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Perception, Production, and Imitation of Time Ratios by Skilled Musicians

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INTRODUCTION

Among the human skills in which timing and time perception are critical, musical skill is distinctive: for most players a notation specifies temporal pattern explicitly and provides a criterion to which performance can be compared. Because of their years of practice in the use of this notation, the behavior of professional musicians can plausibly reveal some of the ultimate capacities and constraints of human timing mechanisms. We have examined the performance of skilled musicians in three laboratory tasks designed to capture temporal aspects of music. We focused on the short time intervals—fractions of a second—that are among the shortest durations specified by musical notation. As in Western music, these intervals occurred in the context of a train of periodic beats and were defined as fractions of the beat interval. Our three tasks—perception, production, and imitation—all appear to be required of musicians during ensemble rehearsal and performance, for example. It is plausible that because players try to "keep together," ensemble experience would cause performance in the three tasks to become at least consistent and probably correct as well (that is, consistent with the notation). Neither of these expectations was borne out by our experiments; instead, we observed surprisingly large systematic errors and inconsistencies.

The principal subjects were three professional musicians: a flutist, a cellist, and Paul Zukofsky (PZ), violinist and conductor. We also obtained a small amount of corroborative data from Pierre Boulez, composer and conductor. A detailed report of our results is available, based on group data.[1] In the present paper we describe only our more interesting findings, illustrated with data from PZ, who is the most musically experienced of our principal subjects, whose performance we examined in a wider variety of procedures than the other subjects, and whose data are more consistent than theirs, both within and across experiments. The picture generated by the group data is somewhat less clear, but leads to the same conclusions.

THREE TASKS OF TEMPORAL PSYCHOPHYSICS

We used two kinds of stimuli, shown on the left of FIGURE 1. A *time pattern stimulus* contained two or more *beat clicks* separated by a *beat interval.* The beat interval was usually 1 sec. One or more of the beat clicks was followed by a *marker click* after a *fractional interval, f,* that defined a fraction of the beat. A *fraction-name stimulus, n,* was presented both as a numerical fraction and in musical notation, where a quarter note was defined as one beat. On the right of the figure are shown the two kinds of response. In making a *fraction-name response, N,* the subject would select a category such as "less than 1/8 beat" or "between 1/8 and 1/7 beat." In making a

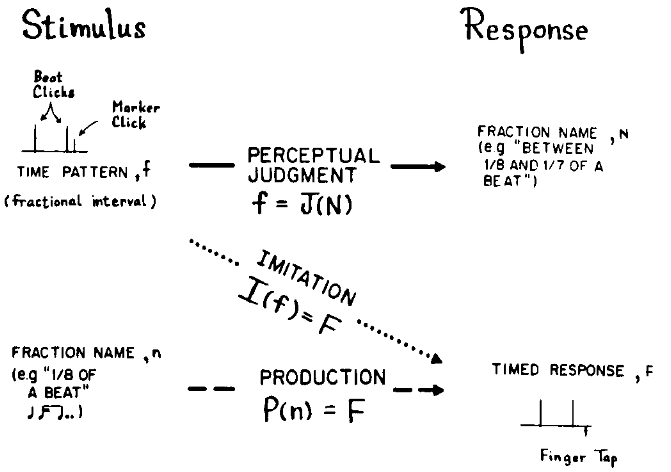

FIGURE 1. Stimuli, tasks, and responses.

timed response, the subject tapped his finger after a beat click, thereby producing a fractional interval, F, between beat click and tap.

Stimuli and responses were linked by three different tasks, as shown in the center of the figure. In *perceptual judgment* the subject assigned fraction names to time patterns. He thereby generated a *judgment function,* $f = \mathbf{J}(N)$, that maps fraction names onto their subjectively equivalent fractional intervals. In *production* the subject made a timed response to produce a fractional interval associated with a specified fraction name. He thereby generated a production function, $\mathbf{P}(n) = F$. In *imitation* (sometimes called the "method of reproduction") a time-pattern stimulus elicited a subjectively equivalent timed response. We thereby obtained an imitation function,

