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# Duration discrimination of empty time intervals marked by intermodal pulses

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In 1973, Rousseau and Kristofferson reported that short empty intermodal time intervals marked by a light flash and a brief tone were poorly discriminated by subjects, and that $\Delta T_{75}$ was constant over a large range of durations. It led them to suggest that short intramodal empty intervals, marked by stimuli from the same sensory modality, might be handled by a "more efficient mechanism" to which intermodal intervals would not have access. Unfortunately, their study lacked the basic evidence needed to make a strong statement: no direct comparison between inter- and intramodal duration discrimination and no within-subject discrimination function were available. To clarify these two issues, three experiments were performed. The data indicate that intermodal time intervals are discriminated more poorly than intramodal ones, and that intermodal duration discrimination functions follow Weber's law. Analysis of data from different experiments lead to the conclusion that inter- and intramodal intervals are timed by a common timekeeper and that intermodal intervals induce a large noise component in the timekeeping operation.

There seems to exist a general agreement on the fact that when an observer is asked to discriminate between intervals of short duration, his performance is little affected by such stimulus characteristics as intensity, frequency, and bandwidth (Allan, 1979). More specifically, if the discrimination is performed on empty intervals marked by short auditory pulses, numerous studies have shown that, for intervals longer than 100 msec, performance is not sensitive to variations in marker intensity (Abel, 1972; Carbotte & Kristofferson, 1973; Divenyi & Danner, 1977; Penner, 1976), frequency or spectrum (Divenyi & Danner, 1977; Divenyi & Sachs, 1978), and duration (Abel, 1972; Carbotte & Kristofferson, 1973; Penner, 1976). Moreover, within the range of 0-100 msec, Nilsson (1969) and Oostenbrug, Horst, and Kniper (1978) have shown the performance to be relatively insensitive to changes in the energy of light pulse markers.

Although these results are of parametric interest, their importance lies in the support they bring to the basic postulate of psychophysical models of duration discrimination, namely, that temporal information is a function of the temporal extent of the stimulus and not of other stimulus parameters. That is, in order for the duration of an interval to be available for psychophysical analysis, it must be put forward that there is an orderly relationship between a stimulus duration and its internal transform. In general, discrimination models consider that the encoding of temporal extent is performed by a central timekeeper common to visual and auditory modalities (Allan, 1979). Most current models do assume that duration information is obtained through the accumulation, over the extent of the interval, of pulses originating in some central source (Abel, 1972; Creelman, 1962; Divenyi & Danner, 1977; Kinchla, 1972; Thomas & Brown, 1974; Treisman, 1963). Although some models (Creelman, 1962; Divenyi & Danner, 1977) have formally defined parameters representing nontemporal stimulus variables, their theoretical importance has remained very minor in view of the empirical evidence. This well-documented lack of influence of nontemporal stimulus parameters on duration discrimination has commonly provided a support for the existence of the central timekeeping device. However, more direct evidence is rather scarce; Allan (1979) only refers to Eijkman and Vendrik (1965), Loeb, Behar, and Warm (1966) and Warm, Stutz, and Vassolo (1975). These studies are extremely different methodologically from one another (none being a discrimination experiment), and they base their conclusions on evidence of transfer or correlation between visual and auditory modalities in judgments of stimulus duration.

A more direct way to gain access to the central timekeeper would be to reduce to a minimum the sensory support of the time intervals to be discriminated. Studies in temporal order judgments have already made use of intermodal signals in order to minimize sensory interactions (Collyer, 1974; Sternberg & Knoll, 1973). Unfortunately, reports on duration discrimination of intermodal intervals are almost inexistent and provide very little information.

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Fraisse (1952) ran an experiment in which a brief stimulus was presented between a pair of tones separated by 1 sec, thus forming two adjacent intervals. His results showed that the interval of uncertainty was three times larger when the middle pulse was a light rather than a tone. Rousseau and Kristofferson (1973) used empty intervals marked by a light flash and a brief tone in a series of duration discrimination experiments. Because theirs was the last published report available on the subject, it will be the point of departure for the studies to be reported in the present paper. They ran four groups of subjects who were required to tell if the single interval presented on each trial was the short one (base duration, T) or the long one (comparison interval, T + dt). A different base duration value was assigned each group, and, from the psychometric function, the difference in duration between base duration and comparison intervals needed to reach a correct response on 75% of the trials, $\Delta T_{75}$, was estimated for each individual subject. The main conclusion was that base duration had no effect on performance since $\Delta T_{75}$ was constant around 165 msec. This is in clear contradiction of psychophysical theories of duration discrimination involving a stochastic counter (e.g., Creelman, 1962), but supports the quantal theories described in Allan and Kristofferson (1974). Moreover, the averaged Weber ratio was 1.64 at T = 100 msec, which is extremely high in comparison with empty auditory intervals in which the ratio is around .25 (e.g., Abel, 1972, Table II) and even as low as .1 (Getty, 1975) for values of T around 100 msec. On the other hand, the ratio of .08 obtained at T = 2,000 msec is very close to the auditory data.

