The perception of temporal deviations in isochronic patterns

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In a study of perceptual synchronization with an isochronic sequence, subjects were given the following task: They heard an isochronic sequence of tones in which the last interval was either correct or too long. Their task was to detect irregularity. The independent variables were the number of tones heard and the time interval between them. The dependent variable was the difference limen (DL) for the detectability of the irregularity. Two experiments were performed in this study, differing in the way in which the trials were blocked: In Experiment 1, stimuli with the same period were presented in blocks, whereas in Experiment 2, the period of the stimulus was randomized. The results show that in Experiment 1 the number of tones in the stimulus did not affect the detectability of the anisochrony. In Experiment 2, the number of the DL was a decreasing function of the number of tones heard. Moreover, the decrease of the DL was larger than one would expect from a simple model of information integration, which assumes that subjects improve their performance by averaging their percepts of the first intervals in the sequence. The difference between this task and experiments on the discrimination of temporal intervals is discussed.

The ability of human subjects to synchronize their internal timekeepers with external temporal patterns of different complexity has been a topic of experimental and theoretical investigations for a long time (see Fraisse, 1982, for a comprehensive summary of the literature). One motivation for the present study was to imitate in a laboratory task the temporal aspect of the performance of musicians or of listeners to music. How precise is a subject when he/she taps in synchrony with a metronome? Are there any systematic errors in the timing? How well can subjects apprehend more complicated temporal patterns and reproduce them?

These matters have essentially been investigated with two different tasks. In *tapping tasks*, the subject has to tap in synchrony with a temporal pattern or to continue tapping after the pattern stops. In *perceptual tasks*, the subject has to make judgments about temporal aspects of the temporal patterns or adjust them to meet certain perceptual criteria. Obviously, in tapping tasks an explicit sensory-motor coordination has to be achieved. The perceptual task may or may not include an implicit motor activity (e.g., tapping with the feet during the perceptual task). Although there have been many perceptual studies in which subjects have discriminated two temporal intervals or judged single intervals (Allan & Kristofferson, 1974), perceptual experiments with several isochronic sequences have been rare.

At least two perceptual experiments with several isochronic sequences have been performed. Lunny (1974) constructed a metronome in which every fourth click could be adjusted. Using the method of limits, he (as his own subject) adjusted the temporal position of this click until an irregularity was just detectable. He found an approximate Weber law in the range of 30 to 1,000 msec. Halpern and Darwin (1982) studied the same problem with a more sophisticated psychophysical technique and 8 subjects. They presented four clicks to their subjects; the first three were equally spaced in time, and the fourth was either too late or too early. The subjects' task was to judge whether the last click was late or early. The difference limen for durations from 400 to 1,450 msec was estimated from the psychometric functions. Weber's law was approximately true, with a Weber ratio between .03 and .04.

Although the purpose of these earlier studies was to test the validity of Weber's law, the aim of the present study was to investigate with a perceptual task the early phase of synchronization, in particular the dependency of the sensitivity to irregularities upon the *length* of the temporal pattern. The basic idea is simple: When the subject is listening to an isochronic temporal pattern of n intervals, then the precision with which he/she can detect an irregularity in this pattern should be an increasing function of n repetitions heard because he/she has been exposed to a larger sample of the stimulus. This phenomenon is expected, at least if we conceptualize the recognition of the temporal pattern in analogy with a statistical estimation process in which the precision of an estimate (in this case, the period of the temporal pattern) is an increasing function of the sample size. Consequently, I wanted to study the synchronization both qualitatively and quan-

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tatively in terms of a simple statistical model of information integration.

EXPERIMENT 1

Method

Stimulus parameters. The stimuli consisted of a series of 2000-Hz square waves of 10-msec duration. The tones were either regularly spaced, or the last interval was increased by a duration of u (see Figure 1). The following stimulus parameters were combined orthogonally: (1) The base duration (d) of the intervals was 100, 200, or 300 Hz. (2) The delay (u) was 5, 10, 20, 30, or 40 msec. (3) The number (m) of intervals was 3, 4, 5, or 6.

Procedure. The subject listened to the temporal pattern, and was instructed to judge whether or not the stimuli were regularly spaced. The subject indicated her decision by pressing one of two buttons. After the response, feedback on a computer screen indicated whether the pattern was regular or irregular. The stimuli were presented in blocks of 20 stimuli, 10 regular and 10 irregular, in random order. Within a block the base duration and delay were constant. In one session each stimulus combination—with 20 trials—was presented once. The order of blocks was cyclically permuted from session to session; however, the largest unit of variation was the base duration of the patterns. Thus, within each third of the session, the base duration was constant. The subjects participated in six sessions. Therefore, each stimulus combination was presented 120 times, resulting in $3 \times 4 \times 4 \times 120$ trials.

