THE DIFFERENTIATION OF HUMAN TIME ESTIMATIONS[1]

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The term "timing behavior" has been applied to the differential reinforcement of relatively prolonged inter-response intervals, a method developed by Wilson and Keller (1953) and based on Skinner's analysis of operant behavior (1938). Timing behavior is not directly studied under the DRL contingency, however, since the only response measured is the one which signals the end of whatever behavior or process served to span the required interval. Another method long used in the study of timing behavior has been Skinner's fixed-interval schedule, in which a response increases in frequency as the time at which reinforcement will be available approaches. Still another feature of the free operant susceptible to temporal differentiation is response duration, the amount of time consumed by a single response. Skinner also included observations of undifferentiated and differentiated response durations in his original treatment. Using approximation methods, Skinner obtained response durations as long as 30 seconds with rats. The holding response is differentiated quite rapidly in humans with the use of verbal instructions and selective reinforcement, as in the experiments to be reported in this paper. Blough (1958) has recently reported a technique for the study of timing behavior which is similar to the bar-holding response. His method required a pigeon to maintain a stereotyped body posture, as measured by photoelectric cells, for a preselected interval. Food reinforcement was given after the posture had been held for a minimum number of seconds. A feature which makes the holding response a timing response and not a simple waiting response is the condition that reinforcement be given only after the response has been terminated by the organism and only when the response has been of adequate duration.

An additional requirement can be placed on response duration by making reinforcement contingent upon termination of the response within certain preselected temporal limits. Under these conditions, responses which are either too short or too long go unreinforced. This is similar to the "limited hold" sometimes inserted into other temporally defined schedules (Ferster & Skinner, 1957). In studying the rat's bar-holding response, Stelter, Barnes, and Homme (1959) imposed such a limited hold on response duration; *i.e.*, the rat was reinforced only if it released the bar after k hundredths of a second but before k + n hundredths of a second has elapsed. When stabilized, such a differentiated timing response showed relatively high precision and sensitivity to experimental manipulation.

For discussion, a timing response of the bar-holding type may be broken down into components. The first component may be called R_1, the initiating response. The actual timing response is R_2, which consists of the response(s) or process whose duration serves to bridge the interval. The release or termination response is R_3. Thus, timing behavior would consist of starting, holding, and stopping a functional unit of behavior. It seems profitable to assume that stimuli are acting to produce R_3. The S^D for R_3 might be R_2, the last subunit of R_2, or some sensory product of R_2. At the time of R_1, the subject conceivably could "tap into" some on-going physiological system and use stimuli arising from the system to bridge the interval. There is here no suggestion that behaviorists should take up renewed interest in "mediating processes." Among the various sorts of response-produced stimuli of possible importance in timing behavior are kinesthetic and proprioceptive feedback mechanisms, visual exploration and ocular movements, and task-extraneous muscular movements. If one assumes that a timing response is a special case of the discriminative operant, the task becomes one of designing experiments that will illustrate the need for the assumption as well as the probable locus and controlling parameters of the immediately prior stimuli. From such an analysis might come an enhancement of a technology for behavioral control. The experiments reported in this paper are the first two in a rather prolonged series.

There would seem to be two alternatives to the isolation of the specific stimuli used in precise timing behavior. One possibility would be for learning theorists to maintain the distinction between response differentiation and stimulus discrimination. Such is unlikely since higher levels of generality are continually sought. The second alternative might involve the elaboration of a more sophisticated set of intervening variables: Such an enterprise has been carried out by a number of theorists in the past to the dissatisfaction of many. The latter alternative is without particular charm, it would seem, because the most striking characteristic of the discoveries generated by such constructs is their rarity.

