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Effect of Deviations From Temporal Expectations on Tempo Discrimination of Isochronous Tone Sequences

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The effect of deviations from temporal expectations on tempo discrimination was studied in 3 experiments using isochronous auditory sequences. Temporal deviations consisted of advancing or delaying the onset of a comparison pattern relative to an "expected" onset, defined by an extension of the periodicity of a preceding standard pattern. An effect of onset condition was most apparent when responses to faster and slower comparison patterns were analyzed separately and onset conditions were mixed. Under these conditions, early onsets produced more "faster" judgments and lower thresholds for tempo increases, and late onsets produced more "slower" judgments and lower thresholds for tempo decreases. In another experiment, pattern tempo had a similar effect: Fast tempos led to lower thresholds for tempo increases and slow tempos led to lower thresholds for tempo decreases. Findings support oscillator-based approaches to time discrimination.

The perception and production of temporal patterns are fundamental abilities that are crucial for a wide range of human activity. Yet, there is still much that is not understood about some of the simplest temporal abilities. In particular, there is considerable disagreement concerning the mechanisms used to make duration and tempo judgments. In this series of experiments, we examined different theories of time perception in the context of a tempo discrimination task.

A common assumption in models of time perception is that duration is measured by an interval timer that records the number of "clock ticks" that fill a presented time interval, such as the duration between the onset times of two tones. According to these interval-based theories of time perception, estimated durations are stored in memory and then retrieved as necessary for judgments of relative duration. A typical task requires that a person distinguish between a standard time interval (T) and a comparison interval ($T + \Delta T$). In the interval model, relative duration judgments are made by comparing the number of recorded ticks filling the two intervals. People's ability to distinguish between the two intervals is modeled by the statistical variability of the interval timer (Drake & Botte, 1993; Ivry & Hazeltine, 1995; Ivry & Keele, 1989; Keele, Pokorny, Corcos, & Ivry, 1985).

Much of the debate has focused on the precise form of the interval timer's variability and whether time perception supports Weber's law. Many researchers have reported data that are consistent with a generalized form of Weber's law within a limited time range, with thresholds of 2–10% reported for a range of T values between 100 and 2,000 ms (Creelman, 1962; Divenyi & Danner, 1977; Getty, 1975; Killeen & Weiss, 1987).

One crucial issue that has received relatively little attention in the development of interval-based models is the effect of a surrounding temporal context on judgments of the relative duration of two time intervals (e.g., when T and $T + \Delta T$ are embedded within a longer pattern, as is found in music). Several recent studies of temporal resolving power have begun to reveal the significance of context on time discrimination. A common approach is to embed to-be-detected time changes within a sequences of intervals (Bharucha & Pryor, 1986; Drake & Botte, 1993; Espinoza-Varas & Watson, 1986; Hirsh, Monahan, Grant, & Singh, 1990; Jones, Jagacinski, Yee, Floyd, & Klapp, 1995; Yee, Holleran, & Jones, 1994). Time discrimination has been examined for simple isochronous contexts for both single-interval changes embedded within an otherwise isochronous sequence (Halpern & Darwin, 1982; Schulze, 1989; ten Hoopen et al., 1994) and for whole-pattern changes (i.e., uniform changes in all intervals) in tasks that require participants to compare the tempo of two isochronous sequences (Drake & Botte, 1993, 1994; Michon, 1964). In both cases, increasing the number of isochronous intervals before the time changes improves time sensitivity (Drake & Botte, 1993; Ivry & Hazeltine, 1995; Schulze, 1989), whereas adding variability to the surrounding context reduces time sensitivity.

Interval-based models account for context effects in terms of the statistics of the intervals constituting a pattern. For example, the intervals in a simple isochronous pattern have

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been proposed to provide "multiple looks" at a recycled duration (T) and thereby improve the statistical estimate of it (Drake & Botte, 1993; Keele, Nicoletti, Ivry, & Pokorny, 1989; Schulze, 1989). Others have suggested that the discrimination of temporal changes within sequences (at least at moderate tempos) is predicted by an average-interval Weber's law in which only the duration of the altered intervals on either side of a temporally displaced tone are considered (Monahan & Hirsh, 1990). According to this view, meter, accent, and other higher level constructs are not necessary to account for the discrimination of temporal changes in sequences of tones.

In contrast, an approach to time perception that involves the entrainment of oscillatory timers (or attentional rhythms) provides a different account of time perception and context effects (Jones, 1976). According to this view, the temporal structure of events in the environment establishes the periodicities of internal (neural) oscillators that are involved in judgments of relative duration (Jones & Boltz, 1989). Temporal distinctions in this framework are based on the temporal contrast that occurs between internal and external periodicities, with time sensitivity predicted by the degree of synchrony and the magnitude of temporal contrasts (Jones & Boltz, 1989; Large, 1994; McAuley, 1995). Because attentional rhythms are driven by the timing of the stimulus patterns, they are affected by the temporal relations within a given stimulus pattern as well as those that span a trial or block of trials (see Jones, Kidd, & Wetzel, 1981; Kidd, Boltz, & Jones, 1984). Although interval-based models (Drake & Botte, 1993; Keele et al., 1985; Schulze, 1989) incorporate some sensitivity to temporal properties of a stimulus (e.g., number and variability of the intervals), these are limited to statistical properties of the stimulus intervals. Other high-level temporal relations, such as the duration of the interval separating to-be-compared patterns relative to the temporal structure of the patterns, are not taken into account (Ivry & Hazeltine, 1995).

Oscillator-based models assume that oscillator pulses are associated with greater attentional focus and correspond to times at which stimulus events are expected. Thus, the interval between a standard and comparison pattern in a discrimination task is crucial because it determines when the onset of the comparison pattern occurs relative to pulses (or beats) of the reference oscillator. If the onset of the comparison pattern coincides with reference pulses of the oscillator, then the subsequent time interval begins at an expected point in time and is resolved more accurately than when the onset of the comparison pattern occurs at an "unexpected" temporal location (i.e., it does not coincide with the reference pulse). In other words, it is the phase relation between the periodicities of the comparison sequence and the reference oscillator that is the critical variable in modeling performance. For interval-based discrimination, relative phase is not an issue in modeling performance.

In a series of time perception studies, Keele et al. (1985, 1989) argued that time discrimination data support interval timers rather than oscillatory "beat-based" timers. As primary evidence for interval-based timing, they cited data from tasks in which the temporal gap between a standard and comparison pattern is varied. Most recently, Ivry and Hazeltine (1995, Experiment 4) examined time discrimination using two- and four-tone isochronous standard sequences with a fixed interonset interval (IOI) of 500 ms, followed by a comparison interval that was either continuous with the standard (maintaining a constant 500-ms IOI) or separated from the standard sequence by a temporal gap of roughly 1 s (IOIs of 950, 1,050, and 1,150 ms). The listener's task was to judge whether the comparison IOI was shorter or longer than the fixed IOI of the isochronous standard. They assumed that if a reference beat is established by the isochronous standard, then listener performance for the continuous condition should be better than for the discontinuous condition. Because they found no difference in listener discrimination performance between the two conditions, they concluded that an oscillator-based mechanism could not be involved.

However, Ivry and Hazeltine (1995) seemed to preclude the possibility that the reference beats continue in the discontinuous condition when the temporal gap exceeds 500 ms. They essentially ignored the precise temporal onset of the comparison sequence relative to a continuation of reference beats through the interpattern interval (IPI). They did not examine performance separately for the three IPIs of the discontinuous condition but instead treated the three IPIs as a single timing condition in analyzing their data. Moreover, for the three IPIs selected for the discontinuous condition, the onsets of the comparison interval were relatively close to an expected onset, defined as a multiple of the 500-ms reference beat (within 50 ms for two IPIs and 150 ms for the third). Thus, the selection of these IPIs provides little basis for distinguishing the interval and oscillator-based theories because the IPIs in both the continuous and discontinuous conditions were in close proximity to expected onsets based on an oscillator theory. Given this selection of IPIs, both theories predict similar performance in the continuous and discontinuous conditions.

