The auditory tau effect and memory for pitch

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The tau effect, which designated the effect of temporal variables on spatial perception, was investigated in the auditory modality. Subjects listened to repeated presentations of a three-tone sequence. The first and third tones were fixed in frequency at 1 and 3 kHz, respectively, and the subject adjusted the frequency of the second tone until it seemed intermediate in pitch between the other two. The two temporal intervals delimited by the three tones were manipulated. As the second tone moves from being closer to the first tone to being closer to the third tone *in time*, subjects' average adjustment of the second tone decreases. While in accordance with previous results, the present data provide new information on subjects' behavior in pitch bisection judgments. An explanation for the auditory tau effect is offered in terms of memory for pitch in which the dynamic role of time is taken into account.

The tau effect (Helson & King, 1930) and the kappa effect (Cohen, Hansel, & Sylvester, 1954; Geldreich, 1934) are usually cited as evidence that the processing of temporal and spatial information is related, at least within some limited set of values of the two stimulus dimensions concerned.

The tau effect refers to situations in which a temporal independent variable influences judgments of a spatial dependent variable. In the terms of Helson's classic demonstration, if three points on a line are marked on the skin of the forearm (delineating two equal distances, d_1 and d_2) and these points are successively stimulated (thereby creating two interstimulus intervals, t_1 and t_2), then d_1 will appear to the subject to be equal to d_2 only if t_1 equals t_2 . If $t_1 > t_2$, d_1 appears greater than d_2 , and vice versa.

The kappa effect occurs when a spatial independent variable is used, and time becomes the dependent measure. Cohen et al. (1954) used three lights to delineate two distances, d_1 and d_2 , on a straight line. These lights were made to flash briefly, in succession, giving rise to two interstimulus intervals, t_1 and t_2 , as before. The subject's task in this case was to adjust the timing of the occurrence of the second light so that it appeared halfway, in time, between the first and third lights. The data from this experiment were analogous to those of Helson. If $d_1 = d_2$, then, when the subject has made his adjustments, t_1 is found (more or less) to equal t_2 . However, if, say, $d_1 > d_2$, then, when the subject has adjusted t_1 and t_2 to subjective equality, we find that, in fact, $t_2 > t_1$.

These basic findings have proved to be quite robust, and both the tau and the kappa effects have

been shown to occur in the visual, auditory, and tactile modalities with a variety of different stimulus displays and display parameters; Ono (1976) has provided a review of the published data in these and related areas.

It seems not unlikely that some common underlying central mechanism is responsible for these two phenomena, and if that is so we should not be surprised to find other examples of sensory judgments which, in the same manner, are not independent of the timing of the stimuli to which they related. A case in point arises in a certain kind of pitch bisection experiment, in which a subject is required to adjust one tone so that it appears to be halfway in pitch between two others. The three tones are presented in a sequence of fixed length which is repeated until the subject is satisfied with his judgment. If the second tone is, temporally, midway between the first and third tones, then the subject can, in fact, bisect the tonal interval, although individual variances tend to be rather large. However, if the second tone occurs closer, in time, to the first tone than to the third, then the subject will bias his adjustment of the pitch of the second tone towards that of the third, and vice versa (Cohen, Christensen, & Ono, 1974; Cohen et al., 1954). It had been suggested that this might be an example of the tau effect, the argument being that each tone would be spatially represented on the basilar membrane by a distinct local maximum of excitation, thus making the situation analogous, in a way, to Helson's original points-on-the-skin demonstration. It is now known, of course, that such maxima are by no means as distinct as was originally supposed, and such an

analogy must be regarded as tenuous to say the least. However, there are distinct similarities between the situations, and the experiment reported here sought to investigate the effects in a more extensive manner than before to see if any further light could be shed on the matter.

METHOD

Apparatus

Three sine-wave tones were generated by three Farnell wave-form generators. A timing device built within the Department of Psychology at the University of Manchester switched these tones on and off according to the scheme shown in Figure 1; rise and fall times were such as to avoid switching transients.

Previous work has shown that monaural and binaural presentation give equivalent results (Cohen et al., 1974), and so the tones were presented to the subject's right ear only through TDH-39 headphones at 56 dB SPL. The apparatus was hidden from the subject, who adjusted the pitch of the second tone using the signal generator dial which was behind a cloth screen. The first and third tones were fixed at 1 and 3 kHz, respectively; the frequency of the adjustable tone was determined with an SLE 2000 timer/counter at the end of each trial.

Subjects

Eight subjects were used in this experiment, five male and three female. They were drawn from the student population of the Department of Psychology and were allocated as part of their course requirements. The only constraint applied was that they possess no musical skills, since pilot work had shown that musically trained subjects are very accurate in this task, showing the effect we were investigating only for a few trials while becoming accustomed to the experimental conditions.