EXPERIMENT I

The purpose of this experiment was to illustrate an automated technique for temporal differentiation in the human and to compare the untrained estimation of a preselected interval with a trained or differentiated estimate of the same interval. The experi-

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ment was designed to evaluate the application of two temporal parameters, t_1 and Δt, to a holding response in human subjects. The parameter t_1 is that time during which a response, once initiated, must continue uninterrupted to bring about reinforcement at the termination of the response. The second parameter, Δt, is that period of time which begins with the lapse of t_1 and during which the termination of the response will be reinforced. A further purpose of the experimenter was to observe the effects of removal of reinforcement at various points during the training procedure.

Subjects

The subjects in this experiment were three students at the University of Pittsburgh, and are designated throughout by the following initials: LJD, female, age 19; SEM, female, age 18; and JHB, male, age 18. They were recruited from undergraduate introductory classes in psychology.

Apparatus

The apparatus, shown as Fig. 1, consisted of three main components: a response box containing an ergograph, an information panel for *S*, and a control circuit. The timing response consisted of holding back the ergograph trigger for what *S* judged to be the proper length of time. If *E* chose, *S* received information about each attempt by way of lights which appeared on the information panel immediately after the termination of each response. The part of the ergograph grasped by *S* was a gripping post, around which the thumb and fingers could be wrapped. A trigger was suspended just in front of the post. A 0.5-inch pull on the trigger closed one microswitch, whereas a 1.25-inch pull brought the trigger against its rear stop and closed a second microswitch. In this experiment, the trigger was weighted so that a force of about 700 grams was required to close the first microswitch. This requirement did not change during this experiment and the next to be reported.

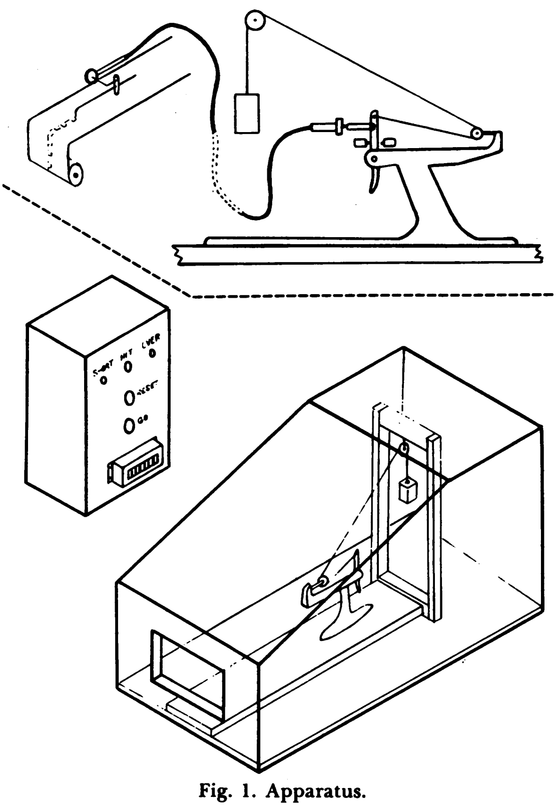

Fig. 1. Apparatus.

The *S* sat in an adjustable swivel chair at a draftsman's table. Since all *Ss* in this experiment were right-handed, the response box was placed to the right on the table and the information panel to the left. A large blackboard screened the experimenter and his control system from view.

The *S*'s information panel was a smooth piece of masonite mounted on the front of a separate box. The information panel and response box were painted neutral semi-gloss gray and were connected with the control circuit through multiconductor cables.

The information panel displayed five pilot lamps and an electric, six-digit reset counter. Three of the lamps, referred to as S^R lights, were mounted in a row at the top of the panel. The center lamp had a 0.625-inch green jewel and was labeled "Hit." The lamps to the left and right of the "Hit" lamp had red 0.375-inch jewels and were labeled "Short" and "Over," respectively. The purpose of these three lights was to inform *S* about his success or the direction of error in producing the required interval. When *S* released the trigger, after what he judged to be the correct interval, one of the S^R lamps came on and remained on until the next trial. The only exception occurred during blocks of unreinforced trials, when no S^R lamps ever came on. At the beginning of the experiment, *Ss* were instructed to increase the next estimation if the "Short" light came on and to decrease the next estimation if the "Over" light came on. With each occurrence of the "Hit" light, a single point was registered on the electric counter.