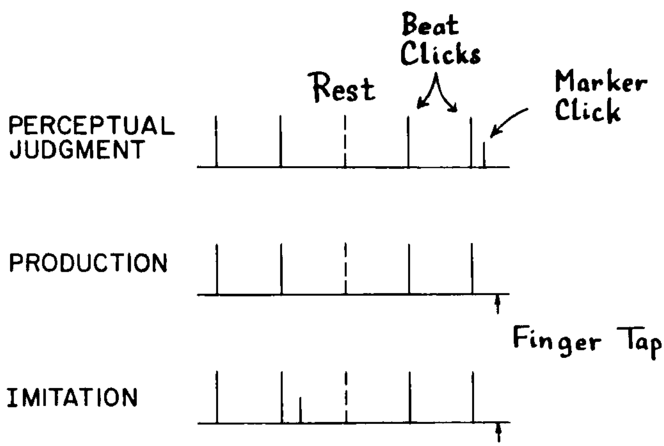

FIGURE 2. Sequences of beat clicks, marker clicks, and finger taps in Experiments $\mathbf{J}_1$, $\mathbf{P}_3$, and $\mathbf{I}_5$.

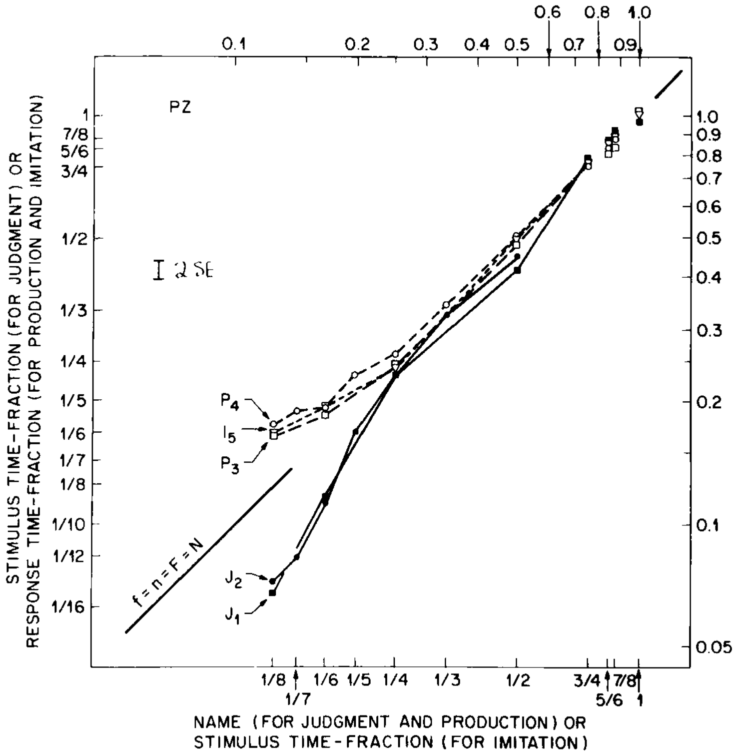

FIGURE 3. Results for subject PZ from five experiments: judgment (**J**), production (**P**), and imitation (**I**). Ordinate *(abscissa)* values are given as fractions on a logarithmic scale on the left *(bottom)* and as decimal values on the right *(top)*. Error bar indicates approximately 2 S.E. based on between-session variability. If the ordinate value is regarded as a function of the abscissa value, the functions shown are estimates of $f = \mathbf{J}^{-1}(N)$, $F = \mathbf{P}(n)$, and $F = \mathbf{I}(f)$.

$\mathbf{I}(f) = F$. To permit performance to stabilize, conditions in all experiments remained constant for at least 25 trials.

PERCEPTUAL JUDGMENT OF BEAT FRACTIONS

The stimulus pattern in our first perception experiment is shown in FIGURE 2. Two pairs of beat clicks separated by two beat intervals (a *rest*) were followed by a single marker click. For each of a set of fraction names we used an adaptive psychophysical procedure to determine the fractional interval that is subjectively equivalent to it. The resulting judgment function is labeled $\mathbf{J}_1$ in FIGURE 3. The fractional interval, f, is plotted as a function of fraction name, N. Both scales are logarithmic.[a] If stimulus and response agreed, data would fall on the straight line with unit slope. Instead, our subject radically overestimated fractions less than 1/4 beat (or 250 msec). Consider

[a]Power functions appear as straight lines on such a plot.

the case of 1/8 beat, for example. Accurate performance would assign this fraction name to a fractional interval of 125 msec; instead, it is assigned to an interval of about 67 msec, or 1/16 beat. Thus, for small fractions, the assigned fraction name is larger than the fractional interval.[b] The *N*-value grows more slowly than the *f*-value, however, coming into approximate agreement at about 1/4 beat. Despite the poor *accuracy* for small fractions, judgment *precision* is high: the difference threshold at 1/8 beat was only 4.3 msec (about 6%), for example.