Since intermodal intervals are assumed to enable access to a central timekeeper, such a large discrepancy in discrimination performance level between inter- and intramodal intervals could be detrimental to theories proposing that duration discrimination is handled by a central timekeeper common to all modalities. Rousseau and Kristofferson (1973) suggested that long intervals could be timed by a given mechanism and shorter intervals by another, more efficient one, and that short intermodal intervals did not have access to that efficient timekeeping device. The inclusion of two timing mechanisms would greatly complicate psychophysical theories of duration discrimination.

However, the impact of the Rousseau and Kristofferson data is somewhat lessened by two methodological weaknesses. First, there is a definite possibility that the intermodal performance could be linked to the use of a light-flash marker and not to the intermodal characteristic of the interval. When compared with auditory signals, light-flash signals have classically been shown to trigger slower reaction times and to have a longer central latency. Furthermore, judgments about the duration of a light signal are less accurate and more variable than those about auditory signals (Allan, 1979). Consequently, it could very well be that a light pulse is not an efficient way to mark a temporal interval and that it therefore decreases discrimination performance in L-T intervals. If this were the case, L-L intervals should induce a level of performance comparable to and or worse than intermodal intervals. Unfortunately, no data is currently available on duration discrimination of empty visual intervals for T values longer than 100 msec. This raises the need for intermodal data obtained with an experimental design that includes intramodal visual and auditory empty intervals. Secondly, because different groups of subjects were used at each T value, the stability of $\Delta T_{75}$ has to be reevaluated. A within-subject discrimination function would go a long way in strengthening that observation.

So the present series of experiments was carried out in order to clearly establish the importance of markers originating in different modalities in accounting for intermodal duration discrimination performance. More specifically, the two major observations made by Rousseau and Kristofferson will be investigated: (1) there is a significant difference between intermodal and intramodal duration discrimination at short T values, and (2) there is no effect of base duration on $\Delta T_{75}$ in intermodal duration discrimination.

## GENERAL METHOD

### Subjects

All subjects were young adult volunteers paid for their participation.

### Apparatus and Stimuli

Each subject was run in an individual sound-attenuated test chamber. Usually there was a single session per day, although on some occasions there were two. The sessions lasted about 40 minutes each, and were subdivided into three blocks for Experiments 1 and 2 and into two blocks for Experiment 3.

A trial started with a 500-msec visual warning signal, followed, after a 1.5-sec foreperiod, by an empty time interval marked by two 10-msec pulses. The subject then gave a response by depressing one of two pushbuttons placed on the armrest of the chair. The trial was terminated by a 500-msec visual feedback signal.

The visual signals were presented from a display panel facing the subject at roughly 1 m. The warning signal and feedback signal were produced by flashing small tungsten lamps. The visual marker was a fast rise/decay pulse from a neon bulb (NE-40). The auditory marker was presented binaurally to the subject through TDH-49 earphones. It was the gated output of a signal generator with rise/fall times of 2.5 msec, frequency at 1 kHz, and average continuous amplitude of 70 dB at the ear. The total signal was generated by a series of Colbourn Instruments audio modules. The experimentation was completely under computer control (Digital Equipment PDP-8/F) with timing accurate up to the nearest millisecond.

### Procedure

The many-to-few version of the single stimulus method (Allan & Kristofferson, 1974) was used throughout the experiments. A set of n intervals ($t_1 \ldots, t_i \ldots, t_n$) was partitioned into two subsets of n/2 intervals, the short subset, $T_0$, and the long subset, $T_1$. These intervals were symmetrically distributed around a center duration value, called midpoint (MP), which was not a member of the set. On any trial, the subject was presented with a single duration value, $t_i$, and had to tell if it was a member of $T_0$, by emitting response $R_0$, or, conversely, a member of $T_1$, by emitting an $R_1$ response. Within a block of trials, each interval was presented an equal number of times in a pseudorandom sequence. The trial-to-trial feedback provided to the subject identified a given interval as being a member of $T_0$ or $T_1$. The computation of the Weber ratio was performed by assuming MP to be equivalent to T, the base duration.

## EXPERIMENT 1: THE COMPARISON OF INTRA- AND INTERMODAL INTERVALS

This experiment provides a direct comparison between intra- and intermodal empty-interval duration discrimination. The subjects were run under four different marker conditions (M conditions), tone-tone (T-T), light-light (L-L), light-tone (L-T), and tone-light (T-L). Furthermore, data were gathered for intervals around 250 and 1,000 msec (T conditions). Every individual was tested under each combination of duration × type of marker.

### Method

**Subjects.** Eight subjects participated in the experiment. They were volunteers paid $3/session.

**Procedure.** Each subject was run through 17 sessions, the first one being a practice session and the last 16, experimental sessions. The subjects were run for 8 sessions at each T value. Subjects 1, 2, 5, and 6 began with $T = 250$ msec and then shifted to $T = 1{,}000$ msec. The other four subjects, 3, 4, 7, and 8, were run in the reverse order. A session comprised four blocks of 70 trials. Within a block, all trials were of the same type, and over the session, each marker-type condition was associated with a different block. The order of presentation of the blocks was according to a balanced square design. Over 8 sessions, a subject would run through two cycles of a balanced Latin square, the last cycle providing the data considered in the analysis.