A lamp with a 1-inch amber jewel and labeled "Reset" was 2 inches below the "Hit" lamp. This lamp came on and stayed on until the end of the trial, whenever *S* pulled the trigger too far back and hit the trigger stop. When the "Reset" light was on, the S^R lights were shut out of the circuit and *S* was not reinforced on that trial. The purpose of not allowing *S* to back the trigger against the stop was to prevent him from amplifying his kinesthetic and tactile feedback. These variables were thus held relatively constant except for adaptation effects. A lamp with a 1-inch white jewel was mounted 2 inches below the "Reset" lamp. This lamp was labeled "Go." It signaled *S* that the apparatus was ready for the next estimation. The "Go" lamp went out at the beginning of the response and stayed out during the trial and

the 2.50-second intertrial interval. The electric counter was mounted at the bottom center of the information panel.

The control circuit was mounted on a small table at which *E* sat during the experimental sessions. A clutch-activated clock of the reset type was used in recording response durations to the nearest 0.01 second. The clock ran as long as the first microswitch in the response box was closed and was reset by *E* during the intertrial interval. Three silent decade interval timers supplied the required time limits. The rest of the control circuit consisted of a synchronous timing motor and the necessary relays and switches.

Because of certain characteristics of the control circuit, *S* could occasionally go unreinforced on trials when he should have had feedback. This occurred on an average of about 5 out of 50 reinforced trials, but only when a response was terminated during the closing time on the finish relays on timers No. 1 or No. 2. A final feature of the control circuit was a set of switches which allowed *E* to withdraw the S^R lights and the counter and to prevent the "Go" light from reappearing at the end of a particular session.

Since no exteroceptive stimuli contingent upon actions of the electronic timers were available to the *S*, it was assumed that whatever cues functioned to terminate the response were produced by *S* himself. Although no audible sounds occurred during a response, single relay clicks could be heard at the beginning and at the end of each response. One other click sounded with the onset of the "Go" light. Although these clicks played no role in evoking response termination, the *S*s in this experiment frequently stated that the clicks helped them to be accurate. A study of this situation indicated that response rate quickly reached an asymptote just under the maximum possible and that *S*s used the clicks to space their responses. For most *S*s, responding soon became independent of the "Go" light. It was frequently necessary to stop them verbally at the end of an experimental session.

Procedure

Each subject was run on two separate sessions for about an hour on each occasion. On each occasion, each subject was given seven blocks of trials with 50 responses per block. Throughout each session, 50 trial blocks of estimation and training were given alternately. The first and last 50 trial blocks during each session were unreinforced estimation blocks. For this experiment, $t_1 = 0.90$ second. This was the least amount of time the trigger had to be held back in order to obtain a "Hit." The Δt was 0.20 second. Thus, *S* was reinforced with a "Hit" during training trials for R-durations which fell between 0.90 and 1.10 seconds. Short breaks were given between blocks of trials.

Instructions. At the beginning of the experiment, each *S* was read instructions in the use of the ergograph for giving estimations of a 1-second interval. The lights on the information panel were explained, and *S* was allowed several practice trials with the reinforcement lights turned off. Every effort was made to put *S* at ease and to inform him of the purpose of the experiment; *S* was told that he could respond at any time after the "Go" light came on, and that he could reset the counter during the breaks if he wished.