The research described in this article establishes a framework for differentiating between interval- and oscillator-based theories of time discrimination. In the three experiments reported here, we examined the tempo discrimination of isochronous tone sequences, manipulating IPI, base tempo, and number of intervals. In the first two experiments, thresholds were determined separately for IPI conditions defined relative to a reference beat established by an isochronous standard pattern. Early, late, and expected onsets of comparison patterns were tested at a single base (standard-pattern) tempo. In Experiment 3, the effect of base tempo and number of pattern intervals was examined, permitting a direct comparison with the tempo discrimination studies of Drake and Botte (1993), who argued that tempo discrimination data favor an interval-based theory. A separate analysis of thresholds for increases and decreases in tempo revealed a pattern of sensitivity that provided a clearer picture of the mechanisms used to make duration comparisons.

Experiment 1

In Experiment 1 we evaluated the role of expectancy in time discrimination by examining tempo discrimination in different IPI conditions. This provided a direct evaluation of Ivry and Hazeltine's (1995) claim that duration comparisons are unaffected by the duration of the interval separating standard and comparison patterns. IPIs were defined here with respect to a reference beat that was assumed to be established by the isochronous standard sequence and to continue through the following temporal gap. The effect of IPI on tempo discrimination was examined for early, late, and expected onsets of the isochronous comparison sequence.

Method

Participants. Nine listeners participated in Experiment 1. All participants were students at Indiana University, reported normal hearing, and had a wide range of musical training. Three levels of musical experience were identified with 3 observers falling into each of the following categories: nonmusicians (no musical training), amateur musicians (less than 10 years of musical training), and professional musicians (more than 10 years of musical training or advanced degrees in musical performance).

Stimuli. The stimuli were standard–comparison pairs of four-tone isochronous sequences composed of 440-Hz, 50-ms tones. The standard sequence had a fixed IOI of 400 ms and was followed after a pause by a comparison sequence that was presented at a slightly faster or slower tempo. The onset of the comparison sequence relative to the onset of the last tone of the standard sequence was manipulated to examine the effect of advancing or delaying the onset with respect to an expected onset (see Figure 1). For the expected onset condition, the IPI was 800 ms, equal to twice the 400-ms IOI of the standard sequence. This expectation was based on the assumption of a continuation of the standard-pattern tempo through the pause separating the two sequences (i.e., one "missing" beat). For two early conditions, the IPIs were 680 and 560 ms, 15% and 30% shorter than the expected IPI, respectively. For two late conditions, the IPIs were 920 and 1,040 ms, 15% and 30% longer than the expected IPI, respectively.

Equipment. Sine wave tones were generated by a Silicon Graphics Workstation using a 44.1-kHz sampling rate and were presented to listeners at comfortable listening levels via headphones (Koss TD/75) connected to the workstation headphone output. Participants made responses at the workstation keyboard. This equipment was used in Experiments 1 and 3.

Procedure. On each trial, listeners heard the standard sequence at the tested tempo followed by a comparison sequence presented at a slightly faster or slower tempo. Listeners indicated which sequence was faster by entering a response on the computer keyboard. The next trial began after a response was entered and the return key pressed. Adaptive tracking (Levitt, 1971) was used to estimate discrimination thresholds corresponding to $P(C) = 70.7$ for each onset condition. Tracks for each onset condition were interleaved, and onset condition was randomly selected on each trial with the constraint that all five onset conditions occur twice every 10 trials. The tempo difference between standard and comparison patterns was decreased after two correct judgments in a given IPI condition, and it was increased after a single incorrect response. The initial tempo difference between the two sequences for each onset condition was 12%, and the step size for all tempo increases and decreases was 1 percentage point (i.e., 4 ms). Each interleaved track consisted of 64 trials, resulting in a total of 320 trials in the experimental session. The session lasted about 1 hr, and listeners received short rest breaks every 40 trials. Listeners participated in two identical experimental sessions on consecutive days.

Results

Thresholds were estimated by averaging the last six reversals of each track. (These thresholds did not differ significantly from thresholds based on the average of the last half of each track.) An analysis of variance (ANOVA) was carried out on the threshold data, with onset condition (five levels) and session (first vs. second) as within-subjects variables and musical training (three levels) as a between-subjects variable.

Although a wide range of sensitivity was observed, listeners' temporal resolution was good: The mean tempo discrimination threshold across all conditions was 2.4%.

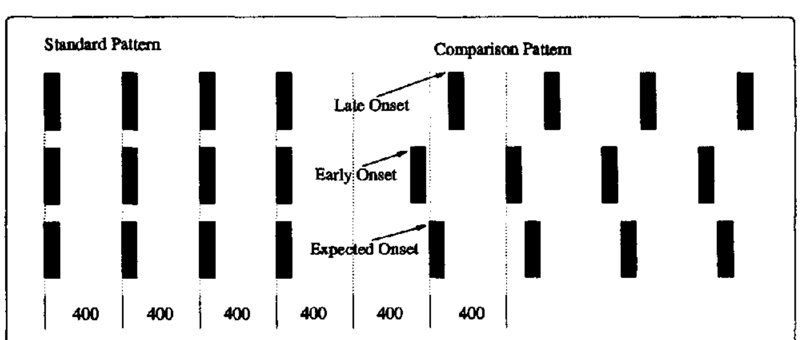

Figure 1. Experiment 1: Listeners heard a four-tone standard sequence followed by a four-tone comparison sequence with an interonset interval (IOI) that was shorter or longer than the IOI of the standard. In the expected onset condition, the interval between the onset of the last tone of the standard sequence and the onset of the first tone of the comparison sequence (the interpattern interval [IPI]) was 800 ms (twice the 400-ms IOI of the standard). For the two early conditions, the IPI was 560 or 680 ms. For two late conditions, the IPI was 920 or 1,040 ms.

Figures 2A and 2B display both group means (solid lines) and individual thresholds (dashed lines) for both sessions. Nonmusicians are labeled 1–3, amateur musicians are labeled 4–6, and professional musicians are labeled 7–9. Although the 2 listeners with the worst overall performance were both nonmusicians (Listeners 1 and 2), overall, the ANOVA did not reveal an effect of musical training, $F(2, 6) = 1.4, p > .3$. However, with only 3 listeners per group, no firm conclusions concerning musical training effects could be drawn.

Thresholds for the two early-onset conditions were found to be higher than the expected or late IPIs. This was supported by the ANOVA, which demonstrated a significant main effect of onset, $F(4, 24) = 3.14, p < .05$. Comparing the performance between the two sessions, thresholds were found to be lower in Session 2 than in Session 1. The ANOVA showed a significant interaction between the onset condition and session, $F(4, 24) = 3.34, p < .05$, but no main effect of session. The improvements observed in Session 2 were mainly for the early conditions. For the 560- and 680-ms IPIs, the mean thresholds were reduced from 3.43% and 3.09% in Session 1 to 2.41% and 2.56% in Session 2, respectively.

Discussion

The results of Experiment 1 suggest that although the timing of the onset of the comparison sequence did affect performance, only the early onsets consistently degraded performance, mainly in the first session of testing. This provides only weak support for oscillator-based models of time discrimination and suggests that listeners can easily learn to compensate for interruptions of the temporal pattern defined by the standard sequence. The findings also suggest that the surprise of an early onset is more disruptive than a delayed onset, perhaps because listeners are in some sense prepared for events that occur late but unprepared for early onsets.

One feature of this experiment that may have helped listeners learn to compensate for the early or late temporal onset of the comparison sequence was the presence of multiple intervals in the comparison sequence. Having multiple-interval comparison sequences made it possible for listeners to discount the first interval of the comparison—the onset of which was sometimes "out of phase" with respect to the expected onset—and base their tempo judgments on the remaining intervals of the sequence after adjusting to the new phase.

Another aspect of the first experiment that may have obscured the effects of onset condition is that no distinction was made between the detection of increases and decreases in tempo (this was also true of the experiments of Ivry & Hazeltine, 1995, and Drake & Botte, 1993). The implicit assumption is that, although sensitivity to increases and decreases in tempo may differ somewhat, both directions of change are similarly affected by the different timing conditions. However, both participants' comments and previous work on the effect of temporal deviations (see Jones & Boltz, 1989; Kidd, 1989) suggest that early and late onsets may not have simply degraded temporal resolving power but that the temporal contrast in these conditions (i.e., the contrast between expected and observed durations) may have differentially affected judgments of increases and decreases in tempo. If temporal contrasts are asymmetrical, then in some situations tempo increases may be easier to detect than tempo decreases, whereas in other cases, the reverse may be true. To explore these issues, we designed a second experiment to obtain separate thresholds for the detection of tempo increases and tempo decreases using only single-interval comparison sequences.

