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The detection of a temporal gap between two disparate stimuli*

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When a temporal gap is bounded by a light and a tone, gap detection performance as a function of gap duration is well described by a simple model which characterizes the discrimination as a purely temporal one. When the gap is bounded by two tones, performance is superior and seems to depend on the frequency difference between the tones, but is not well described by the same model. It is suggested that the light-tone performance represents the operation of a central temporal discrimination mechanism, while the tone-tone cases represent the use by Os of nontemporal cues originating in the peripheral auditory system.

The experiment reported in the present study is concerned with the effect on "gap detection" performance of the choice of stimuli used to bound a temporal gap. This matter is of some consequence, because investigators of human temporal resolution desire to distinguish the perception of time from the perception of particular time markers.

It will be useful to regard gap detection and gap duration discrimination tasks as involving the successive presentation of two stimuli, here denoted I and II. The termination of Stimulus I precedes the onset of Stimulus II by an interval, or gap, which is of zero duration on some trials in detection tasks. The O's task is to discriminate among values taken on by the variable of gap duration.

In some experiments, Stimuli I and II are identical in nature; in this case, the gap merely constitutes a brief interruption of stimulation. Alternatively, Stimuli I and II may be disparate; the gap then also marks the transition from one kind or degree of stimulation to another. Recent studies of gap discrimination with no disparity between the two stimuli include those of Theodor (1972), who employed visual stimuli, and Abel (1972), who employed auditory stimuli. Rousseau and Kristofferson (1973) have studied duration discrimination of gaps with bimodally disparate stimuli.

The degree of disparity between stimuli along intramodal dimensions, particularly tonal frequency, has recently received some study. Perrott and Williams (1971; Williams & Perrott, 1972) found that the detection of gaps between pulsed tones of differing frequencies improved as the difference between the two frequencies was decreased. Collyer (1971) reported that a frequency disparity somewhat larger than one critical bandwidth, appeared to be optimal for discriminating simultaneous from successive tone onsets.

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A problem with these findings as they bear on temporal resolution is that intramodal stimuli used to define short temporal intervals are probably not processed independently. For example, two tones may interact in the peripheral auditory system to produce the sensation of a complex sound, which then becomes the basis for discrimination between two stimulus patterns ostensibly differing only in the presence or absence of a gap between the tones. What appears to be a judgment of time then becomes, in fact, an auditory discrimination. For this reason, Sternberg and Knoll (1972) cautioned against the use of intramodal stimulus patterns in temporal order discrimination. The use of stimuli from two modalities is thought to provide better conditions for independent stimulus processing.

The present experiment documents the effect of stimulus disparity on gap detection performance with respect to intramodal and cross-modal choices of stimuli.

If the stimuli chosen to bound a gap are interchangeable, insofar as they are independently processed and provide good time markers to a central timing mechanism, then performance as a function of gap duration should be equivalent for conditions in which Stimuli I and II are tones of similar frequency, tones of very disparate frequency, or a light and a tone. However, if intramodal stimuli provide modality-specific bases for the discrimination which are more easily discriminated than the gap duration itself, then performance in the first two conditions would be superior to performance in the third.

To illustrate one interpretation of the central timing process, a model for duration discrimination developed by Allan (Allan, Kristofferson, & Wiens, 1971) is adapted for application to the present data. This model is one of a class of models, whose members differ mainly in their distributional assumptions, which attribute the O's response to a univariate statistical decision, the single variate being an internal representation of gap duration.

MODEL

The event "termination of Stimulus I" will be denoted x, and its real time of occurrence, t_x. The event "onset of Stimulus II" will be denoted y, and its real time of occurrence, t_y. The interval between Events x and y has duration $\Delta d = t_y - t_x$.