Within a block of trials, the subjects could be presented with one of two possible time intervals, $t_0 = T - dt$ and $t_1 = T + dt$. The dt was the same for all types of marker at a given T value: 25 msec for $T = 250$ msec ($t_0 = 225$ msec and $t_1 = 275$ msec) and 75 msec for $T = 1{,}000$ msec ($t_0 = 925$ msec and $t_1 = 1{,}075$ msec). For the practice session, $t_0$ was set at 400 msec and $t_1$ at 600 msec. The duration of the session was about 45 min, and one session provided 70 trials for each combination of T × M conditions.

### Results and Discussion

Individual equal-variance d′ were computed from $P(R_1 \mid t_i)$ for each session under each condition. The individual average of the last four sessions was then obtained. Table 1 shows these individual averages and group mean d′. An analysis of variance was run on the individual data following an RBF design (Kirk, 1968). As is often found in within-subjects designs, a significant difference was obtained between subjects [$F(7,49) = 29.9$, $p < .01$]. A very significant effect of type of marker was obtained [$F(3,49) = 142.9$, $p < .001$], and performance was not different between T values, quite likely due to the fact that $\Delta T$ was adjusted to each T value. Finally, the M × T interaction was significant [$F(3,49) = 24.17$, $p < .01$].

When average data are considered, for $T = 250$ msec, the usual superiority of auditory intervals over visual

Table 1
Individual Equal Variance d′ for Each Marker Condition and T Value (in Milliseconds)

| | T Value | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 250 | | | | 1,000 | | | |
| | Marker Condition | | | | Marker Condition | | | |
| Subjects | T-T | L-L | T-L | L-T | T-T | L-L | T-L | L-T |
| 1 | 4.62 | 2.27 | .50 | .65 | 2.23 | 1.74 | .93 | .94 |
| 2 | 3.29 | 1.35 | .01 | .02 | 1.67 | 1.29 | .53 | .62 |
| 3 | 3.41 | 3.00 | .32 | .57 | 1.51 | 1.27 | .90 | .99 |
| 4 | 3.44 | 2.12 | 1.00 | .63 | 2.75 | 1.68 | .87 | 1.15 |
| 5 | 4.47 | 2.86 | 1.03 | .80 | 4.17 | 2.06 | 1.32 | 1.91 |
| 6 | 1.95 | .95 | .13 | .42 | .92 | .42 | .17 | .08 |
| 7 | 4.32 | 2.64 | .85 | .96 | 3.19 | 2.32 | 1.92 | 1.96 |
| 8 | 3.75 | 2.26 | .88 | .68 | 2.56 | 1.77 | 1.46 | 1.45 |
| Mean | 3.65 | 2.18 | .59 | .59 | 2.37 | 1.57 | 1.01 | 1.14 |

intervals (cf. Allan, 1979) is observed, averaged d′ being 3.65 vs. 2.18. Ratios of d′ values obtained under different conditions are displayed in Figure 1. Intermodal d′ are clearly lower than the auditory ones by a factor of 6. This cannot be accounted for by lack of efficiency of the onset or offset of the light pulses, since the intermodal data are the same under T-L or L-T conditions and clearly worse than the L-L condition. The auditory-intermodal d′ ratio falls to 2 when T is increased at 1,000 msec. On the other hand, the auditory/visual d′ ratio remains at 1.5 for both T values.

Since this is the first attempt to replicate the Rousseau and Kristofferson data, it seemed appropriate to compare the level of performance obtained in both experiments. However, such comparison must be carried with caution, since different methods were used to estimate performance indexes. Standard deviation of the internal transform of a given time

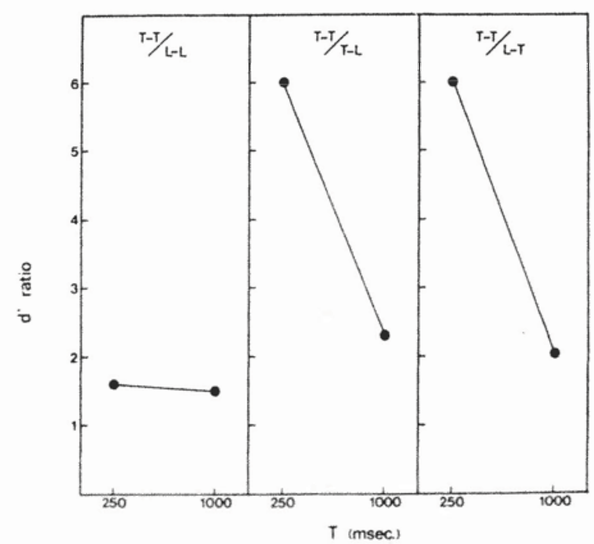


**Figure 1. Ratio of average d′ estimates with auditory (T-T) intervals taken as reference for visual (L-L) and intermodal (T-L, L-T) intervals.**