PRODUCTION OF BEAT FRACTIONS

The large errors in the *perception* of small fractions make it particularly interesting to examine musicians' accuracy in *producing* such fractions. One appealing possibility is that production is mediated by a simple feedback process in which the subject judges the fraction he produces with respect to the fraction name he is trying to produce, and adjusts later productions accordingly. Suppose also that produced fractions are judged by means of the same perceptual mechanism used in the judgment task. The production function should then approximate the judgment function: $\mathbf{P}(n) = \mathbf{J}(N)$ when $n = N$. Thus, overestimation of small fractions (assigning fraction names that are too large) would lead to underproduction (producing fractional intervals that are too small).

The events on each trial in our first production experiment are shown in FIGURE 2. They are the same as in the perception experiment, except for replacement of the marker-click stimulus by a finger-tap response.[c] With each tap the subject heard the thump of his finger striking a hard surface. The production function we obtained is labeled $\mathbf{P}_3$ in FIGURE 3. The expectation from a feedback mechanism is violated dramatically. For small fractions the intervals produced are too large rather than too small. That is, we have overproduction rather than underproduction. Whereas the subject *judged* 67 msec to be 1/8 of a 1-sec beat, for example, he *produced* a mean fractional interval of 164 msec for the same fraction name. Furthermore, he seemed satisfied with his responses, and did not experience his taps as being late.[d] For small fractions in the perception task we have seen that the fraction stimulus, *f*, that is subjectively equivalent to a fraction name, *N*, changes more rapidly than the *N*-value. In contrast, the fraction, *F*, produced changes more slowly than the *n*-value.

Several analyses and experimental variants were directed at understanding the large systematic errors we had found in judgment and production, as well as their inconsistency. In the present report we consider nine of these. Others, together with these, are considered in greater detail in the full report.[1]

FURTHER ANALYSIS OF PERCEPTUAL JUDGMENT

Psychophysical Procedure

One concern is whether aspects of the judgment data may depend on special features of our psychophysical procedure. In any block of trials in the adaptive

[b] Figure 7 provides an outline of our principal findings.

[c] Note that although infrequent in earlier music, the playing of a note after the beat without playing a note on the beat is not unusual in the music of the past 60 years.

[d] This is an informal impression, not based on analysis of systematically collected data.

procedure, subjects judged time fractions with respect to just one fraction name, and the fractional intervals were concentrated in the range where judgments were the most difficult. In a second experiment we used a method more akin to traditional psychophysical scaling in which both these features were altered. The subject categorized a wide range of time-pattern fractions into one of eight categories of fraction names, ranging from "less than 1/8 beat" to "greater than 1/2 beat," in each trial block. Also in contrast to the first experiment, two beat clicks rather than only one were followed by marker clicks, providing two observations of the fractional interval on each trial. Results are labeled $\mathbf{J}_2$ in FIGURE 3. The two judgment functions are almost identical, despite the differences between procedures.[e]

Fractional Interval Defined by Subjective Onset Versus Offset of Marker

A second attempt to discover a source of the judgment errors was based on the possibility that the internal representation of a brief click may have a longer duration than the click itself. Suppose that when beat and marker clicks are close together, the subjective duration of the fractional interval is defined by the *onset* of the internal representation of the beat and the *offset* of the internal representation of the marker. Such a mechanism could then produce overestimation of the kind we observed. To test this possibility we compared judgments of our normal stimuli, in which clicks were 5-msec tone bursts, with stimuli in which the marker duration was prolonged by about 60 msec. Contrary to the idea that offset time is important, this variation produced no change in the judgments, for either small or large fractions.[f]

FURTHER ANALYSIS OF PRODUCTION

We next turn to five of our efforts to understand the systematic errors in the production task and the inconsistency between production and judgment performances for small fractions.