It is assumed thatthe internal representations of x and y, denoted x′ and y′, reach a central display area with independent "perceptual latencies" of a and b, respectively. The internal arrival times of x′ and y′ at the display area are then $t_{x'} = t_x + a$ and $t_{y'} = t_y + b$. It is assumed that a and b are uniformly distributed random variables with equal ranges and maxima of q msec. The value of q determines the O's temporal resolution, and may be thought of as the period of a central periodic process which provides opportunities for the entry of signals into the display area. The interval between arrivals of the two events is then

$$\begin{aligned} I &= t_{y'} - t_{x'} \\ &= t_y - t_x + (b - a) \\ &= \Delta d + (b - a). \end{aligned}$$

I is a random variable with a triangular distribution. This distribution spans one q unit above and one q unit below its mean, which is given by

$$\begin{aligned} E(I) &= \Delta d + E(b) - E(a) \\ &= \Delta d. \end{aligned}$$

A stimulus pattern in which there is no gap between Stimuli I and II will be denoted S_0; a stimulus pattern in which Stimulus I precedes Stimulus II by a gap of d_1 msec will be denoted S_1. In an experiment in which S_0 and S_1 are the only stimulus patterns presented, there will be two conditional distributions of the variate I which describe the O's temporal sensory activity:

$$E(I \mid S_0) = 0$$

$$E(I \mid S_1) = d_1$$

$$\mathrm{Var}(I \mid S_0) = \mathrm{Var}(I \mid S_1) = q^2/6.$$

One index of the O's temporal resolution capability would be

$$\begin{aligned} d_q &= \frac{E(I \mid S_1) - E(I \mid S_0)}{q} \\ &= d_1/q. \qquad (1) \end{aligned}$$

This quantity is analogous to d′ in signal detection theory. The denominator represents a convenient choice of scale, normalizing the quantity in units of q rather than in units of the standard deviation, $q/6^{1/2}$. An estimate of d_q will be developed from a consideration of the O's response rule.

On each trial, the evoked value of I is compared to a criterion value, C. An R_1 response (indicating that the O thought a gap was present) is made if $I > C$; otherwise, an R_0 response (indicating that the O thought a gap was not present) is made. In the model, then, the proportion, $\hat{P}$, of R_1 responses to S_1 (S_0) patterns is the proportion of the area under the S_1 (S_0) distribution lying above C. The estimated difference between C and $E(I \mid S_1)$ in units of q is a transformation of $\hat{P}(R_1 \mid S_1)$; the estimated difference between C and $E(I \mid S_0)$ is a similar transformation of $\hat{P}(R_1 \mid S_0)$. These estimated differences will be denoted $\hat{Q}(R_1 \mid S_1)$ and $\hat{Q}(R_1 \mid S_0)$, respectively. Then an estimate of d_q is

$$\hat{d}_q = \hat{Q}(R_1 \mid S_0) - \hat{Q}(R_1 \mid S_1).$$

Note that $\hat{d}_q$ has a maximum value of 2.0, associated with $\hat{P}(R_1 \mid S_0) = 0$ and $\hat{P}(R_1 \mid S_1) = 1.0$ [$\hat{Q}(R_1 \mid S_0) = 1.0$ and $\hat{Q}(R_1 \mid S_1) = -1.0$]; the usual minimum value of d_q is zero, associated with $\hat{P}(R_1 \mid S_0) = \hat{P}(R_1 \mid S_1)$. The measure $\hat{d}_q$ is predicted to be an increasing zero-intercept linear function of d_1 (Eq. 1). An estimate of q can be obtained from the slope of this function.

EXPERIMENT

Method

Subjects. Two graduate students and a senior undergraduate at McMaster University served as Os in the experiment. All three had had previous experience as Os in psychophysical tasks.

Apparatus. The experiment was controlled by a Digital Equipment Corporation PDP-8/E computer with software written by the author for the purpose. Auditory stimuli were pure tones generated by two Hewlett-Packard audio oscillators, and presented to the O at about 65 dB SPL via crystal headphones. Switching of audio signals was done with a rise-decay time of 2.5 msec by two Grason-Stadler electronic switches. The ambient noise level in the O's room was about 48 dB SPL. The visual stimulus consisted of the illumination of a glow modulator tube with rise and decay times in the microsecond range. Effective luminance of the tube was about 4 fL. An electric horn was constructed to serve as a warning signal during one condition of the experiment.