Table 1
Means and Standard Deviations of Three Individuals During Two Experimental Sessions in Blocks of 25 Responses

Session 1

		E		*T*		*E*		*T*		*E*		*T*		*E*	
LJD	M	3.80	5.02	1.47	1.00	.92	1.00	.93	.92	.91	.90	.89	.92	.81	.64
	SD	.84	1.06	1.17	.83	.96	1.19	.20	.18	.15	.15	.11	.13	.11	.11
SEM	M	1.36	1.43	.94	.98	.93	1.00	.93	.92	1.14	1.27	1.02	1.01	1.11	1.28
	SD	.45	.19	.23	.12	.12	.20	.22	.13	.17	.22	.10	.07	.25	.05
JHB	M	.80	.83	.89	.92	1.13	1.19	1.01	.94	1.11	1.15	.96	.96	1.04	1.06
	SD	.12	.14	.13	.09	.13	.19	.12	.09	.11	.08	.08	.06	.09	.07

Session 2

		E		*T*		*E*		*T*		*E*		*T*		*E*	
LJD	M	.84	.78	.88	.93	.88	.82	.89	.91	1.02	.99	.94	.94	.91	.82
	SD	.14	.11	.12	.13	.12	.10	.08	.21	.09	.10	.12	.09	.08	.10
SEM	M	.78	1.05	.92	.92	1.01	1.02	.92	1.00	1.09	1.14	.95	1.01	1.06	1.15
	SD	.14	.14	.09	.07	.18	.12	.05	.08	.10	.10	.06	.06	.04	.12
JHB	M	1.10	.99	.98	.97	1.03	1.02	.99	1.01	.98	1.08	1.01	.97	1.00	1.02
	SD	.19	.06	.11	.04	.06	.06	.09	.05	.04	.05	.07	.05	.08	.06

E = Estimation trials, uncorrected and unreinforced.
T = Training trials.

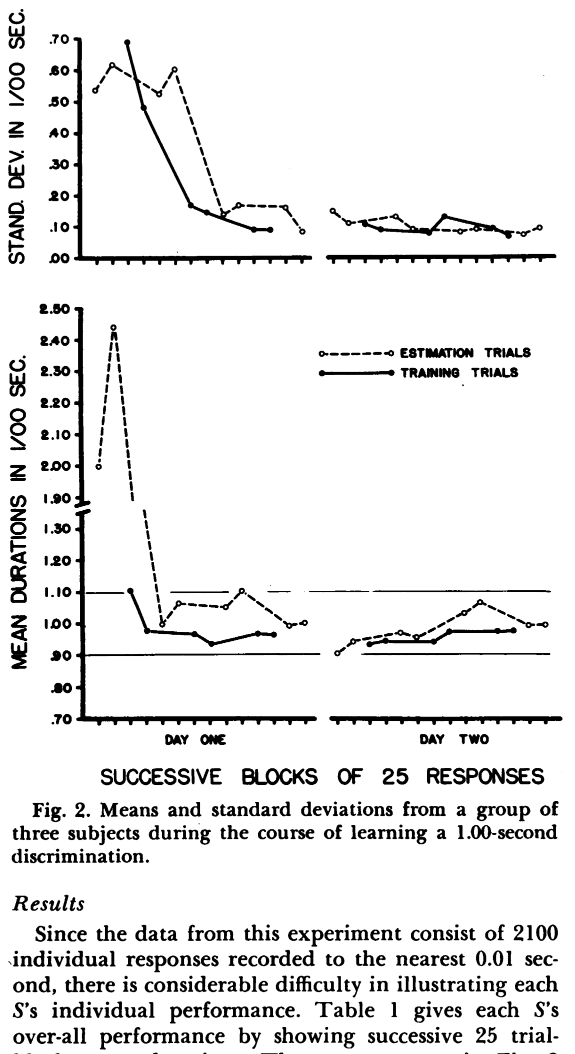

Fig. 2. Means and standard deviations from a group of three subjects during the course of learning a 1.00-second discrimination.