Opportunity for Adjustment to Feedback

As mentioned above, our subject did not report experiencing his finger-tap responses as being late for either small fractions or large. Nonetheless there may have been discrepant feedback from the perception mechanism, but too little opportunity to adjust to it, given only one production per trial. On each trial in a second production experiment the subject produced timed responses after each of ten successive beat clicks. We found no tendency for the error to be reduced over the ten successive responses. Mean produced fractions based on all the responses are labeled $\mathbf{P}_4$ in FIGURE 3. Performance agrees closely with the first production experiment; if anything, the tendency toward overproduction is slightly greater.

[e]The procedural differences did influence judgment precision, however; difference thresholds were about twice as large in the second (multiple-fraction) experiment.

[f]The measured mean change in $f = \mathbf{J}(N)$, averaged over six fraction names, was 0.6 ± 1.9 msec. There was neither a mean effect of marker duration nor an interaction of marker duration with fraction size. This finding may reflect a general property of the perception of timing and rhythm in music: the dominance of the sequence of time intervals between successive *attacks*, and the relative unimportance of *release* times.

Subjective Delay of Tap versus Click

A second potential source of inaccuracies in production might be a difference between two critical subjective delays. One is the interval between the occurrence of a click and its perceptual registration. The second is the interval (possibly negative) between our measurement of a tap and when the subject perceives it to have occurred. If these two delays differed, then direct comparison of the intervals between beat click and marker click in perception and between beat click and tap in production would be inappropriate. To estimate the difference between the two subjective delays we asked subjects to tap in synchrony with one or more beat clicks. The difference can be estimated by the mean asynchrony between tap and click; the asynchrony was small—about 10 or 20 msec, depending on the procedure—clearly too small to explain the observed effects. On the assumption that the difference between subjective delays does not depend on the beat fraction, the production data in FIGURE 3 have been corrected by these small amounts.

Improved Feedback from Finger Tap

The disparity between performances in perception and production led us to question a feedback model of production, which suggested in turn that we scrutinize the feedback itself. The feedback from tapping the finger included tactile, proprioceptive, and auditory cues, but not the marker click used in the perception task. In additional production experiments with both single- and multiple-tap procedures, but limited to the fraction 1/8 beat, each finger-tap generated a marker click. The sequence of clicks in judgment and production thereby became identical. The production performance was virtually unchanged, however; we found only a 10 msec change in the mean interval produced.

Musical Instrument Response

Another potential source of the production error might have been our choice of finger-tapping as a response. (The subject was a skilled violinist but not a skilled finger-tapper, at least at the start of these experiments.) We ran the single-response production experiment again, but now the response was to play a single note on the violin after the final beat click. We measured the onset time of the note as the subject attempted to produce the fractions 1/8, 1/2, and 1 beat. The amount of overproduction of the small fraction did not decrease. (In fact, it was nonsignificantly greater by 12 ± 11 msec for PZ.)

Minimum Reaction Time

The potential sources discussed above of the production error and the production–perception disparity had to be considered. However, we had little *a priori* reason to expect that even if they had been important, their effects would have depended on fraction size. One constraint that might have such differential effects is the existence of a minimum reaction time (RT). The minimum RT to auditory stimuli is between 100 and 150 msec. Furthermore, there are delays between excitation of a musical instrument and its acoustic response. The combination of these two effects makes it virtually impossible to produce a note 125 msec after a signal to respond (such as a beat click) when the signal is the event that initiates the response-timing process. If we assume that the timing of an offbeat response starts with the immediately preceding beat, it follows that the notation often calls for production of discriminably different response delays, some of which are less than the minimum RT. One solution would be to bias productions just as we have observed, so that for different small fractions the mean intervals produced are greater than the minimum RT, but still distinct.

A test of this explanation is provided by variances of the finger-tap delays, *Var(F)*, together with an argument suggested by Snodgrass, Luce, and Galanter.[2] We assume that as its mean increases, the variance of a response delay also increases, where the delay is measured from the event that initiates the timing process. If the responses for all fractions were timed from the final beat click, we would therefore expect *Var(F)* to increase with fraction size. Instead, we found it to vary as a *U*-shaped function of fraction size, with a minimum between $n = 1/4$ and $n = 1/2$.[g] This pattern of variability would be expected if small fractions, but not large ones, were timed from the penultimate beat; if so, overproduction cannot be explained as compensation for a limited speed of response.