Procedure. An O, wearing headphones, sat in a darkened room facing a viewing tunnel, at the end of which a glow modulator tube was mounted. A trial of the experiment began with the onset of Stimulus I, whose duration was 1,500 msec. A brief (100 msec) warning signal was presented after Stimulus I had been on for 500 msec. The warning signal was visual (glow tube) if Stimulus I was auditory, and auditory (horn) if Stimulus I was visual. Stimulus II followed Stimulus I either immediately (S_0) or after a gap of d_1 msec (S_1). Stimulus II was terminated by the O's response, made by pressing one of two buttons corresponding to R_0 or R_1. The O's response immediately initiated the next trial.

Three conditions were defined by the assignment of a particular stimulus to the role of Stimulus I in the trial structure. In all conditions, Stimulus II was a tone of 2,000-Hz frequency. In Condition ST (similar tones), Stimulus I was a tone of 2,130 Hz; in Condition DT (dissimilar tones), Stimulus I was a tone of 5,300 Hz; in Condition LT (light and tone), Stimulus I was an illumination of the glow tube.

Table 1
$P(R_1|S_0)$ and $P(R_1|S_1)$ for Each of Three Observers Under Each Condition

	O	d_1 =	1	3	6	9	12	15	20	30	40	50	75	100	msec
Condition ST	D.D.	$\hat{P}(R_1|S_0)$	.47	.36	.37	.17	.20	.23	.10	.01	.04	.01	.01	.00	
		$\hat{P}(R_1|S_1)$	.49	.65	.72	.87	.91	.92	.95	.98	1.0	.99	1.0	1.0	
	C.C.	$\hat{P}(R_1|S_0)$	.55	.41	.25	.13	.13	.13	.09	.08	.03	.01	.00	.01	
		$\hat{P}(R_1|S_1)$	.49	.57	.79	.84	.93	.94	.95	.97	.99	1.0	1.0	1.0	
	A.P.	$\hat{P}(R_1|S_0)$	.59	.47	.31	.30	.26	.28	.12	.11	.07	.05	.01	.03	
		$\hat{P}(R_1|S_1)$	.51	.53	.65	.71	.77	.87	.89	.95	.98	.95	.97	1.0	
		d_1 =	5	10	15	20	30	40	50	75	100	125	150	175	msec
Condition DT	D.D.	$\hat{P}(R_1|S_0)$	.41	.38	.31	.17	.19	.04	.07	.02	.00	.01	.00	.00	
		$\hat{P}(R_1|S_1)$	.51	.57	.68	.75	.81	.95	.93	1.0	.99	1.0	1.0	1.0	
	C.C.	$\hat{P}(R_1|S_0)$	.52	.37	.35	.21	.15	.07	.07	.03	.04	.01	.00	.01	
		$\hat{P}(R_1|S_1)$	.52	.67	.69	.83	.91	.99	.99	.98	.99	1.0	.99	1.0	
	A.P.	$\hat{P}(R_1|S_0)$	.31	.35	.17	.20	.27	.21	.18	.19	.14	.12	.09	.07	
		$\hat{P}(R_1|S_1)$	.61	.63	.83	.78	.80	.92	.90	.90	.97	.99	.99	.99	
		d_1 =	5	10	15	20	30	40	50	75	100	125	150	175	msec
Condition LT	D.D.	$\hat{P}(R_1|S_0)$	.44	.51	.47	.51	.43	.31	.34	.13	.12	.06	.01	.01	
		$\hat{P}(R_1|S_1)$	.52	.47	.48	.49	.51	.69	.70	.80	.89	.90	.95	.99	
	C.C.	$\hat{P}(R_1|S_0)$	.55	.47	.47	.43	.40	.29	.19	.18	.11	.07	.02	.01	
		$\hat{P}(R_1|S_1)$	.55	.52	.61	.67	.69	.79	.82	.85	.91	.98	.97	1.0	
	A.P.	$\hat{P}(R_1|S_0)$	.46	.45	.51	.47	.46	.37	.35	.20	.19	.11	.17	.11	
		$\hat{P}(R_1|S_1)$	.56	.59	.57	.53	.57	.61	.75	.83	.95	.97	.99	1.0	

The values of d_1 chosen for Conditions DT and LT were 5, 10, 15, 20, 30, 40, 50, 75, 100, 125, 150, and 175 msec. Preliminary testing indicated that most of these values would yield asymptotic performance in Condition ST; accordingly, values of 1, 3, 6, 9, 12, 15, 20, 30, 40, 50, 75, and 100 msec were chosen for this condition.