Subjects. Two female subjects, psychology majors, participated in the experiment.

Data Analysis. Since the trials were blocked with constant delay and base duration, for each stimulus combination the signal detectability parameter d' was estimated. The statistical significance of differences in detectability as a function of the length n of the sequence was tested with the statistical test developed by Gourevich and Galanter (1967).

Results

In Figure 2 the detectability index is shown as a function of the number of intervals for a delay of 20 msec for both subjects. The differences between detectability indices are not statistically significant. The data for the other delays are not shown, because they also are not significant.

Discussion

The data show quite clearly that the detectability of the anisochrony does not improve with the number of inter-

Figure 1. Examples of the temporal patterns used in the study: a pattern with 3 temporal intervals of the same size (lower part) and a pattern with a longer third interval (upper part).

Figure 2. Detectability of an anisochrony of 20 msec as a function of the number of intervals in the pattern by (a) Subject 1 and (b) Subject 2.

vals in the temporal pattern. One reason for this negative result could be that the experimental conditions were blocked with respect to the interval durations. Consequently, the subject did not have to adapt to a different tempo from trial to trial, and could therefore possibly establish a stable perceptual frame for the temporal intervals within one block of trials. Then the subject could, for example, ignore the first temporal intervals and focus her attention on the last interval. One possible way to prevent this strategy is to randomize the period of the temporal patterns from trial to trial. This was done in Experiment 2.

EXPERIMENT 2

Method

Stimulus parameters. As in Experiment 1, the stimuli consisted of 2000-Hz square waves. There was, however, a larger range of periods. The tones were either regularly spaced, or the last interval was increased by a delay duration, u . The base duration, d , of the intervals was 50, 100, 200, or 400 msec. The values of u were chosen after preliminary studies as follows:

<i>d</i>	<i>u</i>
50 msec	0 9 18 27 msec
100 msec	0 10 20 30 msec
200 msec	0 15 30 45 msec
400 msec	0 20 40 60 msec

The number (m) of temporal intervals in a sequence was 3, 4, 5, or 6 for 2 of the subjects, and 2, 3, 4, or 5 for the other 2.

Procedure. The procedure was the same as in Experiment 1. The main difference from Experiment 1 was that the $4 \times 4 \times 4 = 64$ different stimuli were presented in random order within a block of trials. To make the probability of an irregular stimulus presentation equal to .5, the stimuli with $u=0$ were replicated three times in a block such that one block consisted of 96 stimulus presentations. Five blocks were run in a single session, taking approximately 45–60 min. After each session the hit and false alarm rates were shown on the screen to the subjects. With each subject 10 sessions were run after two training sessions.

Subjects. Four staff members from the psychology department (including the author) served as subjects.

Data analysis. Data analysis was performed in three steps: (1) The difference limen (DL) for the perception of the irregularity was estimated by fitting one logistic psychometric function to each set of data of one period using maximum likelihood estimation. The logistic

function was chosen for computational convenience. The results are given in Table 1 and are shown graphically in Figure 3. (2) To test whether the DLs for the different values of m (number of temporal intervals in the stimulus) are statistically significant, a likelihood-ratio test for the equality of the DLs was performed. (3) A model for integration of temporal information was tested for its statistical adequacy. This model is described following the Results.

Results

The difference limen as a function of the number of beats. The relationship of central interest in this study is the change of the DL as a function of the number of beats in the sequence. The results are shown in Figure 3. The data show that there are large individual differences with respect to the absolute performance and the amount of change. The decrease of DL is most prominent for all subjects in the 100-msec condition. In the 200-msec condition, the decrease is observed for only some subjects.

Statistical test for equal DL. To test whether the differences between the DLs were statistically significant, I applied a likelihood ratio test as follows: The likelihood of the data, assuming equal DLs for the four different num-

Figure 3. Difference limen (DL) for the irregularity as a function of the number of intervals in the stimulus for (a) a period of 50 msec, (b) a period of 100 msec, (c) a period of 200 msec, and (d) a period of 400 msec.