PRODUCTION OF MULTIPLE SUBDIVISIONS OF THE BEAT

How can the existence of large production errors for small fractions be reconciled with our belief that musicians are able to fill a beat interval accurately with a sequence of equally spaced actions? Could the production error depend on our use of a single, isolated response?[h] To address this question we studied the three conditions shown in FIGURE 4 in a new production experiment. The beat interval here was ½ sec instead of 1 sec, incidentally testing the generality of our effects. One of the conditions required an isolated offbeat response, with a target fraction of ¼ beat, equivalent to a fractional interval of 125 msec. There were two multiple-response conditions. In one the subject started with a tap on the beat, and alternated between index fingers to fill the beat interval with quarter-beat taps. An unusual interval between the first two taps here would reveal any general distortion of subjective time near the beat. In another condition the initial on-beat tap was withheld. If overproduction depends on response isolation, then the presence of later taps within the same beat interval should eliminate it, especially since the final tap was supposed to be made on the next beat.[i]

Consider first the results from the 5-tap condition. All tap delays, and in particular the delay of the second tap, fall close to the fitted line. There appears to be no general distortion of subjective time near the beat. Furthermore, the slope of the linear

[g] Because imitation performance is virtually identical to production, in variability as well as mean, a good estimate of the effect of fraction size on the variability of tap delay is provided by *Var(F)* averaged over the two production experiments described above and the imitation experiment to be described in Section 9. Fractions that were examined in all three experiments include 1/8, 1/6, 1/4, 1/2, 3/4, 5/6, and 7/8; for PZ the corresponding RMS values of the S.D. are 21.3, 20.3, 16.7, 25.2, 32.4, 42.2, and 42.4 msec, respectively.

[h] Musicians could perhaps learn to fill an interval evenly, without accurate perception or production of isolated beat fractions, by employing judgments of evenness and synchrony, together with the ability to count actions.

[i] The first tap in the 5-tap condition provided the synchronization correction that we used to adjust all taps in the three conditions. Application of the correction in this way requires us to assume that the location of the initial subjective beat as well as the subjective beat rate depend only on the beat clicks, and are influenced neither by whether there is a tap on the beat nor by the number of taps that follow.

function is less than unity, giving a value of 435 rather than 500 msec for position 5. (Since the subject felt satisfied with his productions, we must assume that the subjective beat interval was shorter than the actual beat interval by about 13%.) In other words, with multiple subdivisions starting on the beat there is no evidence for overproduction of the small fraction. Consider next the 1-tap condition. Just as in our other experiments the response is delayed relative to the correct response time of 125 msec. Because of the shortening of the subjective beat interval, the amount of overproduction is even greater when referred to the second tap in the 5-tap condition. Consider finally the 4-tap condition. The first response—the tap in position 2—is delayed here as much as in the 1-tap condition. The overproduction effect therefore does not depend on the offbeat response being isolated. Instead, it appears to result from an onbeat response being withheld.

The displaced parallel lines provide a good description of performance in the two multiple-response conditions, indicating that every tap in the 4-tap condition is delayed

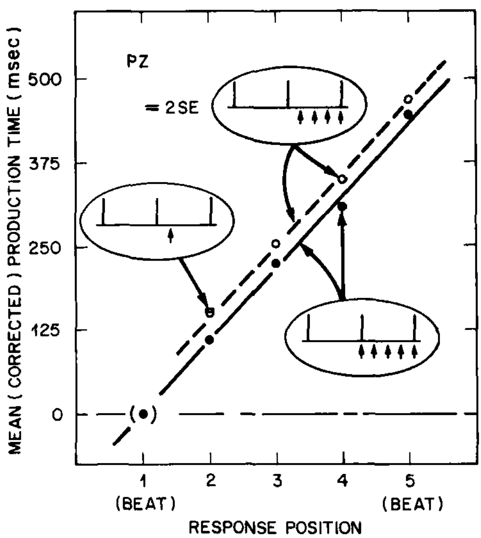

FIGURE 4. Stimulus and response patterns in three conditions in an experiment on multiple subdivisions of the beat, together with results. Mean response delays have all been corrected by the mean delay (−34.7 msec) between the second beat click and the first tap in the 5-response condition. Data from the two multiple-response conditions have been fitted by parallel lines. The displayed ± S.E. bar is appropriate for assessing adequacy of the fitted lines.

relative to the 5-tap condition, and by about the same amount. This phenomenon seems best described as *displacement of the subjective beat.* As in some circadian phenomena, the phase of a periodic process has been changed with no alteration in its period. We find it especially remarkable that the delay of the first tap is propagated all the way through the last tap, despite the presence of a final beat click.