Experiment 2

The design of Experiment 2 was different from Experiment 1 in several important ways. The adaptive tracking

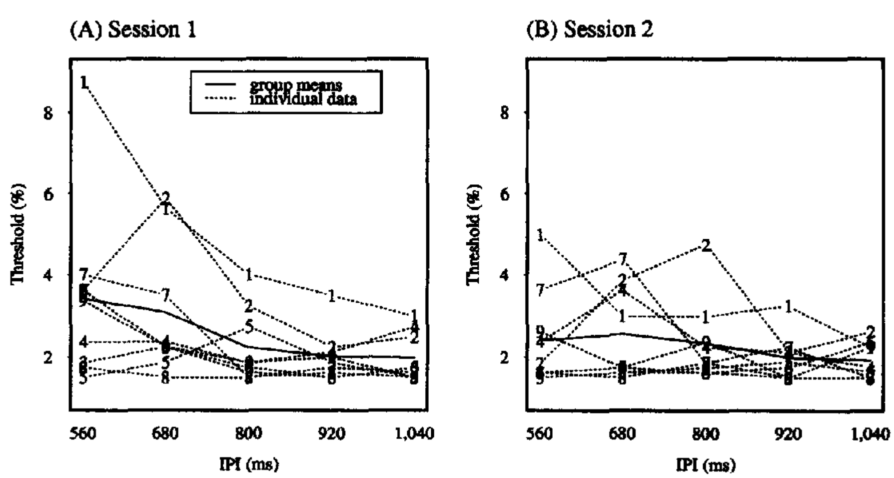

Figure 2. Group means (solid lines) and individual data points (dashed lines) for Sessions 1 and 2 (Panels A and B) of Experiment 1 for interpattern intervals (IPIs) of 560, 680, 800, 920, and 1,040 ms. Nonmusicians are labeled 1–3, amateur musicians are labeled 4–6, and professional musicians are labeled 7–9.

procedure and two-alternative, forced-choice task used in the first experiment provided a single threshold measure for both positive and negative tempo changes. In Experiment 2, increases and decreases in tempo were examined separately using a constant-stimulus method and a same–faster–slower task. Psychometric functions and points of subjective equality (PSEs) were then estimated from responses at each tempo difference level.

An additional independent variable introduced in Experiment 2 was trial-to-trial uncertainty concerning the time between the standard and comparison patterns. The IPI conditions were presented both with blocked presentation (a constant IPI within trial blocks) and mixed presentation (IPIs varied randomly from trial to trial). The first experiment had only a mixed condition. The blocked condition was introduced to assess the extent to which listeners could take advantage of across-trials temporal consistency to learn to anticipate an early or late event, despite the deviation from standard-pattern timing.

Method

Participants. Ten listeners participated in Experiment 2. All listeners were audiologically normal students at Indiana University who were paid for their participation in the experiment. All participants were given a hearing screening following standard clinical procedures. Their thresholds were no higher than 25 dB HL for 250, 500, 1,000, 2,000, and 4,000 Hz.

Stimuli. The standard sequence was an eight-tone isochronous sequence with a fixed IOI of 400 ms. The comparison sequence consisted of a single interval with an IOI that was shorter than, longer than, or equal to the standard sequence IOI. All tones in the sequences were 440 Hz and lasted 50 ms. The same five onset conditions tested in the first experiment were investigated: for the expected onset condition, the IPI was 800 ms; for the two early conditions, the IPIs were 680 and 560 ms; and for the two late conditions, the IPIs were 920 and 1,040 ms.

Equipment. For Experiment 2, tones were generated by a NeXT computer, which also controlled all aspects of stimulus presentation and response collection. Stimuli were output via the built-in NeXT D/A converters (44.1-KHz sampling rate) and simultaneously distributed to up to 4 listeners in a soundproof booth. Tones were presented at 75 dB SPL over Sennheiser HD 250 headphones.

Procedure. On each trial, listeners heard the standard sequence followed by the comparison sequence presented at a slightly faster or slower tempo, or at the same tempo as the standard. The listeners' task was to indicate the relative tempo of the comparison sequence (same, faster, or slower). DEC VT100 terminals were used to present visual prompts for listeners' responses. Responses were entered by the listeners on the numerical keyboard using the digits 1, 2, or 3. There was 1-s pause between the last listener's response and the start of a new trial. In the first 20 trial blocks, the IPI was held constant within blocks (the blocked condition). Each IPI was tested in four consecutive 60-trial blocks. Each trial block was composed of 20 same trials, 20 faster trials, and 20 slower trials. Tempo differences for faster and slower trials ranged between −15% and 15% in steps of 2 percentage points, for a total of 16 levels. Within each IPI condition, there were 80 trials of each comparison type (same, faster, or slower) with 10 trials at each tempo difference level.

After the 20 constant-IPI blocks, 20 mixed-IPI blocks were presented in which the five IPI conditions were randomly mixed within each trial block so that listeners were uncertain from trial to trial about the onset time of the comparison sequence. As in the constant-IPI blocks, there were 240 trials in each IPI condition: 80 same trials plus 10 trials at each of the 16 tempo difference levels.

Results

The data were analyzed by computing PSEs and thresholds for each listener and onset condition during blocked and mixed presentations. The PSE is the tempo difference at which the proportion of "faster" responses equals the proportion of "slower" responses (i.e., the tempo difference at which $P[\text{faster}] = P[\text{slower}]$). A PSE of zero demonstrates that there is no bias to respond faster or slower when the standard and comparison sequences have the same tempo. A positive PSE demonstrates a bias to respond faster when the standard and comparison tempos are the same, whereas a negative PSE demonstrates a bias to respond slower when the standard and comparison tempos are the same.

For each listener and condition, PSEs were computed by determining the proportion of faster, same, and slower responses at each tempo difference. Nonlinear least squares regression was then used to fit logistic functions to the faster and slower response probabilities, plotted as a function of the size of the tempo change. The tempo difference at which the two fitted curves crossed determined the PSE. A separate measure of PSEs obtained by examining the maximum of the "same" response curve was not found to be significantly different from the PSE measures based on faster and slower responses. Consequently, only the latter PSE measure is reported here.

PSEs for all listeners as a function of onset condition during blocked and mixed presentations are shown in Figures 3 and 4, respectively. A two-factor ANOVA carried out on the PSE data revealed both a main effect of onset condition, $F(4, 36) = 21.162$, $p < .001$, and a significant interaction between onset condition and presentation type (blocked vs. mixed), $F(4, 36) = 7.221$, $p < .001$. During the blocked presentation, the PSEs measured for each onset condition were all close to zero, indicating no perceptual bias. (The 95% confidence intervals on each mean, reported in Figure 3, suggested that only the mean PSE for the 680-ms IPI might have been different from zero.) However, during mixed presentations, the PSEs varied systematically across onset condition. When the onset of the comparison sequence was early, the mean PSE was positive, indicating that comparison patterns that matched the standard pattern's tempo were judged to be faster. When the onset of the comparison sequence was late, the mean PSE was negative, indicating a tendency for slower judgments. For expected onsets, there was also a slight bias for slower judgments. All but 1 listener (3 in Figure 4) exhibited the same systematic pattern of PSEs for mixed presentations. (That listener exhibited a faster bias across all onset conditions.)