Procedure

In much previous research, the temporal variable has been expressed as the ratio t_2/t_1 . As has been noted (Huang, 1976), this is unsatisfactory since it gives rise to a nonlinear scale. In this research, therefore, we adopted the convention of representing the values of the variable as the ratio $t_1/(t_1 + t_2)$.

Nine values of this variable, .02, .05, .10, .25, .50, .75, .90, .95, and .98, were chosen, and the subjects made 10 judgments under each value, the whole 90 trials being presented in a random order which was the same for each subject. Subjects completed their judgments in three sessions, separated by at least 2 days previous work having shown that long sessions are tiring and lead to boredom.

At the beginning of the first session, the subjects listened to a few repetitions of the cycle with the time variable set at .5 and the second tone at some arbitrary value between 1 and

3 kHz. They were shown how to change the pitch of the second tone and told that they were to adjust it until it seemed to be "half-way in pitch" between the other two.

After the subject was familiarized with the equipment, the timing was set to the first value on the random list, the second tone arbitrarily reset, and the subject instructed to proceed with the task. When the subject was satisfied with his judgment, the frequency of the second tone was recorded and the timing was set to the next value on the list. (Since the potentiometer which controlled the timing emitted a slight noise when operated, it was twiddled before each trial, even when the random list dictated that the same time interval was to occur on consecutive trials.) The frequency of the second tone was then arbitrarily altered by the experimenter, and the whole process repeated. The subjects were not given feedback about their performance.

At the beginning of the second, and subsequent, sessions, the subject listened to the sequence of tones set to the values of the last trial of the preceding session before carrying on with their judgments. It was hoped that this would provide them with some continuity of reference between sessions.

RESULTS

The data are presented in Table 1 and Figure 2.

Analysis of variance showed a significant effect both of the time variable ($F = 5.00$, $p < .01$) and subjects ($F = 211.10$, $p < .001$). Furthermore, the downward linear trend apparent in Figure 2 was found to be significant ($F = 416.9$, $p < .001$), but the quadratic and cubic trends were not.

In outline, these findings are perfectly in accordance with those reported by Cohen et al. (1974) and Cohen et al. (1954). Both these studies used the same three values of the temporal variable (corresponding, in our notation, to .33, .50, and .67), and their results show the same decreasing curvilinear trend evident in the central portion of the graph, although the slopes differ, as do the actual values of the data points. Our data also agree with the earlier findings of one of us (Huang, 1976), with the same reservations. This agreement is, of course, encouraging, but these earlier researches used limited ranges of values of the independent variable and our intention is to provide a more complete picture by a detailed analysis of data covering the whole range.

A histogram of the raw data (Figure 3) reveals a distribution which appears to have two distinct

Figure 1. The timing of one cycle of the stimulus presentation.

Table 1
Means (M) and Standard Deviations (SD) of Raw Data

	Value of $t_1/(t_1 + t_2)$								
	.02	.05	.10	.25	.50	.75	.90	.95	.98
M	1838	1802	1762	1822	1762	1756	1718	1686	1762
SD	455	403	474	427	483	409	473	392	435

Note— $N = 80$ for each value.

peaks, one in the region of 1,500 Hz and the other in the region of 2,000 Hz. We noted that some subjects made their responses almost exclusively in one region or the other, but others shifted between the two without any obvious pattern. It is possible that we may be dealing with data drawn from a binary mixture of two distributions. Although n is not large enough to apply a formal test (see Falmagne, 1968), a less rigorous technique to investigate the possibility was used. We divided the data at the midpoint between the two peaks (1,750 Hz) and derived two further graphs (Table 2, Figure 4), which are very similar in form to the plot of the complete set of data, but widely separated from each other. The variances of the data points of these partitioned data, are, of course, considerably reduced.

DISCUSSION

Before discussing the meaning of the statistically significant effect of the time variable, it is interesting to consider why the data can be partitioned in the way we have described while retaining the principal features of the pooled data. The task we set the subjects is a difficult one, and we might ask how a person with no musical training might, in fact, carry it out. One answer to this question is suggested by the values of the two peaks of the distribution; 1,500 Hz is 1 octave below the third tone, and 2,000 Hz is 1 octave above the first tone. Subjects' perceptions of the midpoint might very well be influenced by these relationships, and they may indicate satisfaction with their judgments when a consideration of the interval between *either* the first and second *or* the second and third tones seems satisfactory. This finding means that data on pitch bisection in this type of experimental situation should be regarded with caution, because our data at the point where $t_1/(t_1 + t_2) = .5$ (that is to say, where the three tones are equally spaced in time, as they would be in a standard pitch bisection task) have a mean value of 1,762.2 Hz, which is very close to the geometric, or musical, midpoint of the interval (1,732 Hz). Viewed in isolation, one would conclude that our subjects were, *on average*, quite accurate. However, if our data is truly drawn from a binary mixture of two distributions, that figure is unreliable, since it is derived

from averaging results drawn from one distribution with a mean in the region of 1,500 Hz and another with a mean of 2,000 Hz. In this particular temporal condition we made 80 observations and only three of the eight subjects made any responses at all in the range of 1,700-1,800 Hz; two made one response each in that area, and the third made four. The effect of averaging in this situation is simply to create an artifact.

