the whole input time. The data to be reported are instances of such occasions, a phenomenon defined earlier as a response block. Although we could have also analyzed the data for the actual times, it was decided that such measures should await more systematic investigation of response blocking. Our purpose at this time is only to point to the availability of a quantitative criterion for the phenomenon.

During the labeled portion of this experiment all but one of the ten subjects exhibited one or more response blocks as defined. During the unlabeled portion all of them did. Figure 10 presents a plot of the mean frequency of response blocks vs D for the conditions of the experiment. The frequency was

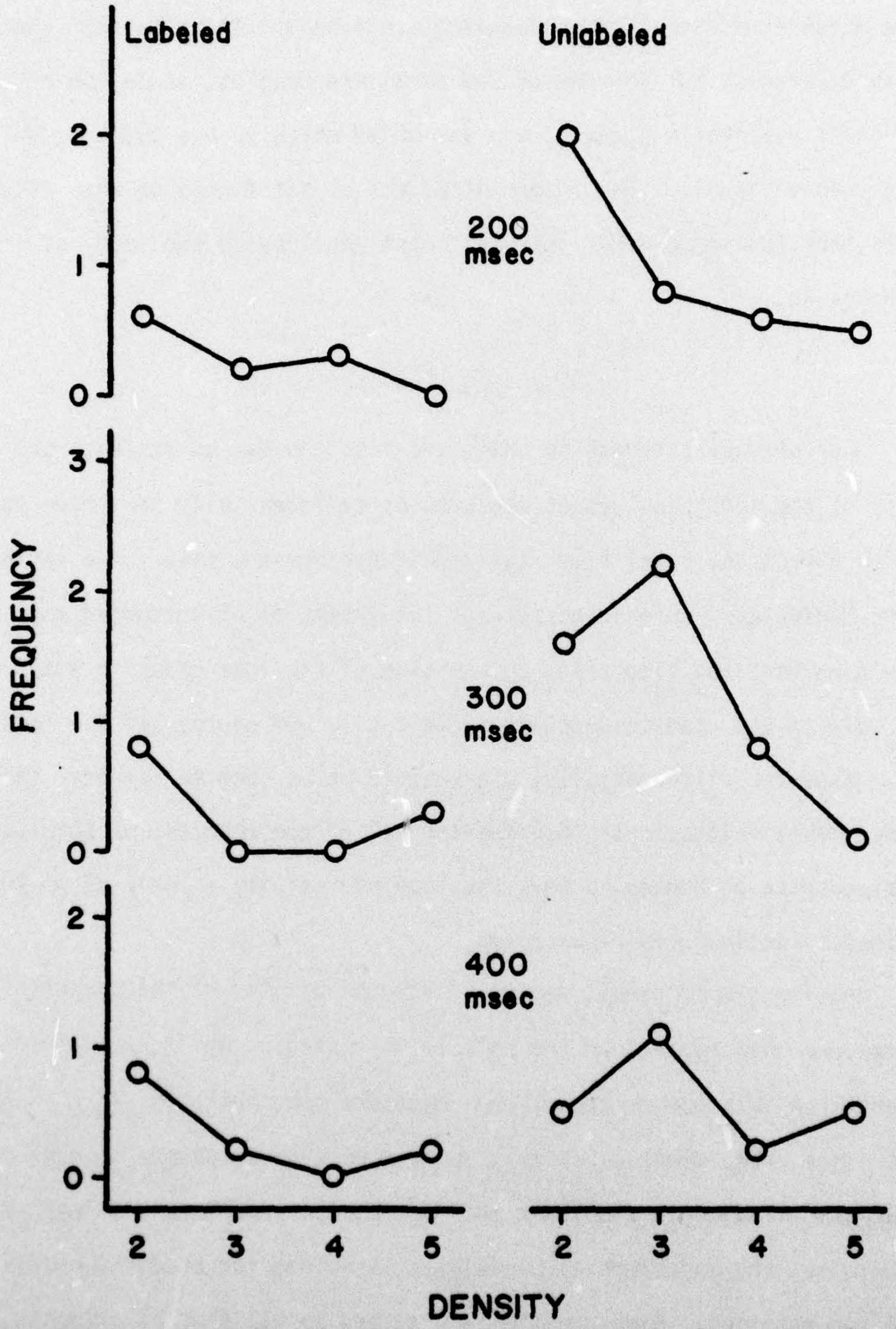

Figure 10. Effects of display density and duration on the frequency of response blocking for the labeled and unlabeled conditions.

not very large in light of the 24 occasions in which each subject could have blocked at each duration-D combination. Nevertheless, the figure shows that the measure was affected by removing the labels. There is also some suggestion of trends, but in view of the small frequencies, it may be more prudent to await systematic study of the variables which induce blocking before taking them seriously. The important aspect of the figure is that it does indicate that the measure has potential applicability to the study of information processing.