Sensitivity to tempo changes was also assessed in each IPI condition. Discrimination thresholds were measured by determining $P(C)_{max}$ at each tempo difference level for both

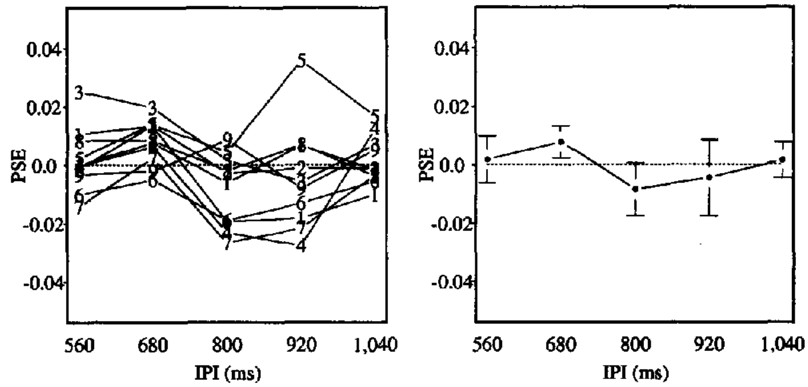

Figure 3. Blocked presentations in Experiment 2. Shown are the points of subjective equality (PSEs) for all listeners for interpattern intervals (IPIs) of 560, 680, 800, 920, and 1,040 ms. Individual data points are shown on the left and group means with 95% confidence intervals on the right.

faster and slower trials.[1] Nonlinear least squares regression was then used to fit logistic curves to the $P(C)_{max} \times \Delta$Tempo data for faster and slower trials. The thresholds reported here are the tempo differences corresponding to unbiased 70.7% correct performance estimated from the fitted curve. This threshold definition facilitates comparison with the adaptive tracking results of Experiment 1.

Mean faster and slower thresholds during blocked and mixed presentations are shown in Figure 5. An ANOVA was carried out on the threshold data, with onset condition (five levels), direction of tempo difference (faster vs. slower), and presentation type (blocked vs. mixed) as within-subjects variables. There were two primary results from this analysis. Overall, listeners were more sensitive to tempo differences when the comparison sequence was faster than when it was slower, $F(1, 9) = 27.858, p < .001$; the mean threshold for faster trials was 5.11% compared with 8.57% for slower trials. For blocked presentations, no effect of onset condition on threshold was evident for either faster and slower trials. However, with mixed presentations, when the onset of the comparison sequence varied from trial to trial, listeners were more sensitive to tempo increases when the onset was early than when it was late. Conversely, listeners were more sensitive to tempo decreases when the onset of the comparison sequence was late than when it was early. The ANOVA demonstrated both a significant interaction between the direction of tempo change and onset condition, $F(4, 36) = 4.08, p < .01$, and a significant interaction between the direction of tempo change and presentation type, $F(1, 9) = 6.76, p < .05$. Planned separate two-way ANOVAs for mixed and blocked presentations revealed a significant interaction between onset condition and the direction of tempo change in mixed presentations, $F(4, 36) = 7.85, p < .001$, but not in blocked presentations, $F(4, 36) = 0.180, p > .9$.

Discussion

The data from Experiment 2 illustrate a systematic shift in bias and threshold as a function of onset condition. Under mixed presentations, early onsets produced more faster judgments and late onsets produced more slower judgments. Timing sensitivity was also affected, with lower thresholds for tempo increases in the early-onset conditions and lower thresholds for tempo decreases in the late-onset conditions. No such systematic shifts in bias and threshold were observed with the reduced temporal uncertainty of blocked presentations.

In Experiment 1 (which used mixed presentations of onset conditions), faster and slower judgments were combined in the "which is faster" task. Overall, early onset of the comparison resulted in higher thresholds than either expected or late, but this effect was variable across listeners and tended to disappear during the second experimental session. How can these data be explained in view of the results from Experiment 2?

The critical distinction between Experiment 2 and the first experiment is the separation of faster, slower, and same responses. An important observation is that averaging the faster and slower thresholds for each onset condition resulted in a pattern of results that closely resembled the results from the first experiment. Essentially, enhanced sensitivity to faster comparisons canceled the reduced sensitivity to slower comparisons and vice versa. Thus, by not separating faster and slower comparisons, the effect of onset condition on tempo discrimination thresholds was obscured.

In the initial discussion of the oscillator-based model, we

[1] $P(C)_{max}$ is a transform of d' that indicates the maximum percent correct possible (with an optimal criterion) for a given d' (see Green & Swets, 1966, pp. 409–410, for computational details). For a three-response task, the computation of hits and false alarms from which d' is computed requires some explanation. Hits are determined for each level of tempo difference. For faster trials, the hit rate is the probability of responding faster when the comparison is faster $P(f|F)$ and the false-alarm rate is $P(f|\text{not F})$. For same (S), faster (F), and slower (SL) response alternatives, $P(f|\text{not F}) = [P(f|S) + P(f|SL)]/2$. Similarly, for slower trials, the hit rate is $P(sl|SL)$, and the false-alarm rate is $P(sl|\text{not SL}) = [P(sl|S) + P(sl|F)]/2$.

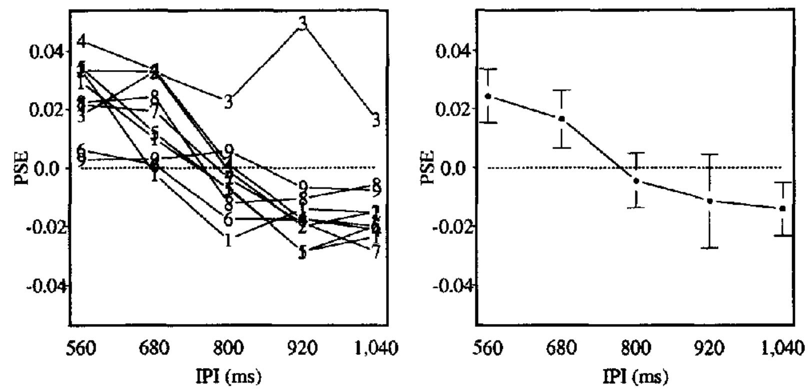

Figure 4. Mixed presentations in Experiment 2. Shown are the points of subjective equality (PSEs) for all listeners for interpattern intervals (IPIs) of 560, 680, 800, 920, and 1,040 ms. Individual data points are shown on the left and group means with 95% confidence intervals on the right.

hypothesized that tempo discrimination performance should be best when the onset of the comparison sequence occurs at an expected temporal location (on the beat) and worse otherwise. The results from the first two experiments do not support this prediction. The first experiment produced a monotonic decrease in thresholds with increasing IPI, and the second experiment revealed that the effects of IPI with faster and slower comparisons were in opposite directions. Although these findings may suggest an effect of the absolute time between standard and comparison patterns, the overall pattern of results makes it difficult to construct a convincing absolute-time explanation. However, these results can be accounted for in terms of a oscillator-based model if the contrast between expected and actual durations is taken into account.

As Jones and Boltz (1989) and Kidd (1989) have shown, the contrast between expected and actual durations tends to influence judgments in the direction of the difference (actual minus expected), such that shorter-than-expected durations are judged as shorter and longer-than-expected durations are judged to be longer than is the case when these same durations are expected. In the tempo discrimination task used in our research, the effect of an unexpectedly long or short IPI appeared to carry over to judgments of the durations of the following intervals (i.e., the tempo). Because a listener cannot immediately synchronize to the new phase represented by an early or late comparison-pattern onset, all tone onsets in the comparison pattern are judged with respect to the expected comparison-pattern onset rather than its actual onset, until the phase is adjusted. Thus, when there is little or no change in tempo, there is a tendency to judge early-onset patterns as tempo increases and late-onset patterns as tempo decreases. This results in a shift in the PSE as well as a greater sensitivity to tempo changes with IOIs that are altered in the same direction as the IPI.

