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Simple reaction time as a race between signal detection and time estimation: A paradigm and model*

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A new paradigm for simple reaction time is described in which signal detection and time production trials are interleaved. A model is proposed which views the signal detection and time production processes as independent and engaged in a race whose outcome determines the observed response latencies. The model also allows the distribution of detection latencies to be extracted from the data.

The ultimate objective of most simple reaction time (RT) experiments is to obtain an index of the detection time for a signal. A typical simple RT trial consists of a warning signal, followed by an action signal to which the S is instructed to respond as quickly and as accurately as possible. Since the simple RT situation does not involve a choice in either the signal or the response, the requirement for accuracy is equivalent to an instruction to avoid premature or anticipatory responses. The S achieves speed by using any of the information in the task which enables him to respond within the time criteria of the experiment: this information is drawn from two principal sources. The first is the very occurrence of the signal itself; the second is the point in time at which the signal occurs or at which the S estimates that the signal will occur. Given the original objective of the experiment, the S's reliance on temporal information may be viewed as contaminating or distorting the detection time index which is being sought.

Two experimental paradigms have been developed with the aim of eliminating or minimizing the role of temporal information in such tasks: the catch trial and the distributed foreperiod procedures (Woodworth, 1938). With the catch trial procedure, the duration of the foreperiod (i.e., the time between the warning and the action signal) is usually held constant for a block of trials and the action signal is omitted on a proportion, p, of the trials; the latter constitute the catch trials on which the S is instructed not to respond. With the distributed foreperiod procedure, the action signal is never omitted and the duration of the foreperiods, instead of being held constant, varies from trial to trial in accordance with a predetermined distribution. Data with the catch trial procedure vary systematically with p (the probability of a catch trial) and the duration of the foreperiod (Gordon, 1967; Carterette, Friedman, & Cosmides, 1965). The distributed foreperiod procedure generates data which vary systematically with the particular distribution of foreperiods as well as with the duration of the foreperiods themselves (Drazin, 1961; Karlin, 1959; Klemmer, 1956; Nickerson & Burnham, 1969). Neither procedure, therefore, succeeds in either eliminating or in separating those responses which are time determined from those which are signal determined. A paradigm and model which attempts to effect such a separation will now be described.

A NEW PARADIGM

The experimental paradigm is a variant of the catch trial procedure, together with a simple model which

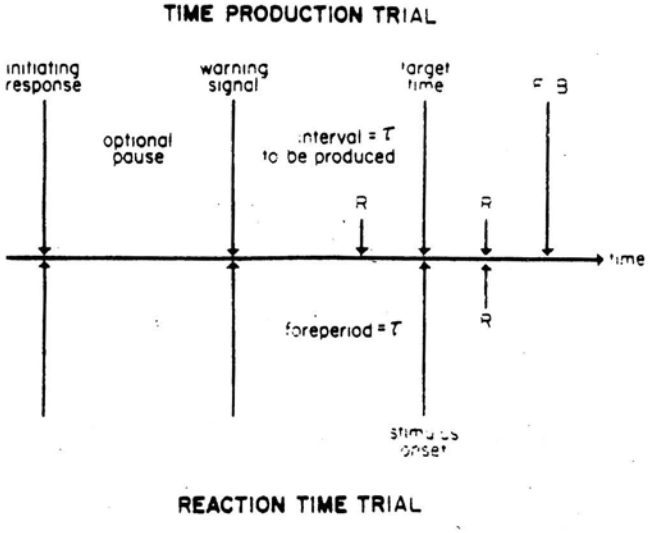

Fig. 1. Event sequence for a single trial of the experimental paradigm showing both a time production trial and a RT trial. If a response were to be made prior to the stimulus onset during a RT trial, then the stimulus would not be presented on that trial.

*A preliminary report on this work was first presented at the Advanced Research Seminar on Temporal Mechanisms in Psychological Processes held at the University of Michigan, Ann Arbor, in June 1969. At that time, similar results were reported by Robert T. Ollman, who had developed them independently at the Bell Laboratories in Holmdel, New Jersey. A further report was also presented by the author and B. Lawrence at the Psychonomic Society meetings of November 1969. This paper has benefited from numerous discussions with J. C. Falmagne. This research was supported in part by NSF Grant GB-30644.