Table 1
Difference Limens (in msec) for the Different Subjects and Periods

Period	<i>m</i>				<i>m</i>			
	2	3	4	5	3	4	5	6
Subject 1					Subject 3			
50	17	12	11	8	8	8	7	7
100	25	20	11	11	24	15	15	15
200	9	16	9	11	16	14	11	9
400	12	7	7	8	16	14	11	10
Subject 2					Subject 4			
50	28	12	10	7	24	14	11	8
100	16	7	10	7	21	11	8	10
200	5	5	4	5	7	6	7	6
400	9	8	8	6	9	8	10	10

Note—*m* = number of intervals in a sequence. Two subjects heard 2, 3, 4, or 5 intervals, and 2 subjects heard 3, 4, 5, or 6 intervals.

bers of beats, was related to the likelihood when the DL in each condition was a free parameter. This analysis was done separately for each subject and standard duration. The result of this analysis is shown in Column 3 of Table 2. Four of the 16 tests were not significant. For those cases in which the improvement of discrimination performance was significant, I tested whether it was compatible with a simple model of information integration (see next section).

An averaging model for the perceptual synchronization with the beat. A simple hypothesis about the mechanism of perceptual synchronization with the beat is as follows: The intervals between successive beats are perceptually represented as random variables due to noise in the system. A sequence of isochronic intervals gives the subject a chance to get a better estimate of the periodicity in the temporal pattern by "computing" an average of those perceptual representations. In other words, the hypothesis is that the subject behaves like a statisti-

Table 2
Likelihood Ratio Test for Equality of Difference Limens and the Fit of the Two Averaging Models with $r = 0$ and $r = -.5$

Condition	Subject	Equality	$r = 0$		$r = -.5$
		Model 1	Model 2		
50 msec	1	30†	20†	14†	
	2	14.8†	7.7	4.6	
	3	5	3.1	2.6	
	4	18.7†	14.4†	14.2†	
100 msec	1	48†	29†	18†	
	2	19.8†	12.4†	8.2*	
	3	84†	2.9	2.4	
	4	21.5†	16.7†	14.2†	
200 msec	1	3.4	3.9	7	
	2	14.2†	11.5†	13.3†	
	3	16†	10.2†	7.4	
	4	2	1.9	2.4	
400 msec	1	10.6*	5.3	5.2	
	2	8†	8.3	4.8	
	3	15.6†	9.8*	7.4	
	4	2.5	4.3	5.5	

Note— $-2 \times \log$ likelihood ratio is asymptotically chi square with 3 *df* under the null hypothesis of equal difference limens. Critical values are 7.81 and 11.3 for a probability of .05 (*) and .01 (†), respectively.

cian who improves the quality of the estimate of a population mean by increasing the sample size. The length of the isochronic sequence then corresponds to the sample size of the statistician. This idea will be stated more formally in the next paragraph. A stimulus with *n* isochronic intervals of duration *d* and a final interval of duration *d* + *u* are given. We assume that the subjective representation is a random vector $\mathbf{X} = (X_1, X_2, X_3, \dots)$ with the following properties: (1) The components X_i are scaled such that their expectation (*E*) is equal to the physical duration:

$$E(X_i) = \begin{cases} d & i = 1, 2 \dots n \\ d + u & i = n + 1 \end{cases}$$

(2) Constant variance σ^2 is in the range of variation of *u*. (3) Constant covariance of successive components of $\mathbf{X}$:

$$\text{cov}(X_i, X_j) = \begin{cases} k & \text{if } j = i + 1 \\ \sigma^2 & \text{if } i = j \\ 0 & \text{otherwise} \end{cases}$$

(In the next paragraph, one reason is given to explain why successive components may be correlated.) (4) Normal distribution of components. (5) *Decision assumption*: The sequence is irregular if $D = X_{n+1} - (1/n) \sum_{i=1}^n X_i > c$, where *c* is the decision criterion.

From these assumptions, it follows that the variance of the random variable *D* is given by

$$\sigma_D^2 = (n+1)/n + 2r/n^2,$$

where $r = k/\sigma^2$ is the correlation coefficient of successive values of *X*.

The psychometric function is then given by

$$P\{D > c\} = \Phi\{(u-c)/\sigma_D\},$$

where Φ is the distribution function of the normal distribution.

For a rough comparison with the data, it is instructive to look at the change of the slope of the psychometric function with varying *n*. Let us denote this slope by *s_n*. Table 3 gives the ratio of *s_n*/*s₁* for various values of the correlation between successive subjective durations.