A Phase-Based Theory of Time Discrimination

The expectancy–contrast explanation for the observed shifts in PSE and threshold is consistent with modeling work

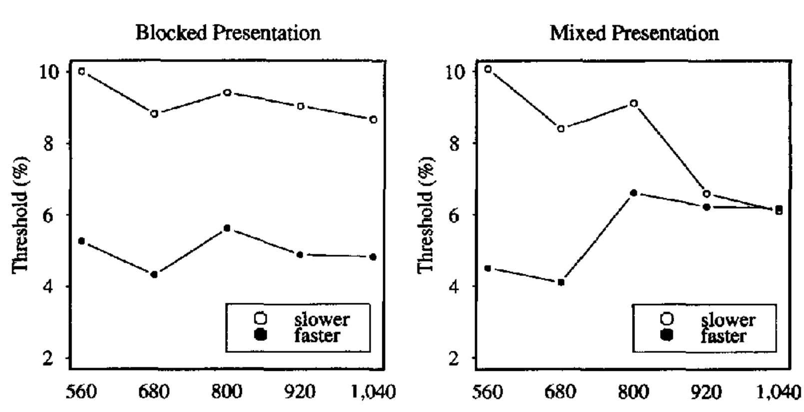

Figure 5. Temporal resolution in Experiment 2. Mean thresholds for tempo increases and tempo decreases are shown as a function of interpattern intervals (IPIs) for mixed and blocked presentations of the IPIs. During mixed presentations, onset condition affected sensitivity, with lower thresholds found for tempo increases in the early-onset conditions and for tempo decreases in the late-onset conditions.

by McAuley (1994, 1995), who evaluated, via simulation, a coupled-oscillator model of time discrimination. This model incorporates the hypothesis that the detection of a time difference (ΔT) in a standard–comparison discrimination task is best explained by examining the phase of the comparison interval relative to the period of an oscillator that has synchronized with the standard-pattern interval. In this section, we develop McAuley's coupled-oscillator model as a phase-based theory of time discrimination that explains our tempo data and makes novel predictions concerning tempo discrimination.

In modeling the standard–comparison tempo discrimination task with a coupled-oscillator model, the oscillator period provides a dynamic estimate of the tempo of the standard sequence. When the standard-pattern interval is recycled in a rhythmic sequence, the oscillator responds by adapting its period to become synchronized with the standard pattern. That is, in a tempo discrimination task, the oscillator is entrained by the standard.

Entrainment of the adaptive oscillator is based on a phase-resetting process. After the initial period P has been set, each successive tone onset resets the phase of the tracking oscillator to zero (restarting the oscillator's cycle). The phase at which the reset occurs is a measure of the discrepancy (or phase error) between the oscillator period and the to-be-estimated time interval. Revised time estimates (P_i) are determined using the phase error following each successive interval (T_i). With an isochronous standard sequence (as in our experiments), all intervals of the standard have equal duration, eliminating the need for a subscript on T.

Many different measures of phase error are possible. To distinguish between positive and negative time changes, we used the following measure:

$$\Delta\phi_i = \begin{cases} \left[\dfrac{T}{P_i} \pmod 1\right] - 1 & \text{if } \left[\dfrac{T}{P_i} \pmod 1\right] > 0.5 \\ \dfrac{T}{P_i} \pmod 1 & \text{otherwise.} \end{cases} \qquad (1)$$

In this equation, phase varies between -0.5 and 0.5 so that when the interval T is shorter or longer than P_i, phase error is negative or positive, respectively. T/P_i provides a measure of the amount of over- or underestimation of the time interval T by the oscillatory timer. When $T/P_i < 1$, P_i overestimates (is longer than) the time interval T. When $T/P_i > 1$, P_i underestimates (is shorter than) the time interval T.

In the model, duration and tempo discrimination are based on the phase errors that occur during the presentation of the comparison sequence (after the oscillator has become synchronized with the rhythmic standard). How detectable a time change is depends on the magnitude of the phase errors that occur during the comparison. These assumptions are similar to those of Jones (1976; Jones & Boltz, 1989), who proposed that temporal judgments are made using the temporal contrast that occurs between internal and external periodicities, with time sensitivity predicted by the degree of synchrony and the magnitude of temporal contrasts.

To simplify this discussion, assume that only the phase error following the first interval of the comparison sequence is used in making temporal comparisons. If one also ignores the IPI, the phase error after the first interval of the comparison sequence is given by $(T + \Delta T)/P_i$ rather than by T/P_i (as given in Equation 1 for the standard). Here, ΔT is the time increment added to the comparison interval. This formulation assumes that the IPI is a multiple of the standard-pattern interval (T; the "expected" condition in our experiments). Thus, when the oscillator period is equal to T, the onset of the comparison sequence coincides with the start of the oscillator's cycle and the phase error accurately reflects the time change ΔT. However, how would early and late onset of the comparison sequence influence performance?

Early Versus Late

The results from the experiments reported in this article can be explained according to our formulation of McAuley's (1994, 1995) coupled-oscillator model via the predicted magnitude of phase errors. As described earlier for the expected IPI condition, shortening and lengthening the comparison interval by ΔT produces phase errors ($\Delta\phi$) of the same magnitude. Because discriminability is based on the magnitude of phase errors, the model in this case predicts no difference between the threshold for detecting a shortened comparison interval (tempo increase) and the threshold for detecting a lengthened comparison interval (tempo decrease). However, when the comparison sequence is early or late, the situation is different. For the early and late conditions, a phase error occurs at the onset of the comparison sequence before the phase error associated with the relevant time change ΔT. It is assumed that this disruptive phase error combines additively with the phase error associated with the time changes ΔT in the comparison sequence. This provides an elegant explanation for the observed effect of early and late onset of the comparison sequence. An additive effect would also result in greater phase errors in single-interval comparison sequences than in multi-interval comparison sequences.

For the early-IPI conditions, the onset of the comparison sequence precedes the onset of the oscillator's cycle, producing a negative phase error. When this phase error is combined with the phase error for the next onset in the comparison, the composite phase error for shortened intervals increases, whereas the composite phase error for lengthened intervals decreases. Consequently, a lengthened interval is required to cancel the effects of an early onset (resulting in a composite phase error of zero). For late-IPI conditions, the onset of the comparison sequence follows the onset of the oscillator's cycle and produces a positive phase error. This has the opposite effect of an early onset: A shortened interval is required to cancel the effects of a late onset of the comparison sequence. If listeners use the magnitude of composite phase errors to make tempo judgments, early-onset conditions should enhance the detection of faster comparisons and late onset conditions should enhance the detection of slower comparisons, which is consistent with the systematic shift in PSEs and threshold observed during the mixed-presentation condition of Experiment 2.

An outstanding question for the phase-based explanation of our data concerns the blocked-presentation condition of Experiment 2. When the IPI was held constant within a block of trials, PSEs and thresholds did not vary systematically as a function of onset condition. This highlights an important question: What determines listeners' temporal expectancies? The blocked results suggest that listeners can develop expectancies that are based on the consistent temporal structure across trials, even when those expectancies do not coincide with oscillator pulses synchronized with the standard pattern. When onsets are predictable (as in the blocked condition), listeners may learn the temporal pattern of the trial, and this can override the effects of a single oscillator synchronized with the standard pattern. This implies that one or more additional oscillator periodicities develop that take into account higher level temporal regularities, thus providing the basis for expectancies that deviate from those based solely on standard-pattern timing on a given trial. When onset timing is unpredictable from trial to trial (as in the mixed-presentation condition), the only expectations that are available are those based on the rhythm of the standard sequence. It is in this instance that the effects of onset are most pronounced, and the single-oscillator model is sufficient to account for the pattern of results. However, to adequately explain performance in both the blocked and mixed conditions requires a generalization of the proposed theory that includes multiple oscillators.

Faster Versus Slower

Another unresolved issue from Experiment 2 concerns the overall lower thresholds observed for tempo increases compared with tempo decreases. In our development of a phase-based theory of time discrimination, it has been assumed thus far that the oscillator period (P_i) is equal to the time interval (T) of the standard sequence. Interval-based theories similarly assume that the mean interval of the clock process is equal to the to-be-measured duration (Wing & Kristofferson, 1973). However, this may not be the case. A discrepancy between (P_i) and (T) could explain the observed greater sensitivity for tempo increases than for tempo decreases.