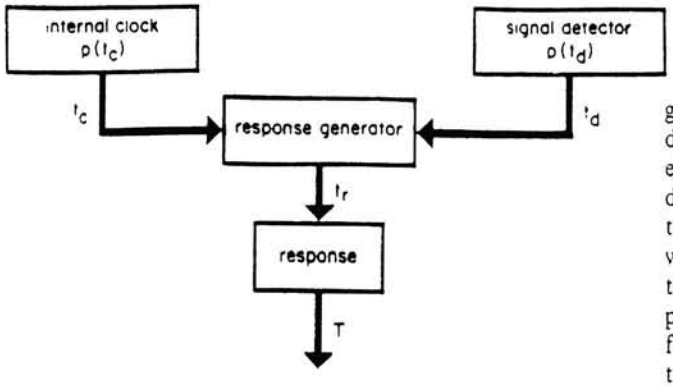

Fig. 2. Graphic representation of the race model, where $T = \min(t_c,t_d) + t_r$.

provides the rationale for the analysis of the data. A typical trial is illustrated in Fig. 1, with the top half representing the event sequence in a time production trial and the bottom half representing the events in a simple RT trial.

Every trial is started by the S with an *initiating response*. This response is followed by, or coincident with, a *warning signal*. The S's task is to estimate the passage of a predetermined interval of time from the onset of the warning signal and to press a key to coincide as closely as possible with the termination of that interval. That is, if the interval is τ sec, the S's task is to press a key when he estimates that precisely τ sec have elapsed since the warning signal. That keypress response may either exceed or fall short of the target time. In either case, *feedback* (FB) is given after each response. If the response exceeds the target time, then either an *action signal* is presented at time τ or no action signal is presented on that trial. If the response falls short of the target time, then no signal is presented. Thus, even though an action signal may have been scheduled for presentation on a particular trial, it may in fact have been omitted if the S's response anticipated the signal. Trials on which an action signal is scheduled for presentation are called *RT trials*, irrespective of when the S makes his response, i.e., whether or not the action signal was actually presented. Trials which do not call for an action signal are called *time production trials*.

These two types of trials are presented in random order, with probability, p, and $(1 - p)$ in a sequence of trials. The S, of course, has no indication of which type of trial is to occur when he makes the initiating response. Thus, when no signal is presented, it may be a time production trial or the early phase of a RT trial. However, at the time the action signal is presented, S knows that his estimate on this particular trial exceeded τ and that he must press his key as quickly as possible. The distribution of responses on *RT trials* will, therefore, include signal detection and time estimation responses. These data are analyzed in terms of the following simple model.

A MODEL

Three processes are postulated: (1) a response generator, (2) an internal clock, and (3) a signal detector. The response generator is triggered by a pulse either from the internal clock or from the signal detector, *whichever of the two gets there first*. Once triggered, the response generator emits an overt response with a constant time lag, t_r. An overt response is, therefore, viewed as the outcome of a race between a pulse coming from the internal clock and a pulse coming from the signal detector (if any). Associated with these two pulses are two probability distributions, $p(t_c)$ and $p(t_d)$ for the clock and signal detector, respectively. The model is illustrated in Fig. 2.

By assumption, the measured overt response time, T, is given by:

$$T = \min(t_c,t_d) + t_r \tag{1}$$

where T is a random variable whose value on any one trial corresponds to the observed time (t_r is assumed to be constant and will be dropped from further consideration).

It is assumed that the clock and the signal detector are independent, i.e.,

$$p(T > t) = p(T_c > t) \cdot p(T_d > t) \tag{2}$$

Now we define the following cumulative probability distributions:

$$F(t) = 1 - p(T > t) \tag{3a}$$

for all responses on trials where a signal was presented, i.e., all RT trials.

$$F_c(t) = 1 - p(T_c > t) \tag{3b}$$

for all responses whose observed time, T_c, was determined by a pulse from the internal clock.

$$F_d(t) = 1 - p(T_d > t) \tag{3c}$$

for all responses whose observed time, T_d, was determined by a pulse from the signal detector.

The function F(t) is, of course, given by the distribution of response times on RT trials and includes signal-determined responses as well as clock-determined responses. However, an estimate of the distribution of clock-determined responses, $F_c(t)$, is given by the response times on time production trials where no signal occurred. Hence, the function $F_d(t)$, which is the theoretical distribution of detection times, can be calculated. Since we assumed that the internal clock and the signal detector were independent and that the observed time, T, was the minimum of the two:

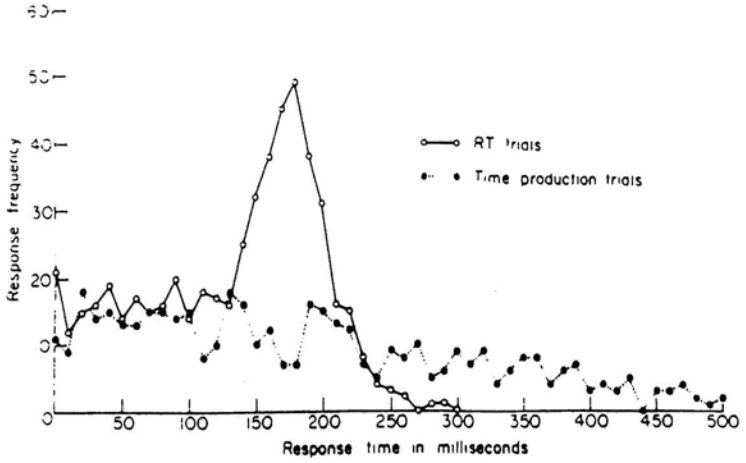

Fig. 3. Response frequency distribution for one S whose value of τ was set at 3 sec: only the responses that were made after the target time are shown: on the abscissa, the target time is labeled as zero rather than τ on this and all subsequent figures.