CONJECTURES ABOUT FAILURE OF THE FEEDBACK MODEL OF PRODUCTION

The beat-displacement effect suggests one possible source of failure of the feedback model. It is plausible that subjects judge their response delays relative to the *subjective* train of beats. If so, the beat displacement associated with the delayed offbeat response would reduce the apparent delay of this response. Such an effect might explain a subject's inability to recognize and correct his overproduction. It would be too small an effect, however, to explain the major part of the discrepancy between overproduction and the underestimation we observed in the judgment task, which would require that the magnitude of beat displacement *exceed* the delay of the offbeat response, rather than merely equaling it.

The expectations from the feedback model of production that were violated depend on the assumption that the time-perception processes that accompany production are the same as those used in the judgment task. The beat-displacement effect leads us to question this assumption. The existence of the effect reminds us that in production the fractional interval terminated by the finger tap must not only be timed, but must also be placed in proper phase relation to the train of beats. Performance of small fractions in the production task therefore requires the timing of both a beat interval and a beat fraction within the same sequence. In contrast, there is no reason to believe that *judgment* of a beat fraction depends on concurrent judgment of a full beat interval.[j] It is possible that this difference between tasks contributes to the failure of the feedback model.

Results from a final judgment experiment provide weak evidence that favors this possibility, indicating that if successive long and short intervals must both be judged, the perception of at least one of them may be dramatically altered. We used click patterns like those shown in FIGURE 5, with a 1-sec beat interval, and asked whether judgment of the large interval between the final beat click and the pair of marker clicks would be influenced by the requirement also to judge the small interval between markers. On each trial the subject had to judge whether the interval between markers was large or small relative to $\frac{1}{8}$ beat, and then also to judge whether the interval between the final beat click and the markers was large or small relative to a full beat. Judgments of the small beat fraction were very similar to performance in a single-judgment control condition. Judgments of the larger interval were enormously more variable than in its control condition, however: The difference threshold was increased by a factor of ten, from about 4% of the beat interval to about 40%.[k]

IMITATION OF BEAT FRACTIONS

Imitation of beat fractions is of interest partly because it provides a further opportunity to determine the sources of error in perception and production. In judgment and production tasks, subjects must associate beat fractions with fraction names. In imitation (see FIGURE 1), the stimulus of the judgment task is mapped onto the response of the production task; fraction names are not explicitly involved. If the errors in judgment and production are due to the input or output of fraction names, it follows that imitation performance should be accurate.[l]

Such accurate imitation of time intervals is one possibility that has been considered in previous research.[3] A second possibility that has been advanced is that imitation is

[j] Judgment of a fractional interval could use a stored representation of the beat interval. Alternatively, the beat interval might not be directly represented at all, but would determine the calibration of a mechanism that assessed beat fractions.

[k] In further work along these lines it will be important to force high accuracy in judgments of the large interval and to search for effects on both mean and variability of judgments of small fractions.

[l] The converse does not follow: if imitation were accurate, we would know only that the function that relates stimulus fractions to their internal representations must be the inverse of the function that relates internal representations to produced fractions.

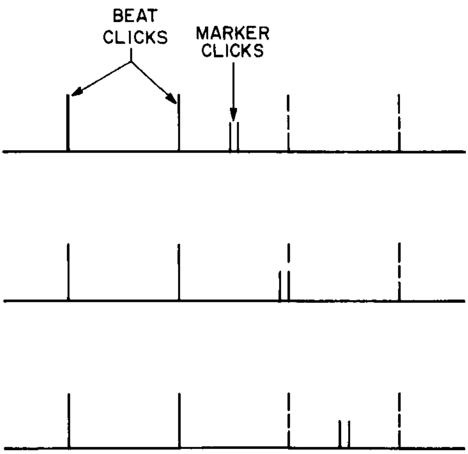

FIGURE 5. Examples of sequences of beat clicks and marker clicks in a dual-judgment experiment. *Broken lines* represent beats for which no beat click was presented.