Early experimental work examining the nature of the psychophysical law for time provides some relevant insight (see Allan, 1979, for an in-depth review). When listeners are presented with two durations and asked to judge whether the second duration is shorter or longer than the first, there is often systematic bias that depends on the order of the two stimuli (i.e., whether the shorter or longer duration is presented first). The proportion of longer responses when the second duration is longer, $P(\mathrm{L}|\mathrm{SL})$, may be greater or less than the proportion of shorter responses when the second duration is shorter, $P(\mathrm{S}|\mathrm{LS})$, depending on the base duration used. The signed difference of the two conditional probabilities $P(\mathrm{S}|\mathrm{LS}) - P(\mathrm{L}|\mathrm{SL})$ has been called the *time-order error* (TOE). Early discrimination studies have shown a positive TOE for brief durations and a negative TOE for longer durations (Woodrow, 1951). The duration that produced a zero TOE has been called the *indifference interval.*

Woodrow's (1951) explanation of the TOE was that the perceived duration of the first presented duration gravitated toward a remembered standard (equated with the indifference interval), and the greater the discrepancy between the stimulus duration and the remembered standard, the greater the effect of the gravitation. Thus, durations shorter than the indifference interval were overestimated and durations longer than the indifference interval were underestimated. In the past 30 years, duration perception researchers have attempted to pinpoint the source of the TOE and the precise nature of the relationship between stimulus and perceived durations. This has been a controversial issue, but a conservative interpretation of the data suggests a linear relationship between stimulus and perceived duration (Allan, 1979).

The proposed theory posits an oscillatory source for the TOE, equating Woodrow's (1951) remembered standard with a preferred period ($\overline{P}$). The assumption is that $\overline{P}$ (conceptualized as a periodic attractor) describes a global property of the neural mechanisms underlying time discrimination. For isolated-interval discrimination, it is assumed that the initial period P_0 of the oscillator is determined by the following linear relationship:

$$P_0 = \frac{1}{g} T + \tau. \tag{2}$$

This linear assumption places psychophysical constraints on the initial period of the tracking oscillator. The parameters $\tau > 0$ and $g > 1$ correspond to a minimum subjective duration (on the order of 25 ms) and the gravitational pull exerted by a remembered standard (periodic attractor $\overline{P}$). The preferred period ($\overline{P}$) is determined by the choice of g and τ according to

$$\overline{P} = \tau\left[\frac{g}{g-1}\right]. \tag{3}$$

This is the point at which the initial period (P_0) is equal to the time interval (T). Durations shorter and longer than $\overline{P}$ are over- and underestimated, respectively, and have a systematic effect on phase errors. The amount of initial over- and underestimation is determined by both τ and g. This operationalizes Woodrow's (1951) initial proposal and allows us to introduce three cases.

Case 1: T/P_i = 1.0. As discussed earlier, the assumption thus far has been that the oscillator period is equal to the time interval of the standard sequence. In this case, phase error reduces to

$$\Delta\phi = \frac{\Delta T}{T}. \tag{4}$$

Lengthening or shortening T by ΔT results in equal-magnitude phase errors. Suppose that if the comparison interval lengthens the standard interval T by 10%, then the resulting phase error is 0.1. On the other hand, when the comparison interval shortens the standard interval T by 10%, the resulting phase error is -0.1. Although the phase errors are different, the magnitudes of the phase errors are equal, predicting equivalent discrimination performance for tempo increases and tempo decreases.

Case 2: $T/P_i > 1.0$. Underestimation occurs when the oscillator period (P_i) is shorter than the standard interval (T). An important consequence of underestimation is that shortening and lengthening the standard interval by ΔT do not have the same effects on performance. Instead, the magnitude of the phase error when lengthening the comparison interval is larger than when shortening the comparison interval by the same amount. As a result of this underestimation, tempo discrimination thresholds are predicted to be lower for tempo decreases than for tempo increases.

Case 3: $T/P_i < 1.0$. Overestimation occurs when the oscillator period (P_i) is longer than the standard interval (T). The effect of overestimation on tempo discrimination is the opposite of that observed with underestimation. The magnitude of the phase error when lengthening the comparison interval is smaller than when shortening the comparison interval by the same amount. Consequently, tempo discrimination thresholds during overestimation are predicted to be lower for tempo increases than for tempo decreases.

The predictions of Case 3 are consistent with the data from Experiment 2, which revealed greater sensitivity for tempo increases than for tempo decreases as well as the systematic effects of the onset of the comparison sequence on performance. This suggests that there was a tendency to overestimate the IOI of the standard sequence, perhaps as a function of the standard IOI.

If this were the case, then an examination of sensitivity to tempo increases and tempo decreases as a function of the base IOI will provide a test of our predictions and will help to clarify the basis for the faster advantage in Experiment 2. This was the rationale for Experiment 3. Previous models of tempo discrimination have ignored possible asymmetries in discrimination, treating faster and slower comparisons as a single timing condition (Drake & Botte, 1993; Ivry & Hazeltine, 1995). The predictions of the phase-based theory suggest that there is an important link between the concepts of early versus late, faster versus slower, shorter versus longer, and what have been broadly labeled TOEs of temporal judgment. The phase-based theory posits that the basis of the TOE is oscillatory and suggests a common source for early–late, faster–slower, and shorter–longer asymmetries in discrimination.

Experiment 3

The primary question addressed by Experiment 3 concerned whether listeners' tempo judgments would be influenced by slight over- or underestimation of the base IOI. The hypothesis was that, in making tempo judgments, listeners may over- and underestimate the base IOI relative to a preferred tempo (Fraisse, 1982). If this is the case, then tempo discrimination based on phase errors predicts that for overestimation of short IOIs (Case 3), listeners' thresholds for tempo increases should be lower than for tempo decreases. Conversely, for underestimation of long IOIs (Case 2), tempo-decrease thresholds should be lower than tempo-increase thresholds. For the first two experiments, the IOI of the standard sequence (the base IOI) was 400 ms. On the basis of the phase-based theory of tempo discrimination, the data from these experiments suggested a slight overestimation of the base IOI. In this experiment we evaluated the model's predictions for base IOIs of 100, 400, 700, and 1,000 ms.

The choice of these IOIs for investigation was based on a long history of research on preferred and spontaneous tempos (see Fraisse, 1982, for a comprehensive review). Fraisse defined "preferred tempo" as the rate at which a simple isochronous rhythm is judged to be neither too fast nor too slow, whereas the related concept of "spontaneous tempo" (or mental tempo) refers to an individual's natural speed of tapping. For both presentation and production, a wide range of natural-seeming tempos have been reported, but the most representative rates are roughly 500–600 ms. Under the assumption that preferred tempos have an oscillatory basis, we predicted that for the 100- and 400-ms IOIs, faster judgments would be easier than slower judgments, whereas for the 700- and 1,000-ms IOIs, slower judgments would be easier than faster judgments.

Method

Participants. Nine listeners participated in Experiment 3. All participants were students at Indiana University, reported normal hearing, and had a wide range of musical training. Participants completed a musical training questionnaire, which was then used to classify them into three categories of musical experience (as in Experiment 1): nonmusicians (having no musical training), amateur musicians (having less than 10 years of musical training), and professional musicians (having more than 10 years of musical training or holding advanced degrees in musical performance). Given the null effect of musical training in Experiment 1, we did not expect that musical training would interact with the predicted asymmetry in performance. However, to test for this possibility, we decided to include musical training in the design.

Stimuli. The stimuli were two- and four-tone isochronous sequences composed of 440-Hz, 50-ms tones. The four base IOIs of 100, 400, 700, and 1,000 ms were crossed with both sequence lengths, resulting in eight experimental conditions. The IPI separating sequences within a discrimination trial was always equal to twice the IOI of the standard, so that the onset of the comparison sequences occurred at an expected temporal location (i.e., after one "missing" beat of an extension of the standard pattern).

Equipment. The equipment used was the same as that used in Experiment 1.