$$1 - F(t) = [1 - F_c(t)] \cdot [1 - F_d(t)] \quad (4)$$

or

$$F(t) = F_c(t) + F_d(t) - F_c(t) \cdot F_d(t)$$

it follows that

$$F_d(t) = \frac{F(t) - F_c(t)}{1 - F_c(t)} \quad (5)$$

PILOT RESULTS AND DISCUSSION

A series of pilot experiments have been conducted with this paradigm and model, with rather encouraging results. The probability of RT trials in all our experiments thus far has been 1/2. Figures 3, 4, and 5 illustrate the data for a S whose target time (τ) was 3 sec. The warning and action signals were two neon lights, and he was run on a sequence of 100 trials per day for 18 days. Figure 3 illustrates the response frequency distributions over time for time production and RT trials starting from time zero, i.e., from termination of the interval to be estimated, at which point the action signal was presented on the RT trials. It is quite clear that for the first 100-130 msec following the presentation of the action signal, the distributions of time production and RT responses are indistinguishable from each other. Following this initial lag, during which the signal appears to have had no overt effect, there is a rapid accumulation of responses for the RT trials while the time production responses gradually diminish in frequency; the mode of the RT distribution occurs at approximately 180 msec.

The cumulative distributions are plotted in Fig. 4. These plots are made on normal probability paper on which a straight line fit would provide strong evidence for an underlying normal distribution. The line that has been fitted through the points of the $F_c(t)$ distribution, i.e., the responses of time production trials, was made to go through the mean and the two points corresponding to the mean ±1 SD ($\bar{X}$ = 42 msec, σ = 230 msec). As can be seen, a straight line provides a reasonably good fit to the data, as one would expect from Michon's extensive work on time estimation and time production tasks (Michon, 1967). As can be seen in Fig. 3, the F(t) distribution begins to depart from $F_c(t)$ at approximately 140 msec after the presentation of the

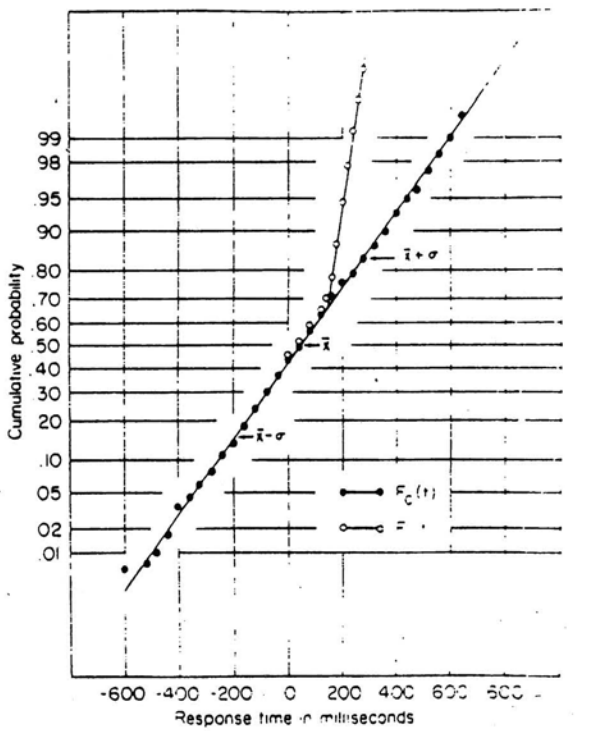

Fig. 4. Cumulative response probability distribution for RT[F(t)] and time production [$F_c(t)$] trials. Responses on RT trials that were made prior to the target time, i.e., prior to the occurrence of the action signal, are not shown since they are identical to the time production responses up to that point. The line that is drawn through the $F_c(t)$ points has been drawn through the points $\bar{X}$ and $\bar{X} \pm \sigma$; the line drawn for the F(t) points was fitted by eye.