The largest changes would be with a correlation of -1 . However, this degenerate case cannot be realized. A correlation of $-.5$ would occur with the following specification of the general model: Each beat in the stimulus triggers a perceptual representation with a random delay *e*. Suppose that this is the only source of variability of the subjective representation and that successive delays are stochastically independent. Suppose, for example, that the delays to the first three beats are *e*₁, *e*₂, *e*₃. Then the first two subjective intervals are

$$X_1 = d - e_1 + e_2$$

$$X_2 = d - e_2 + e_3$$

$$\text{cov}(X_1, X_2) = -\sigma_e^2$$

$$\rho(X_1, X_2) = -0.5.$$

Models in this spirit with random on-off latencies have been applied to time discrimination data by Vorberg and Wandmacher (1973). In the following section, both a model with $r = -0.5$ and $r = 0$ are tested.

Test of the averaging models. The two averaging-models were tested with a likelihood ratio statistic. The result is shown in the last two columns of Table 2. Two points are noteworthy: (1) In those conditions in which the hypothesis of the equality of the difference limen was not rejected, both models were not rejected either. This means that the test is not powerful against the alternative hypothesis of small decrease of the DL with the number of beats. (2) In 50% of the cases in which a significant change of DL was observed, the change could be accounted for by the averaging model. In the other 50% of the cases, the model had to be rejected. The main discrepancy between the data and the model was that the DL decreased by a larger amount than predicted by the model.

Discussion

The results show, in general, that the detectability of an irregularity in an isochronic sequence is an increasing function of the number of beats in the sequence up to about five to six beats. The size of the effect is largest with a period of 100 msec. Moreover, the effect is larger than one would expect from a model that assumes that the subjects use the average of the first subjective temporal intervals to predict the temporal position of the next beat. Consequently, we have to look for an alternative model.

One reason for the discrepancy between the model and the data may be that although the period of the temporal pattern varies randomly from trial to trial, there are only four different periods in the experiment. It is conceivable that, given the extensive training, the subjects develop an absolute sense of the periods in the experiment, which helps to detect the irregularity. The negative result of Experiment 1 can be interpreted in this direction. Thus, the uncertainty of the period from trial to trial seems to be a critical variable for the results in this study. It would be interesting to repeat the experiment with periods that vary in smaller steps from trial to trial so that an absolute representation of the periods is made more difficult.

Finally, I want to point out some discrepancies between the size of the difference threshold found in this study and the studies referred to in the introduction. Although Halpern and Darwin (1982) and Lunny (1984) did not address the same question that I did in this study, there is an important difference in the results: Both Lunny and

DL for $m=2$

Figure 4. The difference limen (DL) for the discrimination as a function of the period in the stimulus.

Halpern and Darwin found approximate Weber laws in their data, Lunny in a range up to 1,000 msec and Halpern and Darwin in a range from 400 to 1,450 sec. In my data, the surprising result was that the DL for a standard of 100 msec is larger than for 200 msec, and the DL for 200 msec is very close to the DL for 400 msec (see Figure 4).

Similar contradictions appear in the literature on the discrimination of temporal intervals: Allan and Kristofferson (1974) reported data similar to those in this study; for some subjects, they found that the DL was a decreasing function of the standard duration. Rousseau & Kristofferson (1973) found an invariant DL for standard durations in the range of 100 to 2,000 msec! On the other hand, Getty (1975), in an extensive study, found a reasonable approximation to a generalized Weber law for standard durations in the range of 50 to 1,500 msec.

The variety of experimental results in the duration discrimination literature is indeed very puzzling, and I do not see how the differences can be accounted for by the slightly different experimental procedures. With respect to the absolute value of the DL, only the 400-msec condition of the present study can be compared with Halpern and Darwin's (1982) study. They found an average DL of 17.5 msec, whereas, in the present study, DLs ranged from 5.7 to 11 msec. One reason for the difference may be training. Moreover, their task may have been more difficult because their subjects had to judge whether the last click sounded "late" or "early," whereas subjects in the present task had to decide only whether or not the sequence was irregular. In general, unordered discrimination is easier than ordered discrimination. It is conceivable that one can correctly judge a sequence as irregular without being able to tell whether the last click was late or early.

One limitation of the present experiment is that the anisochrony is at the end of a primitive isochronic pat-

Table 3
The Change of Slope of the Psychometric Function as a Function of the Number of Intervals (n) Predicted by the Different Versions of the Averaging Model

r	n				
	2	3	4	5	6
-1	1.41	1.6	1.7	1.8	2
.5	1.3	1.44	1.51	1.55	1.73
0	1.15	1.22	1.16	1.29	1.41

tern. In further experiments, it would be interesting to study the detectability of delays *within* a temporal pattern, and moreover to use richer temporal patterns than isochronic ones. Experiments of this kind could give useful information about the perception of expressive timing in music, which often consists of subtle temporal deformations of a regular structure.

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