Procedure. On each trial, listeners heard the standard sequence at the tested tempo, followed by two comparison sequences, one of which was presented at a slightly different tempo from the standard. The listeners' task was to indicate which of the two comparison sequences was different in tempo from the standard (see Figure 6). Responses were entered on the computer keyboard, and the next trial did not begin until a response was entered and the return key was pressed. No feedback was provided. For each tempo and interval condition, an adaptive tracking procedure (using the

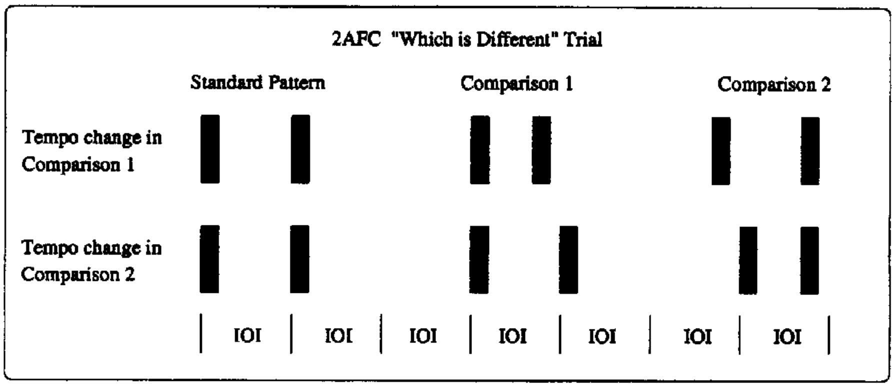

Figure 6. Experiment 3: Listeners heard a one- or three-interval standard pattern at the tested tempo followed by two comparison patterns, one of which was faster or slower than the standard. The listener's task was to indicate which of the two comparisons was different in tempo from the standard. This figure illustrates both possibilities of a one-interval trial (change to Comparison 1 or change to Comparison 2). In both cases, the different interval was shortened. 2AFC = two-alternative, forced-choice task; IOI = interonset interval.

algorithm described in Experiment 1) was used to measure separate discrimination thresholds for tempo increases and tempo decreases. Tempo increases and decreases were tracked independently within each block of 80 trials.

The initial tempo difference at the beginning of each block was 12%. Within each block, the number of tones and the IOI of the standard sequence remained fixed, with half the tempo differences applied to the first comparison and the other half applied to the second comparison. Each block contained 40 tempo-increase trials and 40 tempo-decrease trials, with the additional constraint that every 10 trials contain 5 increases and 5 decreases. Thresholds were computed by averaging the last six reversals of each 40-trial track. Thresholds were also measured by averaging the last 20 trials of each track (to examine the reliability of the reversal measure), but no threshold differences between the two measurement procedures were found.

Each listener participated in four experimental sessions, with each session consisting of threshold measurements in each of the four IOI conditions for one of the sequence lengths (two- or four-tone sequences). A second threshold estimate was obtained in each condition in the last two sessions. Each threshold measurement took between 10 and 20 min, with a short rest break at the halfway mark of each block and a somewhat longer rest break between blocks. The presentation order of the blocked IOI conditions was counterbalanced between sessions, and the presentation of the sequence length conditions was counterbalanced between subjects.

Results and Discussion

A five-factor ANOVA was carried out on the thresholds measured in the experiment. Three groups, differing in the amount of musical training, were tested with four IOI conditions, three sequence lengths (one or three interval sequences), and two directions of tempo difference (increase or decrease) in two experimental sessions.

The ANOVA demonstrated a main effect of tempo, $F(3, 18) = 24.76$, $p < .001$. Figure 7A shows mean thresholds (averaged across the 9 listeners) for the four IOI conditions for both one- and three-interval sequences. In this figure, thresholds for tempo increases and tempo decreases are averaged to compare these threshold data with those of Drake and Botte (1993), who did not obtain separate thresholds for tempo increases and tempo decreases. For all listeners, thresholds were lowest for the 400- and 700-ms IOIs. The mean thresholds for the 400- and 700-ms IOIs (combining one- and three-interval sequences) were 4.9% and 5.3%, respectively. The mean thresholds for the 100- and 1,000-ms IOI were 10.3% and 6.5%, respectively. Tukey's honestly significant differences (HSD) post hoc analysis of the main effect of IOI revealed that only the 100-ms threshold was significantly higher than the 400-, 700-, and 1,000-ms thresholds ($p < .01$). This is consistent with previous studies reporting higher thresholds and departures from Weber's law for IOIs less than 300 ms (Drake & Botte, 1993; Hirsh et al., 1990; Michon, 1964; Schulze, 1989; ten Hoopen et al., 1994).

Examining the effect of the number of sequence intervals showed a reduction in thresholds as the number of intervals were increased, especially for the 100-ms IOI (replicating Drake & Botte, 1993, and Michon, 1964). The ANOVA demonstrated a main effect of the number of intervals, $F(1, 6) = 117.8$, $p < .001$, as well as a significant interaction between the number of intervals in the sequence and the IOI condition, $F(3, 18) = 23.6$, $p < .001$. For the one-interval sequences, the mean threshold was 8.6%, whereas for the three-interval sequences, the mean threshold was 4.8%. When increasing the number of sequence intervals, the reduction in threshold was 9.2% for the 100-ms IOI but only between 1.7% and 2.7% for the 400-, 700- and 1,000-ms IOIs. Tukey's HSD post hoc analysis of the interaction between the IOI and the number of intervals showed that the 100- and 400-ms IOIs were the only conditions for which increasing the number of intervals significantly reduced thresholds ($p < .05$).

The higher thresholds reported for short IOIs (in particular, the 100-ms IOI in this experiment) and the greater

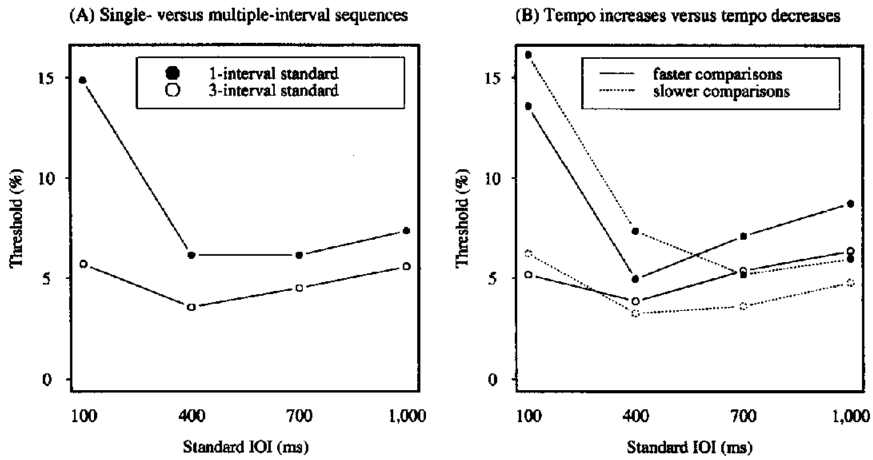

Figure 7. Temporal resolution in Experiment 3. The mean thresholds for all listeners for base interonset intervals (IOIs) of 100, 400, 700, and 1,000 ms in Experiment 3. A: The thresholds obtained for one- and three-interval sequences (averaging thresholds for tempo increases and tempo decreases) for comparison with Drake and Botte (1993). B: Separate thresholds for tempo increases and tempo decreases to evaluate the predictions of the oscillator model.

reduction in thresholds that occurs with short IOIs for multiple-interval sequences may be partially explained by overestimation of the time interval T (Case 3). In the proposed phase-based theory, Weber's law is a special case. For example, when $g = 1$ and $\tau = 0$, $P = T$ for all Ts and the $\Delta\phi$ associated with a time change ΔT is proportional to T (i.e., Weber's law holds). However, when $P > T$, the $\Delta\phi$ associated with a time change ΔT is smaller than would be expected (and harder to detect) than for the same ΔT when $P = T$. Thus, Case 3 predicts an increase in the Weber fraction for intervals T that are overestimated. However, as the oscillator is entrained by the standard sequence (as in the three-interval condition), the amount of overestimation reduces. Moreover, the effect of entrainment on reducing thresholds is greater for overestimation than for underestimation. Case 2 (underestimation) predicts a slight decrease in the Weber fraction and an overall weaker effect of increasing the number of intervals in the standard sequence. Although a smaller threshold reduction was observed for the multiple-interval condition, the predicted departure from Weber's law at the slow rates was not evidenced in these data, suggesting that other factors come into play at the slower rates.

To assess the predictions of the oscillator model concerning differential thresholds for tempo increase and tempo decreases, we created Figure 7B to show the mean thresholds obtained for tempo increases and tempo decreases for the four IOI conditions for the one- and three-interval sequences. As predicted by the oscillator model, tempo-increase thresholds were lower than tempo-decrease thresholds for the 100- and 400-ms IOIs, whereas for the 700-ms and 1,000-ms IOIs, tempo-increase thresholds were higher than tempo-decrease thresholds. The ANOVA demonstrated both a significant interaction between tempo and the direction of the tempo change (increase vs. decrease), $F(3, 18) = 6.23$, $p < .01$, as well as a significant three-way interaction among tempo, the direction of the tempo change, and the number of intervals in the sequence, $F(3, 18) = 7.25$, $p < .01$. The three-way interaction indicates that threshold differences between tempo increases and tempo decreases were smaller for three-interval sequences than for one-interval sequences, but mainly for the 100- and 400-ms IOIs.