We must now consider whether this possible use of octaves might not have given rise to the shape of the function we have plotted, and to do this we must make an assumption about how the subjects, in fact, behaved. The obvious one is that when the second tone was closer in time to the first tone, then the influence of the latter predominated, and when the second tone was closer to the third, then the latter predominated. The effect of this, in simple terms, would be that as $t_1/(t_1 + t_2)$ varied from .02 to .98,

Figure 2. Mean frequency of the second tone as a function of the temporal position of that tone.

Figure 3. The distribution of subjects' responses.

Table 2
Partitioned Data

	.02	.05	.10	.25	.50	.75	.90	.95	.98
Responses Under 1,750 Hz									
M	1521	1501	1508	1538	1508	1511	1492	1475	1464
SD	130	110	102	105	116	140	130	124	135
N	38	39	36	38	37	43	44	49	41
Responses of 1,750 Hz and Above									
M	2171	2064	2108	2151	2099	2112	2122	2085	2134
SD	305	393	228	268	275	240	250	217	293
N	42	41	44	42	43	37	36	31	39

the judgments of our subjects would vary from the region of 2,000 Hz to the region of 1,500 Hz. A glance at Figure 2 will show that this is apparently what happens, the linear trend being significant. However, this is oversimplifying the matter. In the first place, if our assumption (or, for that matter, its converse) were true, then one would expect the subjects, collectively, to make more responses in the region of 2,000 Hz when $t_1 < t_2$ and more in the region of 1,500 Hz when $t_1 > t_2$. This is not the case; Table 2 shows that the number of responses in each region is approximately equal under each temporal condition ($\chi^2 = 6.88$, $df = 8$, n.s.). The fact that the partitioned data show the same trends as the overall data is added evidence to suggest that although our subjects' judgments were not made in the manner that the classical psychophysical literature might lead one to expect, overlying this there remains an effect of the temporal variable which is apparently the tau effect.

Figure 4. The data partitioned at 1,750 Hz into two samples.

What is Recalled from Pitch Memory?

Deutsch (1970a) did an experiment in which subjects heard two brief tones, a standard (S) and a comparison (C), separated by a 6-sec silent interval. C was either the same as S or one semitone away from it in either direction, and subjects had to respond "same or different" to the two tones. A group of subjects who scored 100% on this task went on to do an experiment in which their task was the same, but the interval between S and C was no longer silent but was filled with eight notes which they were instructed to ignore. Under these conditions, the subjects' performance deteriorated to nearly chance level. Deutsch (1970b) further showed that this deterioration might be ascribed to the degradation of information in a *specialized* pitch memory rather than to disturbances of attention, or to interference with information in a general memory store of limited capacity. There is evidence to show that material in this store is capable of consolidation, since if the S tone is included in the interpolated sequence, recognition performance is enhanced; this effect is more pronounced if the S tone is included earlier rather than later in the sequence (Deutsch, 1975).

Following the initial observation of the degradation of recognition performance when irrelevant tones were interpolated in the retention interval, Deutsch (1972) examined more closely the relationship between performance and the frequency of the interpolated notes. In this experiment, six notes were inserted in the retention interval. Five of these were chosen at random from a range of 24 centered on the F above middle C, while the sixth, which was always in the second serial position in the sequence, bore a critical relationship to the S tone. On any trial, the S tone itself was chosen at random from the octave middle C to the B above. The critical relationship was varied, in intervals of 1/6 tone, from 1/6 to a whole-tone separation. Again, the C tone was either the same as the S tone or 1 semitone above or below it, and when they differed, the critical tone was placed on the same side of the S tone along the pitch continuum as was the C tone. As before, the subjects were simply required to say whether the S and C tones were the same or not. The data revealed a systematic relationship between subjects' performance (measured as percent correct) and the tonal separation between the S tone and the critical tone. As the separation increased, there was a smooth rise in error rate to a maximum of about 35% at a separation of 2/3 tone, falling away to about 12% at a whole-tone separation.