interval will be used to assess the efficiency of the timekeeping device under different experimental conditions.[1] Estimates of SD are presented in Table 2. For the L-T condition, SD is estimated at 84.7 msec for t = 250 msec and at 131.6 msec for T = 1,000 msec; in Rousseau and Kristofferson, the estimates[2] are 86 msec for T = 100 msec, 130 msec at T = 600 msec, and 108 msec for T = 1,200 msec. Both sets of estimates are in the same range and show intermodal discrimination as being relatively insensitive to procedural conditions. It is further worth noting that estimates of SD from the Rousseau and Kristofferson data are not as uninfluenced by duration as the $\Delta T_{75}$ reported in their paper. The main reason for that is likely to come from the use of the total psychometric function in estimating SD, which includes very high performance data points having a strong influence on the slope estimate. The present data analysis would tend to weaken the statement made in Rousseau and Kristofferson about the stability of $\Delta T_{75}$ as a function of T. However, it is not a sufficiently strong test, and more systematic results will be reported later in this paper. It is interesting to note in Table 2 that the Weber ratio is relatively constant in the intramodal condition, whereas the intermodal ratio is halved by the increase in T value.

So these data do indicate that (1) intermodality is very detrimental to duration discrimination of empty intervals, and (2) the performance decrement, in comparison with intramodal performance, is reduced with an increase in the absolute duration of the intervals to be discriminated. This is in direct support of Rousseau and Kristofferson, and confirms the possibility that the access to efficient timing devices would be very difficult, if not impossible, for intermodal time intervals. This conclusion is warranted by the surprising power of intermodality as a variable. Rarely, in the duration discrimination literature can one find stimulus variables that produce such a large performance decrement, without consideration to the duration range. It is only in Divenyi and Danner (1977) that a comparable decrement was observed when intensity of auditory markers was reduced from 65 to 5 dB SL at a base duration of 25 msec. Although Divenyi and Danner interpreted their results in terms

Table 2
Estimates of SD From the Average d′ Under Each Marker Condition

| | Marker Condition | | | |
|---|---|---|---|---|
| T Value | T-T | L-L | T-L | L-T |
| 250 | 13.7 | 22.9 | 84.7 | 84.7 |
| | 5.5* | 9.16* | 33.9* | 33.9* |
| 1,000 | 63.3 | 95.5 | 148.5 | 131.6 |
| | 6.3* | 9.5* | 14.9* | 13.2* |

*Note*—*T value given in milliseconds. *Classical Weber ratio SD/T (%).*

of auditory sensory mechanisms, other types of mechanisms will have to be called for in order to explain the current results.

Unfortunately, a simpler, and in a way more trivial, explanation could be that intermodal conditions require more systematic training in order to reach the intramodal performance level. Duration discrimination is known to be particularly sensitive to training (Kristofferson, 1980). In the present experiment, marker conditions were varied between blocks of 70 trials. This is a rather small number of trials per condition by duration discrimination standards (e.g., Divenyi & Danner, 1977). Furthermore, training might have been hindered by the mere variation of marker condition within sessions. Consequently, a second experiment was run in which two groups of three subjects ran through 16 sessions of either intramodal or intermodal empty-interval duration discrimination.

## EXPERIMENT 2: CONSISTENT PRACTICE

### Method

**Subjects.** Six subjects served in the experiment. Except for Subject 1, none had had any experience in duration discrimination tasks.

**Stimuli.** The intramodal intervals were marked by two auditory markers; six (t values) were used: $T_0$ = 238, 242, 247 msec and $T_1$ = 253, 258, 262 msec. Intermodal intervals were marked by an auditory marker followed by a visual marker (T-L intervals). The temporal intervals were: $T_0$ = 205, 220, 235 msec and $T_1$ = 265, 280, 295 msec. The actual values for inter- and intramodal intervals were chosen in order to give comparable discrimination performance levels.

**Procedure.** The subjects were divided randomly into two groups of three subjects each. Group A ran through 16 sessions with intramodal intervals and, Group B did the same with intermodal intervals. There were 270 trials per session divided into three blocks of 90 trials. During a session, a subject would be presented with 45 trials/interval.

### Results and Discussion

Individual SD estimates were computed for each session by fitting a straight line to the normal deviate functions $Z(R_1 \mid t_i)$ vs. $t_i$. Figure 2 displays the average SD for each group. It is readily apparent that both groups show the usual improvement in performance over the first sessions, and moreover that they stabilize at performance levels very much comparable to the data obtained in Experiment 1 with similar markers.