Conditions and values of d_1 were blocked such that, within a series of 100 trials, only one condition and one value of d_1 were used. The 12 values of d_1 in each condition were used sequentially in a randomized order for each O, and three 100-trial blocks were run under each combination of condition and d_1 before the condition was changed. This procedure was followed to ensure that the Os would be maximally familiar with the stimuli of each condition during data acquisition, so as to minimize performance effects due to stimulus uncertainty.

Half of the trials in each block of 100 were S_0 trials (Δd = 0 msec), and half were S_1 trials ($\Delta d = d_1$ msec). The data collected consisted of the total number of R_1 responses to each trial type in each block of trials. Typically, Os completed four blocks of 100 trials during each daily experimental session.

Results and Discussion

The proportions of R_1 responses to each stimulus pattern, under each condition and value of d_1, are shown in Table 1 for the three Os. Each proportion is based on 150 trials. Discriminability was highest under Condition ST and lowest under Condition LT for all three Os. This nonequivalence of the three conditions is the central empirical result of the experiment.

Os reported that, in the ST and DR conditions, the transition from Stimulus I to Stimulus II was marked by auditory transients sounding like a "slide" from the frequency of the first to that of the second tone. This report lends credence to the suspicion that intramodal stimuli interact in ways which provide nontemporal cues to Os. If, indeed, such cues were available in this experiment, their effectiveness seems to have been related to the frequency similarity of the two stimuli. In the LT condition, we should presumably approximate most closely the independent-processing assumptions of Allan's model.

One problem with the LT data for Os D.D. and A.P. is that $\hat{P}(R_1 \mid S_1)$ does not clearly exceed $\hat{P}(R_1 \mid S_0)$ until d_1 exceeds about 30 msec. These Os reported that, at small values of d_1, they did not believe they could perform the discrimination, and sometimes "gave up" on the task. It was decided to forego either a threshold interpretation or a modification of the model's simple zero-intercept form, because this feature of the data is of minor importance relative to the comparison of experimental conditions. The theoretical analysis which follows indicates that the model still gives a good characterization of data from the LT condition.

The measure $\hat{d}_q$ is plotted as a function of d_1 in Fig. 1, for each O under each condition.

A value of $\hat{q}$ was chosen for each O and condition which minimized the squared vertical deviations of the $\hat{d}_q$ estimates from the function $d_q = d_1/q$. These values of $\hat{q}$ and the associated proportions of variance in $\hat{d}_q$ accounted for by the model are given in Table 2.

The LT condition appears to be well described by the model for all three Os; there is a consistently good fit to the data, and q is of roughly the same magnitude for each individual. Zero-intercept straight lines also seem to characterize at least two of the other sets of data also. However, the overall patterns of results from the ST and DT conditions seems to indicate systematic departures from linearity: all deviations from the predicted functions as they approach d_q = 2.0 are negative, and represent a major component of the residual variation about the function in all six cases.

Perhaps more important, in terms of Allan's model, is the interpretation of q as a psychological constant: it is