Results

Since the data from this experiment consist of 2100 individual responses recorded to the nearest 0.01 second, there is considerable difficulty in illustrating each S's individual performance. Table 1 gives each S's over-all performance by showing successive 25 trial-block mean durations. The upper curves in Fig. 2 show standard deviations for training and estimation trials throughout the two sessions of the experiment. These standard deviations are taken from successive blocks of 25 trials and represent the over-all performance of the three subjects taken together. Learning, as represented by the decreased variability on training trials, was quite rapid. Lagging somewhat behind this was the variability demonstrated on estimation trials. By the second session, however, variability of both training and estimation trials had reached a low level, and response-duration variability without feedback was hardly greater than the variability with feedback. The lower curves in Fig. 2 illustrate the mean performance for all three Ss on successive blocks of 25 trials. It may be seen that the average performance of the three Ss was well within the "Hit" range. The three Ss showed great divergence of their mean estimation of a 1-second interval in the initial estimation trials. The lower curves of Fig. 2 show that in general there is a slight upward drift in response duration during the estimation blocks. There is also a slight upward drift in over-all performance on the estimation trials in the second experimental session. This upward drift was typical of two of the three Ss. It is to be concluded from the data in this experiment that the variability observed in the estimations of a 1-second interval may, through training, be cut by a factor of at least 6. Under the conditions used in this experiment, approximately 70% of the S's unreinforced responses fell within a 0.20-second range around 1 second. The elapsed time between Session 1 and Session 2 for each S was as follows: LJD, 24 hours; SEM, 6 days; and JHB, 44 days. Table 1 shows that there was very little loss of the differentiation over a considerable period of time. All of the essential features in these data have been repeatedly found in the data gathered from other Ss under slightly different conditions.

EXPERIMENT II

Method

In order to evaluate the effects of the parameter t_1 on relative accuracy, a second experiment was run using two well-practiced laboratory workers as Ss. The initials of these Ss were JIT, male, age 30, and APC, male, age 27. The apparatus and general situation in this experiment were the same as in the first one except that no estimation trials were run. Each day for 6 days, the Ss practiced on a new interval, giving 300 to 400 reinforced responses per day. Short breaks were taken between each block of 50 trials. The six intervals which were used (values of t_1) were 0.50, 1.00, 1.50, 2.00, 3.00, and 5.00 seconds. Data on a seventh interval, 0.20, were also collected; but since the behavior of the apparatus was slightly erratic at this short interval, these data are not included. The "Hit" range, Δt, for each t_1 was a constant fraction of t_1. The fraction arbitrarily selected was 1/10. For example, a t_1 of 1.00 had a Δt of 0.10 added to it, and a t_1 of 5.00 had a Δt of 0.50 seconds added to it. Each S practiced the six intervals in a different random order.

Results

Figure 3 shows the results of this experiment by graphing coefficients of variation as a function of t_1 for each of the two Ss. The coefficient of variation is defined as the standard deviation divided by the mean, multiplied by 100. This is a measure of relative variability, not of absolute variability. It makes possible a comparison of the variability of timing performance for different values of t_1, considering that the absolute values of the standard deviations would automatically increase with increases in t_1. Guilford (1956) and Edwards (1950) both recommended that the coefficient of variation be used only for scales having an absolute zero; also, when this condition is met, as it is with the time scale, the coefficient is especially

well suited to the representation of psychophysical data. Weber's Law would predict that coefficients of variation would yield a straight line as a function of stimulus intensity. In other words, the "j.n.d." as inferred from an expression of relative variability would be constant. The dotted lines in Fig. 2 represent the coefficients of variation taken from the first 25 training trials at each value of t_1. It can be seen that for both *Ss*, relative variability is much higher for these early training trials and that the coefficient is much smaller for the 5.00 value of t_1 than it is for value 0.50. There is an over-all decrease in early training coefficients of variation from small values of t_1 to the larger values. If similar curves for a number of *Ss* were to be added together, the resulting curve would undoubtedly be very similar to the usual empirical Weber function found in studies of stimulus discrimination. It remains a question whether or not the curve of early-training trial coefficients would begin to rise again above the values of t_1 greater than 5.00. The solid lines in Fig. 2 show the curves for *last* blocks of 25 training trials for each *S*. These curves represent a well-practiced performance at each value of t_1. Again, for the well-practiced trials, the relative variability declines with increases in t_1. However, this decline is not nearly so marked, and the curves for well-practiced trials are closer to those that would be required by Weber's Law. Although this is a study in response differentiation and not a study in stimulus discrimination as in the usual psychophysical experiment, the data indicate a strong similarity between the two paradigms. It should also be noted that there were marked individual differences between the two *Ss* in this experiment. During both early and late training trials, APC consistently demonstrated lower coefficients of variation. It is of interest to note that APC has since been observed to use approximately twice the amplitude of finger movement shown by JIT. Kymographic records from a number of different *Ss* reveal that response amplitude shows great interindividual variation but little intraindividual variation. A further analysis of amplitude data is in preparation.