The rate of improvement was estimated under the assumption that it was a power function (Newell & Rosenbloom, 1980). A straight line fitted to the log-log transform of the performance functions, shown in Figure 2, gave slopes of −.22 for the intramodal condition and −.25 for the intermodal one. Moreover, intramodal SD remains at roughly 28% of the intramodal value all along the practice period. Finally, averaged over the last 10 sessions, the intermodal and intramodal SD are 73.2 and 21.7 msec,

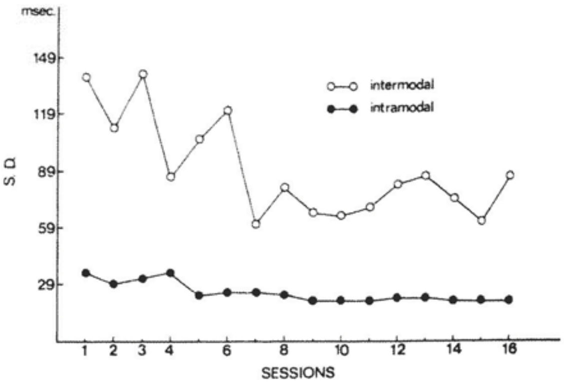


**Figure 2. Average SD estimates for two groups of three subjects over 16 sessions with intramodal, T-T, and intermodal T-L intervals.**

respectively. These values are quite close to the ones reported in Experiment 1.

So, in general, the present data indicate that the results of Experiment 1 hold even in a group design, under prolonged training conditions, and also with different duration discrimination methods, that is, "single stimulus" (Experiment 1) and "many-to-few" (Experiment 2).

## EXPERIMENT 3: INDIVIDUAL WEBER FUNCTIONS

Rousseau and Kristofferson (1973) obtained, with a design in which a different group of subjects was run under each value of standard duration, evidence pertaining to the violation of Weber's law. The present experiment represents an attempt to replicate such a finding in a within-subject design. Auditory duration discrimination has been shown by Getty (1975) to follow Weber's law over a wide range (200-2,000 msec). Although strict proportionality of SD/T was not obtained, both Getty (1975) and Treisman (1963) conclude that, under some generalized form, Weber's law holds for duration, at least up to 2 sec. On the other hand, fine-grain experimentation showed SD to be stable over certain portions of that range (Allan & Kristofferson, 1974). Kristofferson (1980) has been able to demonstrate that, with extensive practice at each MP value (20 sessions), the continuity of the discrimination function breaks down and a step function unfolds. These steps are very orderly and bring strong support to a quantal model of duration discrimination. On the other hand, if only early data is considered, the SD vs. T function is linear and clearly in line with Weber's law, with a ratio value of .05 and intercept of less than 1 msec. However, up to now, Rousseau and Kristofferson's (1973) data have represented the strongest case of invariance of $\Delta T_{75}$ over T (Allan, 1979). Since Experiment 1 data had indicated that intermodal SD could increase as a function of T, the present experiment aimed at clarifying the issue by generating individual discrimination functions with intermodal intervals over a larger range of T values.

### Method

**Subjects.** Six naive subjects participated in the experimentation.

**Procedure.** The intervals were marked by a brief 1-kHz tone followed, after d msec, by a flash of light. Five T values were investigated: 600, 900, 1,200, 1,500, and 1,800 msec. A different set of six intervals was used at each T value, $T_0 = t_1$, $t_2$, and $t_3$ and $T_1 = t_4$, $t_5$, and $t_6$. The spacing between the stimuli was arbitrarily set at .075 T, except for $t_3$ and $t_4$, which were separated by a value of .15 T. The same set of intervals was used for all six subjects. Two subjects, 1 and 2, ran through the T series in decreasing order, and the other four subjects, 3, 4, 5, and 6, did it in an increasing order.

Each subject was first given two training sessions and then groups of four sessions each, one for each T. The first session of each group was used as practice, and the experimental data were taken from the next three sessions. There were two blocks of 120 trials per session, in which each interval was presented 20 times in random order.

### Results and Discussion

The $P(R_1 \mid t_i)$ were computed at each session and SD was estimated from psychometric functions averaged over the last three sessions. The linear goodness of fit of the normal deviate functions is quite acceptable when the number of points (6) is taken into account. For only 9 of a total of 25 functions, $r^2$ was lower than .98, with the lowest at .946. The SD estimates were obtained with a procedure identical to the one used in Experiment 2, for all subjects but Subject 5. Because of the high level of performance of Subject 5, estimation was done by linear interpolation from $P(R_1 \mid t_3)$ and $P(R_1 \mid t_4)$.

Individual and average SD are presented in Table 3. An analysis of variance (RB-k, Kirk, 1968) was performed on the data. It indicates that SD varies significantly as a function of T [$F(4,20) = 10.4$, $p < .001$]. Individual differences are statistically significant [$F(5,20) = 17.8$, $p < .01$] and represent 60% of the variance of the data, as indicated by the ratio SSBlocks/SSTotal in the analysis of variance. Rousseau and Kristofferson had reported similar individual

Table 3
Individual SD Estimates Under Each T Value (in Milliseconds)

| Subjects | T Value 600 | 900 | 1,200 | 1,500 | 1,800 |
|---|---|---|---|---|---|
| 1 | 86 | 92 | 138 | 167 | 187 |
| 2 | 220 | 221 | 247 | 320 | 384 |
| 3 | 130 | 228 | 144 | 166 | 172 |
| 4 | 89 | 123 | 172 | 241 | 237 |
| 5 | 69 | 102 | 144 | 179 | 252 |
| 6 | 50 | 55 | 77 | 105 | 101 |
| Mean | 107 | 136.8 | 153.6 | 196.3 | 222.2 |
| | 17.8* | 15.2* | 12.8* | 13.1* | 12.3* |

*Classical Weber ratio SD/T (%).*

differences. Nevertheless, average data were used as an indication of the general trend of the SD vs. T function. A straight line was fitted to the function, and it indicates that intermodal duration discrimination follows a generalized Weber law where SD = .096 (T + 489) msec. The goodness of fit of the function is good ($r^2 = .985$). This function is in agreement with the data of the two previous experiments, since, by extrapolation, SD is estimated at 71.3 msec for T = 250 msec.