Discussion and Conclusions

Our primary interest in this investigation was to evaluate the usefulness of the input and output measures as differentially sensitive to variables which affect the total time required to perform the task. The variables that were manipulated were selected with the intention of producing data which would do that and also allow an exercise of the four cases in which $N_s > N_r$ as well as the case in which they are equal. Of course, if the measures had not responded differentially, there would be no need to consider those five experimental situations. Considering all of the results, we conclude that the measures do appear to have the required utility as well as status as operationally defined empirical terms.

Another, more risky, way to assess the utility of the measures is to compare them with respect to the effects of variables which we believe should operate on only one or the other. Exposure time ought to affect only the input since, regardless of stimulus persistence in a sensory memory, the time that the stimulus is available must precede storage in a non-sensory memory. Otherwise, the experimental paradigm as a method for studying recall confounds the two memories. Exposure time was varied in all five experiments, and never found to affect the output measure even under those conditions of large D when it affected the input. This seems to provide further support for the input-output distinction and its usefulness. Also, in this regard, the results indicate that the major effects of stimulus duration are on the number of responses made, and their correctness rather than on the input processing time.

Density is also a variable which ought to affect the input, assuming serial processing. However, D should also affect the output time given serial output processing and an increased store in memory as D increases. Whether or not it ought to affect t/r is another question. The data suggest that it may do that when the response uncertainty is large enough, but more systematic study is needed.

If we accept the measures and then consider the implications of the results, it seems reasonable to conclude that at least part of the input processing beyond stimulus reception is a serial process and that the output for the multiple response recall situation is also at least partly a serial process. As much as possible we have avoided discussing possible component processes in the input and the output to avoid the implication that the input and output measures require a model more complex than the time to completion of storage and the time following that to completion of response. Further methodological efforts are required which develop models of component processes and associated procedures for defining the times that they require. Inferences to component processes from measures which confound processes would not seem to offer the quickest route to an understanding of how information is processed no matter how well the process models predict the confounded result.

Another finding of interest, assuming the measures, is that encoding for the response takes place in both the input and the output. This was shown by Experiments 3 and 4 and by the effects of labeling in Experiment 5. It seems reasonable to suppose that items are partially or completely encoded for responding by the time that they are in storage and that the output selects the actual responses for each coded item; in a sense it verifies the input encoding. More complex situations may be different, however. That is, it is conceivable that the input code must be translated to a new code in the output. That may also happen early in the learning of the stimulus names and their relationship to modes of responding, but with advanced learning, the output encoding may drop out or be transferred to the input somehow. These are speculations, of course until tested.

Finally, we note that although the experimental paradigm is that of immediate recall, it is actually characteristic of a wide range of stimulus-response situations which require more than one response, e.g., serial reaction situations, patterned response situations, speech, etc. The measures described appear relevant in those situations if properly used. Of further interest is the fact that response blocking is an occasional, but important, characteristic of sequential responding and that it too can be studied with these measures.

References

Atkinson, R. C., & Shiffrin, R. M. The control of short-term memory. Scientific American, 1971, 225(2), 82-90.

Baddely, A. D., & Patterson, K. The relation between long-term and short-term memory. British Medical Bulletin, 1971, 27, 237-242.

Broadbent, D. E. Decision and stress. New York: Academic Press, 1971.

Christ, R. E., Stevens, A. L. & Stevens, D. Color research for visual displays (NMSU-JANAIR-FR-74-1, JANAIR Report 741103). Las Cruces, New Mexico: New Mexico State University, Department of Psychology, July 1974.

Posner, M. I. Abstraction and the process of recognition. In K. W. Spence & C. Bower (Eds.), Advances in learning and motivation (Vol. III). New York: Academic Press, 1969.

Sperling, G. A model for visual memory tasks. Human Factors, 1963, 5, 19-31.

Teichner, W. H., Christ, R. E., & Corso, G. M. Color research for visual displays (ONR Report CR213-102-4F). Las Cruces, New Mexico: New Mexico State University, Department of Psychology, June 1977.

Teichner, W. H., Reilly, R., and Sadler, E. Effects of density on identification and discrimination in visual symbol perception. Journal of Experimental Psychology, 1961, 61(6), 494-500.