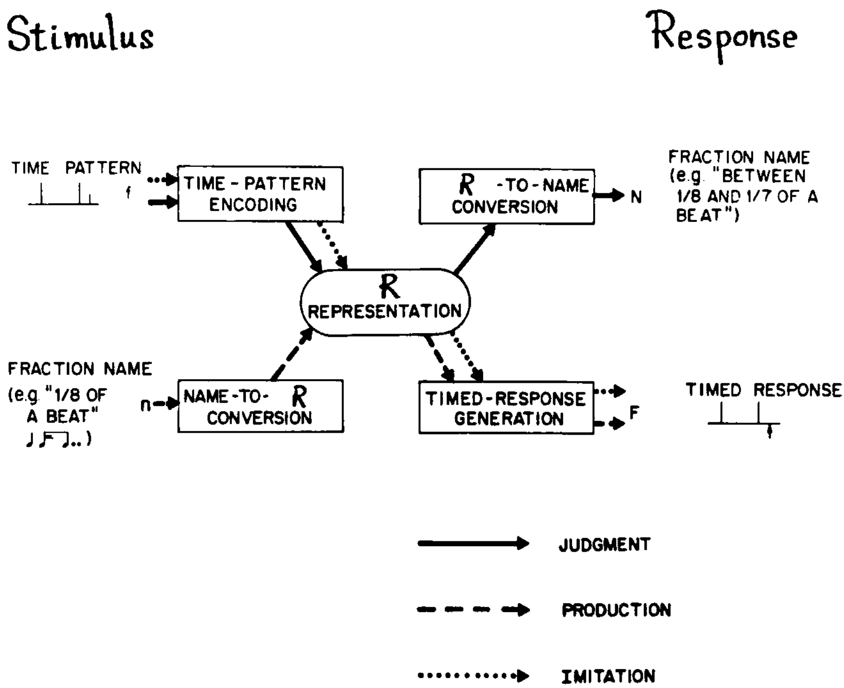

FIGURE 6. An information-flow model of perception, production, and imitation of beat fractions. The model incorporates four processes that convert time-pattern (f) or fraction-name (n) stimuli into time-pattern (F) or fraction-name (N) responses, and that make use of a common internal fraction-representation. Paths of information flow for the three tasks are represented by *arrows*.

accomplished by concatenating two processes: a judgment process that covertly assigns a name to the time pattern, and a production process that converts this name into a timed response.[4] Given our findings of overestimation as well as overproduction of small fractions, this *full-concatenation model* implies that the response fraction in imitation will be too large by the *sum* of the errors in the other two tasks; we call such an outcome *strong overimitation.*

The imitation data are labeled I_5 in FIGURE 3. Results conform to *neither* possibility. Instead, responses to small fractional intervals in imitation were virtually identical to responses to the *names* of these fractions in production. The significance of this outcome is best explained in the context of the following model of performance in our three tasks.

AN INFORMATION-FLOW MODEL OF THE PERCEPTION, PRODUCTION, AND IMITATION OF BEAT FRACTIONS

In the skeleton model diagrammed in FIGURE 6 we limit ourselves to accounting for the relations among performances in our three tasks. Each task involves processes that perform input, output, and possibly translation functions. Parsimony leads us to postulate the minimum number of processes consistent with our data, and hence the maximum number of processes shared between tasks.

The processes underlying perceptual judgment are shown by the two upper boxes. A time-pattern stimulus generates an internal fraction representation. This representation is converted into a fraction name to generate the required response. The processes underlying production are shown by the two lower boxes. A fraction-name is converted into an internal representation of the same kind as in the judgment task. This representation is then used to produce the required timed response. A full-concatenation model of imitation would most naturally be represented by a mechanism in which the upper and lower pairs of processes made use of distinct internal representations. In such a mechanism information could not flow directly from time-pattern encoding to timed-response generation. Instead, to connect these two operations the covert output of the pair of processes used in judgment (a fraction name) would become the input for the pair of processes used in production. Because such a model can be rejected, we adopt a *partial-concatenation model* in which imitation makes use of a common internal representation, and shares only the encoding process with the judgment task and only the response-generation process with the production task.