## GENERAL DISCUSSION

The aim of the present paper was to test the generality and the validity of the Rousseau and Kristofferson (1973) report on intermodal duration discrimination. Figure 3 is a composite figure, which displays the data reported in the present paper with the Rousseau and Kristofferson data. There is a very good coherence between the data points yielded by the different experiments when the lower portion (T ⩽ 1,000 msec) of the discrimination function is considered. Inter- and intramodal functions have quite comparable slopes, with the intercepts of intermodal functions being much larger. However, the higher part of the function is more uncertain because the few intermodal data points are very different in level of performance, and also because no data is available for empty intramodal intervals. Consequently, the discussion will focus on the lower portion (T ⩽ 1,000 msec) of the discrimination functions.[3]

A straight-line curve fitting was applied on the seven intermodal data points. The slope was estimated at .067 and the intercept at 71.6 msec. A similar procedure over the intramodal data points (two) gives slopes of .067 for the auditory intervals and .096 for the visual ones, with intercepts of −2.3 and −1.0 msec, respectively. The major discrepancy between inter-

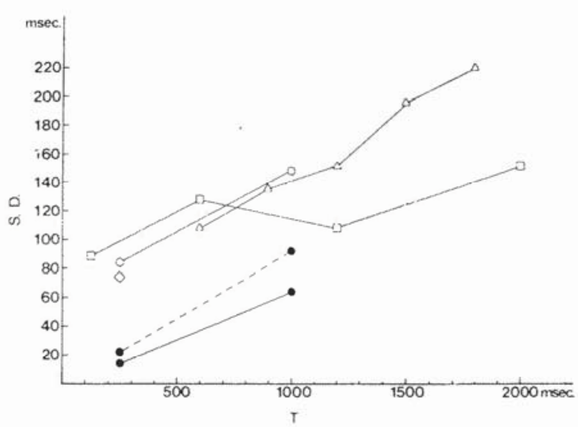


**Figure 3. Composite figure of available intermodal (open symbols) and intramodal data from Experiment 1 (filled symbols). □—□, Rousseau and Kristofferson, 1973 (L-T); ○—○, Experiment 1 (T-L); ◊, Experiment 2 (T-L); △—△, Experiment 3 (T-L); ●---●, Experiment 1 (L-L); ●—● Experiment 1 (T-T).**

and intramodality is obviously in the intercept values. While these data do not show intermodal performance to be insensitive to variations in T value, as reported by Rousseau and Kristofferson, differences in the range of T values, parameter estimation method, and psychometric method do not warrant a simple rejection of their claim but do limit its generality.

Duration discrimination functions have commonly been considered as being formed by two independent processes: a stimulus-duration-dependent process that determines the slope parameter and a duration-independent process that sets the intercept (Allan, 1979; Getty, 1975), sometimes considered as noise. Given this interpretation, the overall picture suggests that: (1) the duration of inter- and intramodal intervals is assessed by a common timekeeper, and (2) intermodal intervals are associated with an increase in the importance of a noisy process that is independent of the timekeeping. The problem then is not to define an altogether different timekeeping process for intermodal intervals, but rather to understand why accessing a central timekeeper through pulses originating from different sensory modes induces an increase in noise. Within the intramodal discrimination work, performance decrements produced by changes in stimulus parameters of the interval markers have commonly been accounted for by a reduction in the efficiency of the markers to trigger accurate onsets and offsets of the timekeeper (Abel, 1972; Creelman, 1962; Divenyi & Danner, 1977). The onset-offset variability is considered as originating in an energy detector whose operation is affected by the energy level of the pulses or by a direct interaction, through masking, of pulses in very close temporal proximity. In the present investigation, pulses are clearly detectable and their intermodality characteristic on top of the sizable time interval between them precludes an interpretation in terms of an energy detector.

A possible explanation could be that an attentional shift between auditory and visual channels, required during an intermodal interval, increases the variability of the timekeeping. The attentional shift could induce some intermittence in the metering process (Thomas & Brown, 1974). Moreover, if channel switching has a variable switch time, it could make the temporal encoding of an interval very noisy. Since switch time can be assumed to be independent of interval duration, its relative importance would be reduced by increasing the value of base duration. However, attention switching between independent channels has proven to be an elusive problem (Swets & Kristofferson, 1970). The difficulty in defining a priori channels as being independent makes the testing of that interpretation somewhat difficult. For instance, besides using sensory modalities to define independent channels, spatial location and frequency disparity have commonly been considered for that purpose within the auditory modality (cf. Massaro, 1976).