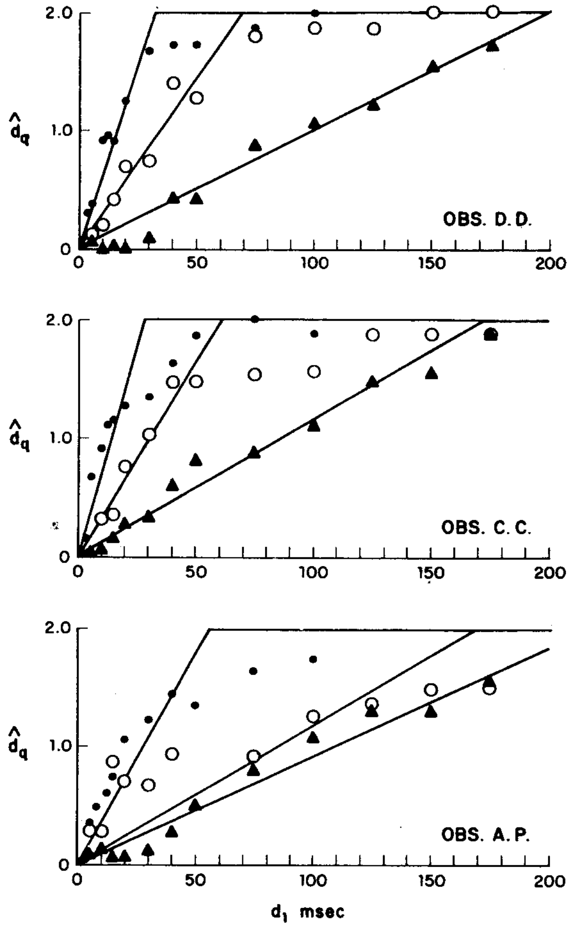

Fig. 1. Estimates of $\hat{d}_q$ (points) and predicted d_q (lines) for each O under each condition. Filled circles, ST; open circles, DT; triangles, LT. There are 300 observations per data point.

clear that the ordering of conditions by discriminability is reflected in the estimates of q from each. This, of course, implies that, if the value of $\hat{q}$ obtained from one of the conditions is accepted as a valid estimate of q, then the values of $\hat{q}$ obtained from the other conditions are not estimates of the same thing. If different discrimination mechanisms are responsible for ST and DT than for LT performance, then it would be inappropriate to reject the model's interpretation of central timing on the basis of the differences in performance among these conditions. On prior grounds, it was suspected that the LT condition would better satisfy the assumptions of the model than would the intramodal conditions. The LT data do agree better with the model's linearity prediction than do the intramodal conditions. However, if the model is to be accepted for the LT condition, then it must be discarded for the intramodal conditions because of the assumption that q is a constant.

Table 2
Least-Squares Estimates of q and Proportions of Variance Accounted for in Applying Allan's Model to Each Condition

Condition	O	$\hat{q}$	Proportion of Variance Accounted For
	D.D.	16	.917
ST	C.C.	14	.822
	A.P.	28	.841
	D.D.	34	.963
DT	C.C.	30	.888
	A.P.	84	.093
	D.D.	102	.967
LT	C.C.	90	.977
	A.P.	108	.962

Elaborations of this analysis, and alternatives to it, are both possible. One elaboration would be to add the use of auditory cues to a model for purely temporal judgments. It appears from the data that intramodal performance is always at least as good as LT performance, and that the superiority is greatest at small values of d_1, where the greatest temporal overlap and hence interaction between events in the sensorium would be expected. However, because of the difficulty of representing these interactions, it is not clear how to develop such a composite model.

An alternative approach to the data is to treat the three conditions as points on a continuum of stimulus disparity, equivalent to psychological "distance" in a multidimensional "stimulus space" (cf. Moray, 1969). Temporal comparison of two stimulus events may depend on the traversing of this distance by the central timer, such that the greater thedistance, the more difficult the comparison. This notion requires more specification to become tractable.

The Allan model is probably not the only one which would support the claim that LT performance reflects a central judgment of temporal magnitude, while ST and DT performance is based on mixed temporal and auditory cues; however, it does seem that there are differences in the form of the discriminability functions between the two cases, which the model helps to reveal.

In conclusion, the effects of stimulus assignment on gap detection are profound. Performance when the gap is bounded by two tones is markedly superior to performance in the light-tone case. Furthermore, the frequency disparity between tones in the intramodal case seems to figure in the discrimination; this is interpreted as further evidence that auditory cues provide a basis for judging the presence or absence of a gap in the stimulus pattern. Finally, the theoretical analysis lends support to the belief, shared by other investigators, that cross-modal stimulus pairs are to be preferred where an assumption of independent stimulus processing is made.

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