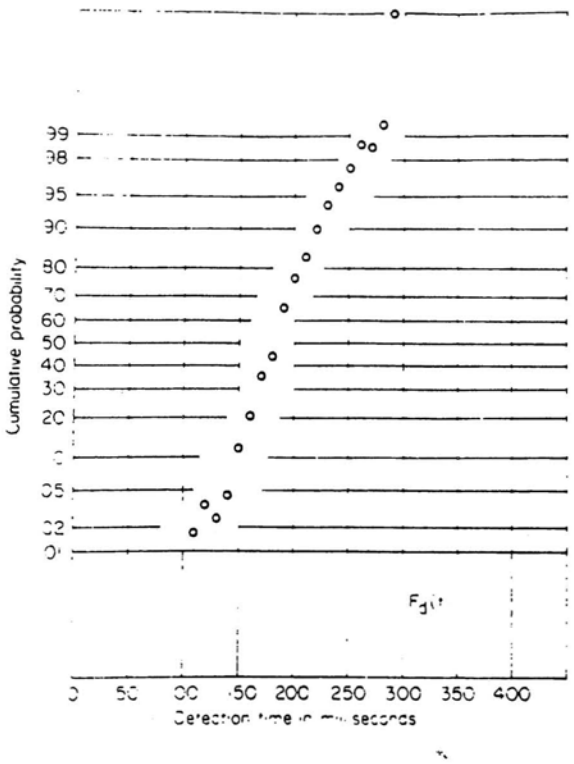

Fig. 5. The cumulative probability function for detection responses as derived by Eq. 5 (cf. text).

action signal and appears to be fitted reasonably well by a straight line beyond that point. This would suggest that the raw simple RT distribution may be normal; however, as has been pointed out throughout this discussion, the ordinary simple RT distribution, F(t), includes clock- as well as signal-determined responses. The next step, therefore, was to extract the distribution of detection times, $F_d(t)$, from these data according to Eq. 5 in the model. The resulting function is plotted on Fig. 5. The median of the $F_d(t)$ distribution is approximately 180 msec, with a standard deviation of about 27 msec and a starting point at about 110 msec. It is worth noting that this minimum value for the $F_d(t)$ distribution corresponds closely to the criterion that has often been used informally as a cutoff to separate anticipations from "true" reaction times. This cutoff is usually justified on the basis of latency measurements that have been obtained for the ERG, evoked potentials, and EMG in simple RT tasks (Bartlett & Bartlett, 1959; Bartlett, 1963; Monnier, 1952). However, the present paradigm and model provide *logical* grounds for distinguishing these two types of responses and eliminates the arbitrariness inherent in previous procedures. Furthermore, not only does the model deal with the problem of minimum detection times, but time-determined responses are presumably eliminated from the entire $F_d(t)$ distribution as well.

The general properties of the F(t), $F_c(t)$, and $F_d(t)$ distributions that have been obtained in this preliminary experiment have encouraged us to explore this paradigm further. Several Ss have, thus far, been run with auditory signals, various feedback procedures, and several payoff matrices, with target times of 2 and 6 sec. While their results are in general agreement with our initial findings, the median of the $F_d(t)$ distribution for a 2-sec foreperiod appears to be faster than for 6 sec for some Ss, although that difference did not exceed 10 msec for any S and the variances were virtually identical.

The paradigm has several potential sources of difficulty. Among these is the fact that with extended training, some Ss become extremely accurate in their time production responses, i.e., $F_c(t)$ distributions with means within 10 or 20 msec of time zero and standard deviations of 40-50 msec. Since this paradigm and model exploit the fact that a considerable proportion of the response distribution remains to be generated after time zero *and* that on RT trials some of these responses can then become associated with the signal detector, the closer the mean of the $F_c(t)$ distribution is to time zero *and* the smaller the variance of that distribution, the less the likelihood of obtaining signal-determined responses.

This difficulty is, of course, not unique to this paradigm; precisely the same problem arises with the catch trials procedure. For if a S is extremely accurate in estimating time and his distribution of time estimates has a small variance, he could set his target time at some point, t, after the actual time of arrival for the signal, and all his responses could, in principle, be clock- rather than signal-determined responses.[1] The advantage of our procedure in this regard is that *if* that is what the S is doing, the data will so indicate, unequivocally.

A further advantage of our proposed approach lies in the fact that the model attributes signal and time effects to different factors, and that the paradigm provides independent estimates of these factors. In principle, therefore, it should be possible to reexamine the relationship between foreperiod and simple RT which has been inferred from previous data and to interpret these results in terms of detection and time estimation processes. That is, to the extent that the ordinary simple RT distribution, F(t) in our context, includes responses that are clock determined, the foreperiod effect may simply be a consequence of the effects that temporal uncertainty has on $F_c(t)$, and the function $F_d(t)$ may well be found to be invariant for different time uncertainty conditions.[2] If such an invariance is not found in the data, it would suggest that the independence assumption (Eq. 2) needs to be modified.

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NOTES

1. cf. Ollman & Billington (1972) for further development of some aspects of the paradigm and model.

2. Such an invariance was also pursued by Snodgrass (1969), who devised an interesting experimental technique in which instructions were explicated as temporally narrow payoff bands.

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