Unfortunately, Divenyi and Sachs (1978) report no decrement in performance when subjects discriminate between empty auditory intervals shorter than 80 msec, whether the markers are similar or very different in frequency ($\Delta f = 2$ octaves). Moreover, Penner (1976) reports that, for durations longer than 10 msec, binaural and dichotic empty auditory intervals are discriminated equally well. Given these data, a simple attention switching interpretation for the intermodal data is indeed highly debatable. However, it might accommodate the data if switching time properties (mean and variance) were assumed to be proportional with the distance separating pulses on a "stimulus disparity" dimension. Pulses originating in different modalities would be considered as "much more" different than auditory pulses differing in frequency or spatial location. Consequently, with intramodal intervals, the disturbance in the timing process triggered by channel switching would be of very short duration and show little variability. This leads to a complex interaction involving a similarity metric and a selective attention mechanism.

An alternate explanation could be developed through the concept of distance within a processing space, somewhat on the line of Collyer's (1974) suggestion to account for successiveness data. For the purpose of the present analysis, events or pulses are considered to activate modality-specific areas within an internal processing space. The activation converges over time through modality-specific pathways towards a nonspecific processing area. Temporal information is assumed to be available anywhere within the processing space and, in order for the information to be tapped, events (onsets/offsets) simply need to occur in the same locale within the processing space.[4] The properties of the temporal information are the same across the processing space. Given such a processing space, two assumptions are brought forward: (1) the time taken to reach a locale, the arrival latency, is proportional to the locale's depth within the processing space, and (2) the variability of the arrival latency increases with the magnitude of the latency. Hence, when events occur in different sensory modalities they will have to travel a longer distance in order to reach a common nonspecific locale than will intramodal events, which can be handled by a common modality-specific one. Thus, with intermodal intervals, the increase in discrimination variability would be due to the fact that the temporal judgment is linked to the longer arrival latency. So, in summary, the characteristics of the temporal timekeeper are constant across all locales within the processing space, but the performance is affected by onset-offset variability related to the depth of a given locale within the processing space.

Duration discrimination is viewed as being a function of two independent processes: onset-offset triggering and internal timekeeping. This is not unlike the model proposed by Divenyi and Danner (1977) to incorporate detection latencies into auditory duration discrimination. On the other hand, it bears no relationship to the onset-offset model developed by Allan, Kristofferson, and Wiens (1971), inasmuch as in their model on-off latencies are determined by the intrinsic properties of the internal timing mechanism. Thus, as long as onset-offset latencies are not systematically varied within a particular experimentation, models that do not deal with onset-offset variability will not be affected in their power to account for the discrimination data. Consequently, since they address themselves to the problem of timekeeping properties as such, models like Kristofferson's (1977) real-time criterion as well as Creelman's (1962) counting model are compatible with the present theoretical suggestion. Although the present elaboration is speculative, it is not altogether very different from other theoretical propositions (cf. Allan, 1979). However, it has the advantage of setting a broad conceptual context within which the effect of marker characteristics on temporal discrimination of empty intervals can be considered.

## REFERENCES


Abel, S. M. Discrimination of temporal gaps. *Journal of the Acoustical Society of America*, 1972, **52**, 519-524.

Allan, L. G. The perception of time. *Perception & Psychophysics*, 1979, **26**, 340-354.

Allan, L. G., & Kristofferson, A. B. Psychological theories of duration discrimination. *Perception & Psychophysics*, 1974, **16**, 26-34.

Allan, L. G., Kristofferson, A. B., & Wiens, E. W. Duration discrimination of brief light flashes. *Perception & Psychophysics*, 1971, **9**, 327-334.

Carbotte, R. M., & Kristofferson, A. B. On energy-dependent cues in duration discrimination. *Perception & Psychophysics*, 1973, **14**, 501-505.

Collyer, C. E. The detection of a temporal gap between two disparate stimuli. *Perception & Psychophysics*, 1974, **16**, 96-100.

Creelman, C. D. Human discrimination of auditory duration. *Journal of the Acoustical Society of America*, 1962, **34**, 582-593.

Divenyi, P. L., & Danner, W. F. Discrimination of intervals marked by brief acoustic pulses of various intensities and spectra. *Perception & Psychophysics*, 1977, **21**, 125-142.

Divenyi, P. L., & Sachs, R. M. Discrimination of time intervals bounded by tone bursts. *Perception & Psychophysics*, 1978, **24**, 429-436.

Eijkman, E., & Vendrik, A. J. H. Can a sensory system be specified by its internal noise? *Journal of the Acoustical Society of America*, 1965, **37**, 1102-1109.

Fraisse, P. La perception de la durée comme organisation du successif. *Année Psychologique*, 1952, **1**, 39-46.

Getty, D. G. Discrimination of short temporal intervals: A comparison of two models. *Perception & Psychophysics*, 1975, **18**, 1-8.

Green, D. M., & Swets, J. *Signal detection theory and psychophysics*. New York: Wiley, 1966.

Kinchla, J. Duration discrimination of acoustically defined intervals in the 1-to-8-sec range. *Perception & Psychophysics*, 1972, **12**, 318-320.