DISCUSSION

The most crucial problems of psychophysics have involved the elaboration of "measurement" scales for subjective phenomena and the relationships of these scales to physical scales of stimulus quality and intensity. Although the role of experimental factors in the production of psychophysical data has concerned theorists in the field, few attempts within the context of psychophysics have been made to sharpen sensory discriminations through experimentally arranged learning. The experiments reported in this paper do not, of course, illustrate "discriminative capacity" any more than studies in psychophysics. Perhaps they illustrate again the futility of the search for it. If one accepts the proposition that the timing response measured by the present technique results from a sensory discrimination, one still might argue that this type of discrimination is far more susceptible to modi-

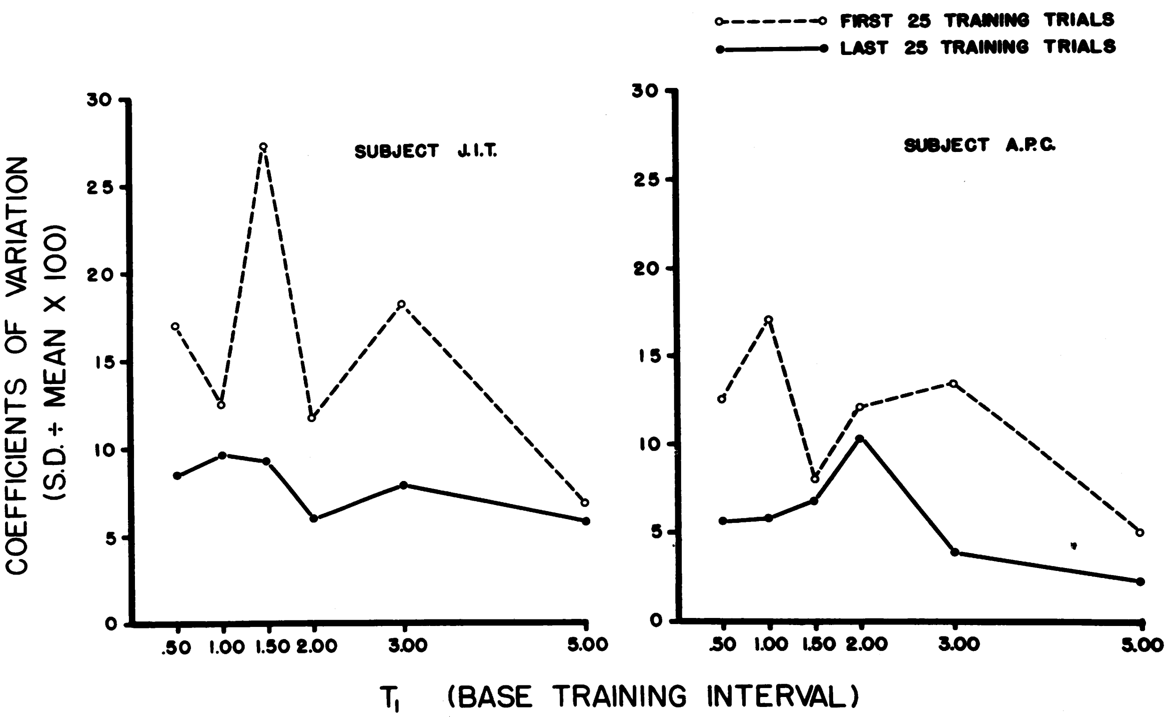

Fig. 3. The relative variability of temporal discrimination in two subjects as a function of the interval discriminated.