Each of the four processes in the model can be thought of as a function or transformation that maps its input onto its output. Qualitative aspects of our data restrict the relations among these transformations. The most important of these relations is based on the close agreement of the data from production and imitation: When time-pattern and fraction-name correspond, they lead to the same timed response, so that $\mathbf{P} \cong \mathbf{I}$. This in turn means that they must have produced the same internal representation; thus the two input transformations are the same. The internal representation therefore creates a veridical mapping between the two kinds of stimuli.[m] By a complementary argument from the finding that responses to the same fractional interval in imitation and judgment are *not* the same ($\mathbf{J}^{-1} \neq \mathbf{I}$) we conclude that the two output transformations are distinct.

Both the production and judgment tasks generate psychophysical scales that

[m] By a mapping or psychophysical scale that is veridical we mean one that associates the beat fraction $1/n$ with the fractional interval b/n, where b is the beat interval.

describe the subject's mapping of musical notation onto time fractions. As we have already seen, neither of these scales is veridical, and, moreover, they disagree with each other. Both scales are *explicit*, in that the subject's response is identified directly with one of the terms in the psychophysical function. By combining results from imitation, $F = \mathbf{I}(f)$, and production, $F = \mathbf{P}(n)$, which involve the same response, we generate an *implicit* psychophysical scale that relates musical notation, n, to time fractions, f, when both are presented as stimuli: $n = \mathbf{P}^{-1}\mathbf{I}(f)$. Our data indicate that this implicit scale is veridical, despite the systematic errors in each of the three explicit relations, **J**, **P**, and **I**.[n]

FOR SMALL FRACTIONS (< $\frac{1}{4}$ Beat)

- **PERCEPTUAL JUDGMENT**

  Results: Overestimation — $f = J(N) < N$

- **PRODUCTION**

  Expectation:

  Underproduction (Feedback Model) — $F = P(n) < n$

  Results: Overproduction — $F = P(n) > n$

- **IMITATION**

  Alternative Expectations:

  a) Veridical — $F = I(f) = f$

  b) Strong Overimitation (Full-Concatenation Model) — $F = I(f) >> f$

  Results: Overimitation — $F = I(f) > f$,

  and, for $f = n$, — $I(f) = P(n)$

FIGURE 7. Summary of principal expectations and findings.

SUMMARY

We have described our exploration of the judgment, production, and imitation of fractions of a beat by skilled musicians, illustrating our findings with data from violinist and conductor Paul Zukofsky. For small fractions we found systematic and

[n]Given our model it is tempting to inquire whether "error" or "distortion" in any single constituent in the model can account for the performance errors in all three tasks, and their relations. Such an inquiry succeeds qualitatively: The only such single constituent that could be responsible is the internal representation, R, since this is the only constituent common to the three tasks. Suppose that for small fractions, R is "expanded" so as to correspond to a larger fraction. Examination of FIGURE 6 reveals that such an expansion, alone, would produce the three effects we observed: overestimation, overproduction, and overimitation. Quantitatively, however, this explanation fails, because it requires that $\mathbf{J}^{-1} = \mathbf{I}$, a relation we can reject reliably if we use the full range of data. The explanation might succeed, however, if we limited it to small fractions.

substantial errors. In the judgment task small stimulus fractions are associated with names that are too large (overestimation). In both production and imitation tasks the fractions produced were too large (overproduction, overimitation). A summary of our findings and of the expectations they violate is provided in FIGURE 7.

The temporal patterns we used are perhaps the simplest that qualify as rhythms, incorporating just a beat interval and a fraction. The phenomena we discovered in relation to these simple patterns, and their implications for underlying mechanisms, must be considered in attempts to understand the perception and production of more complex rhythms, as in actual music.

We explored and rejected several plausible explanations for the overestimation and overproduction of small fractions. Although we have as yet no satisfactory explanations of the errors themselves, relations among the errors have powerful implications for human timing mechanisms. The relation between the errors in judgment and production requires us to reject a feedback model of production, in which a subject uses the same processes as in the judgment task to evaluate and adjust his performance in the production task. An explanation of the inconsistency between judgment and production seems most likely to lie in a change in time perception induced by the production task. Together with the existence of systematic errors in judgment, the equality of the errors in production and imitation argues that imitation is not accomplished by concatenating all the processes used in judgment and production. Our results are instead consistent with a model containing four internal transformation processes, in which judgment and production share no process, but do involve the same internal-fraction representation, and in which imitation shares one process with judgment and another with production.

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