This finding is of considerable interest to us here, and we may be in a position to extend the discussion, since our data was collected in a rather different manner. A limitation of the "same-different" paradigm is that while it can tell you what the subject could *not* do, it does not, by a study of mistakes,

give you any insight into what he was doing when he was wrong. The best kind of model that can be evolved from these data is a kind of "muddy water" system in which the interfering tone is assumed to increase the variance of the trace of the S tone stored in memory so that when a response is required the subject compares the C tone (which presumably is virtually undegraded) with a sample drawn from the S-tone distribution and responds accordingly. The nature of the interference, and of the sample, is unspecified. While some very powerful inferences can be drawn from these models (e.g., Wickelgren, 1969), they are of no use when considering phenomena such as the one reported above, since they predict changes in the *variances* of observations (and hence in the accuracy of performance in same-different experiments) but not in the *mean values* of these observations.

Let us consider how a subject might behave in our experiment. On the first presentation, he has to compute the midpoint of the first tone (T_1) and the third tone (T_3) by means of some algorithm, $\Gamma(T_3, T_1)$, which need not be specified but which we shall assume is consistently applied. We shall call this midpoint T_2' . Since T_2' did not arise from direct sensory input (and also because it simplifies the argument), we shall assume for the time being that it is stored in a manner which renders it proof against interference by incoming tones but not, of course, against decay. On the second presentation of the cycle, T_2 can be compared with T_2' as soon as the former is available and the trial is over if they are judged to be the same. If they are not, then T_2' can be "refreshed" by another calculation and the process is repeated, T_2 on the n^{th} trial being compared with the T_2' derived from the $(n-1)^{\text{th}}$ trial.

If the comparison is made in this way, then the variation we observed in our data is due to variation in T_2' and the systematic main effect reported is due to a *systematic* variation in T_2' . This, in turn, must be due to the way in which T_2' is internally derived rather than to a simple degradation of T_2' in memory, leading to increased variance.

In order to compute T_2' , T_1 must be held in memory until T_3 arrives, by which time T_2 will have been presented. Deutsch's data indicate that T_2 will have interfered with T_1 , and our data seem to indicate that the effect of this interference is not to increase the variance of T_1 (or, at least, not *only* to increase the variance of T_1), but to make the retrieved value of T_1 appear closer in pitch to T_2 than was physically the case. Thus, T_2' has a larger value than would otherwise be the case. A more conventional formulation of this would be that whatever the representation of T_1 in memory, the effect of T_2 is to skew the distribution of T_1 towards T_2 . This effect, reasonably enough, diminishes with time and would presumably asymp-

tote at some point where we would be able to make some comment on the nature of $\Gamma(T_3, T_1)$. One further point adds weight to this argument. If the tonal sequence used in our experiment were reversed so that $T_1 = 3$ kHz and $T_3 = 1$ kHz, then for small values of $t_1/(t_1 + t_2)$ the representation of T_1 would again be skewed towards T_2 , giving a *lower* value of T_2' than might be expected. As $t_1/(t_1 + t_2)$ increased, this effect would diminish and the resulting graph would have a positive slope, the opposite to that obtained in the present situation. The limited data presented in Cohen et al. (1974) indicates that this would indeed be so.

If T_2' is stored in the same way as the stimulus tones, then, in the scheme of things we have described, its value would be subject to interference by T_1 before comparison with T_2 takes place. Furthermore, this interference would be in the opposite direction to that described above. However, in our experiment, the interval between the end of T_3 and the onset of T_1 on the next trial is more than twice that of the maximum delay between T_1 and T_2 on the same trial, so that any interference of T_1 on T_2' would be small compared to that of T_2 on T_1 .

Applying the above reasoning to the data from Deutsch (1972) cited earlier, we might conclude that when her subjects were wrong it was because the sample of the S tone which they retrieved from memory to make their comparisons was of the order of 1 semitone removed from its "true" value. This is because, presumably in order to judge as identical two tones which were in fact 1 semitone apart, one of them must have been distorted by roughly this amount. This does not contradict our present findings; the maximum interference we obtained (1,838 Hz) is almost exactly one semitone above the musical midpoint of our sequence, 1,834 Hz being the calculated value. Why it should be that, as Deutsch (1972) noted, performance is better when the S and C tones are the same compared with when they differ is not accounted for in the above reasoning. It may, of course, be simply due to a response bias on the part of the subjects; Deutsch herself does not appear to attach much importance to the difference.

Deutsch and Faroe (1975) proposed that this interference effect could be accounted for by a lateral inhibition process. The suggestion was based on three pieces of evidence: the shape of the initial error curve (Deutsch, 1972), the range over which the effect operated, and the accumulation of errors when two critical tones were used, one on either side of the S tone on the pitch continuum (Deutsch, 1973). They derived a mathematical model which accurately predicted the shape of a *disinhibition* function using the initial error curve as an input. It seems that the present data are less likely to be accounted for by such a process if only because the range of frequency dif-

ferences we used is much larger than that employed by Deutsch. However, we do seem to have observed interference in pitch memory, and whatever processes underlie that phenomenon, it appears that they are the basis of the auditory tau effect.

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(Received for publication March 7, 1979;
revision accepted August 17, 1979.)