Kirk, R. E. *Experimental design: Procedures for the behavioral sciences*. Belmont, Calif: Wadsworth, 1968.

Kristofferson, A. B. A real-time criterion theory of duration

discrimination. *Perception & Psychophysics*, 1977, **21**, 105-117.
KRISTOFFERSON, A. B. A quantal step function in duration discrimination. *Perception & Psychophysics*, 1980, **27**, 300-306.
LOEB, M., BEHAR, I., & WARM, J. S. Cross-modal correlations of the perceived durations of auditory and visual stimuli. *Psychonomic Science*, 1966, **6**, 87.
MASSARO, D. Auditory information processing. In W. K. Estes (Ed.), *Handbook of learning and cognitive processes* (Vol. 4). Hillsdale, N.J: Erlbaum, 1976.
NEWELL, A., & ROSENBLOOM, P. S. Mechanisms of skill acquisition and the law of practice. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition*. Hillsdale, N.J: Erlbaum, 1980.
NILSSON, T. H. Two-pulse interval vision thresholds. *Journal of the Optical Society of America*, 1969, **59**, 753-756.
OOSTENBRUG, M. W. M., HORST, J. W., & KNIPER, J. W. Discrimination of visually perceived intervals of time. *Perception & Psychophysics*, 1978, **24**, 21-34.
PENNER, M. J. The effect of marker variability on the discrimination of temporal intervals. *Perception & Psychophysics*, 1976, **19**, 466-469.
ROUSSEAU, R. *Duration discrimination of bimodal empty intervals*. Unpublished doctoral dissertation, McMaster University, December 1975.
ROUSSEAU, R., & KRISTOFFERSON, A. B. The discrimination of bimodal temporal gaps. *Bulletin of the Psychonomic Society*, 1973, **1**, 115-116.
STERNBERG, S., & KNOLL, R. L. The perception of temporal order: Fundamental issues and a general model. In S. Kornblum (Ed.), *Attention and performance IV*. New York: Academic Press, 1973.
SWETS, J. A., & KRISTOFFERSON, A. B. Attention. In P. H. Mussen & M. R. Rosenzweig (Eds.), *Annual review of psychology*. Palo Alto, Calif: Annual Reviews, 1970.
THOMAS, E. A. C., & BROWN, I., JR. Time perception and the filled-duration illusion. *Perception & Psychophysics*, 1974, **16**, 449-458.
TREISMAN, M. Temporal discrimination and the indifference interval: Implications for a model of the "internal clock." *Psychological Monographs*, 1963, **77**(13, Whole No. 576).
WARM, J. S., STUTZ, R. M., & VASSOLO, P. A. Intermodal transfer in temporal discrimination. *Perception & Psychophysics*, 1975, **18**, 281-286.

## NOTES

1. The internal transform, I, of a stimulus duration, t, is defined as a random variable, I, normally distributed with mean, i, and variance, VAR(I). Following signal detection theory (Green & Swets, 1966), given two intervals to be discriminated, $t_0$ and $t_1$, the performance is assumed to be a function of the variance of the internal distributions and the distance between their means. It is further assumed that, for a set of n intervals to be discriminated, $VAR(I_0) = VAR(I_1), \ldots, = VAR(I_n)$ and their respective means are $i_0 = t_0, i_1 = t_1, \ldots, i_n = t_n$.

In the single-stimulus method, a criterion-free performance index can be defined as

$$d' = \frac{t_i - t_0}{\sqrt{VAR(I_0)}} = \frac{\Delta T}{SD(I_0)},$$

and d′ is a linear function of ΔT with slope 1/SD and 0 intercept. d′ is obtained by adding the normal transform (Z scores) of $P(R_1 \mid t_0)$ and $P(R_1 \mid t_1)$. In the many-to-few method, each interval to be discriminated can be scaled with reference to a decision criterion in units of $SD(I_j)$. Thus, for each interval, $P(R_1 \mid t_j)$ yields a performance index $Z(R_1 \mid t_j)$ defined as

$$Z(R_1 \mid t_j) = \frac{t_j - t_c}{SD(I_0)},$$

where $t_c$ is the decision criterion value. If $t_c$ is assumed to be constant, $Z(R_1 \mid t_j)$ appears as a zero crossing linear function of t with slope 1/SD.

2. Estimates of SD were obtained from d′ vs. ΔT psychometric functions, which were not provided in the Rousseau and Kristofferson paper but are available from Rousseau (1975).

3. The basic difficulty with such a position lies in the assumed independence of the data points within the discrimination functions. It amounts to stating that the data points for $T > 1{,}000$ msec are unreliable and that a better understanding of the data can be gained by considering the coherence of the various data points when $T \leqslant 1{,}000$ msec. This is a somewhat uncomfortable position in view of the difference in slope estimate of the early points of the Rousseau and Kristofferson data and that of the total function. However, since these points were obtained from independent groups of subjects, we feel justified to do that in view of the gain in simplification of the data to be explained.

4. This view is conceptually related to the model presented in Figure 12b of the Sternberg and Knoll (1973) paper on temporal order judgments.

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