fication through learning than are discriminations of visual or auditory variety. Such an argument has logical merit, but the rejection of the timing response as representative of sensory discrimination in general might lead to the neglect of a number of important issues. It is well recognized that vision and audition carry into the experimental situation a much heavier experiential load than does the "time sense," and they are relatively "precise" modalities. For these reasons alone, they should show much lower relative variability. Visual and auditory discriminations are heavily and differentially reinforced under the normal conditions of life, whereas temporal judgments are not. A second consideration is that methods of production, of which the present technique was a special case, typically yield greater variability than comparison methods. A visual task analogous to the timing task reported in this paper would be one in which *S* adjusts the brightness of a light to fall within preselected tolerances. In such a task, *S* would be differentially reinforced as his response was isomorphic with the criteria, and his discriminative ability would be, to a large extent, a function of the restrictions imposed by *E*.

A further point concerns a common observation made in the psychophysics of sensation. Judgments at extreme values of the physical stimulus continuum are relatively more crude with respect to stimuli in the mid-ranges; *i.e.*, Weber's Law does not hold precisely throughout the range of perceptible stimulus values. The increase in judgmental variability that occurs with movement away from the stimulus mid-range may be due to structural sensory mechanisms or to the small amount of experience *S*s usually have had with the more extreme stimuli. In more functional terms, an organism would profit much by avoiding dependency upon extremely intense or difficult-to-perceive stimuli and stimulus differences. A reasonable position to take, in advance of an adequate analysis of the whole problem, would be to assume that both variables (structure and experience) play an important part in producing the phenomena. Any conclusions about the discriminative capacity of a human organism based on psychophysical data should be restricted to relatively untrained *S*s. The difference between trained and untrained estimation is quite evident in the data presented here. The many tests of Weber's Law which have been made for the different modalities are, in this sense, not tests of anything approaching discriminative capacity. The usual psychophysical method involves the use of a standard stimulus applied prior to the appearance of the discriminative response. This procedure is somewhat analogous to backward conditioning, a situation in which little learning has ever been found to occur. Our studies of timing behavior differ from this procedure in that they present, in effect, the standard stimulus after the occurrence of the response. This is essentially the same operation used in operant successive approximations or differential reinforcement.

A number of considerations lead one to suppose that no single pattern or source of stimulation could be isolated as the essential one in accounting for timing accuracy. Even within a single methodology, since a notion of response-produced cues is so difficult to define, it is difficult to assume that all *S*s draw upon the same sources of stimulation. One *S* might "fill" his interval with a pattern of visual exploration of the surround, whereas another might use counting, distractions of various sorts, and even pulse beats. Since it seems worthwhile to attempt to isolate the immediately prior stimuli connected reflexively with the termination response (R_3), new experimental designs and techniques will probably be needed and a psychology of the individual organism will be most profitable. The advantage of such an analysis would, perhaps, be a more unified theory of learning. Further problems in human timing behavior which are currently under analysis concern the value Δt as it affects reinforcement rate and as it is related to other parameters. The problem of individual differences in timing accuracy would traditionally be eliminated by averaging curves of different *S*s; but by extending the analysis of timing behavior to other dimensions such as the amplitude of the finger movement and the latency to the signal light, these individual differences themselves may yield information about the sorts of stimuli functioning to provide accuracy in timing. Although the problems raised by the question of stimulus origin in timing are complex and important to theory and experimental design, a still more important point for behavioral science is that timing, as a human skill, is subject to remarkable modification and improvement. Conditions affecting the learning of the timing response and the relationship between stimulus contingencies and accuracy remain largely unexplored. Analysis at this level should prove fruitful even in the absence of a detailed knowledge of stimulus origin.

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