As expected, musical training did not interact with the observed asymmetrical performance on the faster and slower comparisons. However, in contrast to Experiment 1, musical training was found to influence overall tempo sensitivity, $F(2, 6) = 5.23$, $p < .05$. The mean thresholds for the professional musicians, amateur musicians, and nonmusicians, averaged across experimental session, tempo, and number of intervals, were 4.1%, 7.1%, and 9.0%, respectively. The best listener was a professional musician who was able to reliably detect a 2.0% change for both the 400- and 700-ms IOIs. Tukey's HSD post hoc analysis of the main effect of musical training showed that the only significant difference in mean tempo sensitivity was that between the professional musician's group and the nonmusician's group ($p < .05$). As in Experiment 1, the examination of musical training was weakened by the small group sizes.

Tukey's HSD post hoc analysis of the interactions among direction of tempo change, number of intervals, and IOI showed that for the one-interval sequences, thresholds for tempo increases and tempo decreases were significantly different for the 100-, 700-, and 1,000-ms IOIs ($p < .01$), but not for the 400-ms IOI. However, for the three-interval sequences, thresholds for tempo increases and tempo decreases were not found to be significantly different ($p > .05$). One possible explanation for the observed interaction is that multiple intervals reduce the estimation error (over- or underestimation) by the entrainment of the oscillator and thus gradually eliminate threshold differences between tempo increases and tempo decreases as the number of sequence intervals is increased. However, the overall faster bias observed in Experiment 2 for eight-tone isochronous sequences is not consistent with this explanation. This issue requires further investigation.

Overall, these results provide support for the proposed model of tempo discrimination. The pattern of thresholds suggests that tempo judgments are influenced by a preferred tempo (oscillator period), as predicted by the model. In related research in the area of motor control, Collyer, Broadbent, and Church (1992) reported that when participants were required to tap their finger at a specific tempo, some tempos were reproduced too slowly, and some were produced too quickly. The observed pattern of biases in tempo production (termed the *oscillator signature* by Collyer et al.) is consistent with the pattern of biases and threshold differences reported for tempo perception observed in our experiments. To explain the oscillator signature, Collyer et al. proposed that time production is controlled by multiple reference oscillators, each with its own preferred tempo. To test this hypothesis, Collyer, Broadbent, and Church (1994) used an unconstrained tapping task to explore preferred rates of tapping. In support of a multiple-oscillator model, they found a bimodal distribution of preferred tempos (with modes at 272 and 450 ms) rather than a unimodal distribution, as has been generally assumed (see Fraisse, 1982).

The bimodal distribution of preferred tapping rates reported by Collyer et al. (1994) suggests that a more fine-grained investigation of tempo discrimination (using more than four base tempos) is warranted. If the faster–slower asymmetry, found for tempo discrimination for base tempos of 100, 400, 700, and 1,000 ms, is consistent with a bimodal distribution of preferred tapping rates, then examining a large selection of IOIs should reveal the signature of multiple reference oscillators, which would require revision of our theory.

General Discussion

The results from the three tempo discrimination experiments reported in this article provide support for an oscillator model of time perception. Much of the supporting evidence was found only when thresholds for positive and negative time changes were evaluated separately. In the first experiment, tempo discrimination thresholds were examined for early, late, and expected comparison-pattern onsets without separately evaluating responses to faster and slower comparison patterns. The assumption was that reference beats of an internal oscillator entrained to the standard pattern would continue through the IPI and provide the basis for tempo judgments of the comparison pattern. We hypothesized that discrimination thresholds for the expected standard-pattern onset would be lower than for either the early or late onsets. As predicted, discrimination thresholds were higher for the early onsets than for the expected onset. However, thresholds for late onsets were the same or lower than those for the expected onset. The results also indicate that the disadvantage for early onsets of the comparison sequence could be reduced or eliminated with practice.

The effect of the timing of comparison-pattern onset was clarified in Experiment 2 by obtaining separate thresholds for tempo increases and tempo decreases under mixed and blocked presentations of onset conditions. During mixed presentations (when comparison-pattern onsets were unpredictable), lower thresholds were found for tempo increases than for tempo decrease in the early-onset conditions, whereas lower thresholds were found for tempo decreases in the late-onset conditions. In addition, a systematic shift in PSEs as a function of onset condition was found, indicating a tendency to judge patterns as faster when they were presented early and to judge them as slower when they were presented late. During blocked presentations of onset conditions (when comparison-pattern onsets were predictable), no systematic shifts in PSEs or threshold were observed. These results are explained by an oscillator model in terms of the magnitude of phase errors (i.e., deviations from the expected phase) that occur when the comparison sequence is presented. The lack of an effect of onset condition observed during blocked presentations was explained in terms of the development of an expected phase angle that reflected listeners' learning of the consistent within-trials timing. When learning the temporal pattern of a trial, multiple periodicities may develop in response to the higher order temporal regularities within trials that become apparent when all trials have the same temporal structure. These periodicities may provide a basis for the anticipation of the onset of a comparison pattern, independent of the local IOI-based expectations. This explanation generalizes the notion of expectancy, suggesting that what becomes expected depends on both beat-based expectancies that develop within a trial and pattern-based expectancies that develop over the course of a block of trials. The precise contribution of pattern-based expectancies in tempo discrimination requires additional investigation.

Experiment 3 was designed to test whether a separate analysis of responses to faster and slower comparison patterns would reveal effects of increases or decreases in the standard-pattern tempo that resemble the effects found for early and late comparison-pattern onsets. Tempo discrimination thresholds were found to vary systematically as a function of the base tempo, with tempo-increase thresholds lower than tempo-decrease thresholds at the faster tempos, and tempo-decrease thresholds lower than tempo-increase thresholds at the slower tempos. This result is strengthened by a recent independent study by Vos, van Assen, and Franek (1997), who reported an identical pattern of faster–slower threshold differences for base IOIs of 250, 500, and 1,000 ms. These results are significant because interval-based models have assumed no difference between positive and negative time-change thresholds. Previous researchers of tempo discrimination of isochronous auditory sequences (Drake & Botte, 1993; Ivry & Hazeltine, 1995) have used data from experiments in which thresholds for tempo increases and tempo decreases are combined to argue for an interval model of time measurement. The results from our research indicate that when responses to positive and negative time changes are examined separately, the data favor an explanation in terms of an oscillator model of time perception.

In the single-oscillator model of tempo discrimination described in this article (see also McAuley, 1994, 1995), the detection of a tempo difference in a forced-choice discrimination task is based on the magnitude of the phase error ($\Delta\phi$) after the first interval of the comparison sequence in which a tempo change has been introduced ($T + \Delta T$). The phase error for a positive or negative time change (ΔT) varies with the extent of the temporal deviation from the expected onset of the comparison sequence (as shown in Experiment 2) and with the amount of over- or underestimation of the interval of the standard sequence by the reference oscillator (as shown in Experiment 3).

The distinction between the detection of phase differences in an oscillator model and the detection of time differences in an interval model has implications for the predictions that can be generated by a theory of time perception or production. Interval models accurately predict the perception and production of isolated durations based on the statistical variability of a "clock" timer that is uncoupled with the environment. However, the comparison or production of isolated durations in a laboratory setting is an artificial task that people rarely encounter in day-to-day functioning. This limits the explanatory power of the interval model when applied to more naturalistic tasks such as the perception and production of temporal patterns (e.g., music and speech).

The theory developed in this article emphasizes contextual effects in tempo discrimination, but it also applies to the discrimination of isolated durations. We have not distinguished between tempo discrimination and duration discrimination because these two tasks are thought to be fundamentally the same. The demonstrated link between fast and slow tempos, short and long durations, and early and late onset of the comparison sequence becomes clear when one assumes that the relevant psychological variable in time discrimination is relative phase.

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