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Tempo sensitivity in isochronous tone sequences: The multiple-look model revisited

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Factors affecting tempo sensitivity in isochronous tone sequences were investigated in two experiments. Participants listened to tones in sequence conditions in which the number of time intervals in isochronous standard and comparison sequences was varied, and they were asked to judge the tempo of the comparison relative to the standard. When the duration of the standard interval was held constant, tempo sensitivity was affected by the number of comparison intervals, but not by the number of standard intervals. In contrast, when the duration of the standard interval was varied randomly from trial to trial, tempo sensitivity was affected by the number of intervals in both sequences. The present findings are discussed in the context of a generalized multiple-look model that posits independent contributions of both sequences to tempo sensitivity. Quantitative model fits suggest that the relative contribution of the number of the standard intervals to tempo thresholds depends on (1) the availability of a stable long-term referent for the standard tempo and (2) a priori knowledge about the number of standard intervals.

There is increasing evidence to support the view that rhythm and tempo (rate) play an important role in attention to event sequences (Barnes & Jones, 2000; Jones & Boltz, 1989; Jones, Moynihan, MacKenzie, & Puente, 2002; Large & Jones, 1999; Martin, 1972; McAuley & Jones, 2003). This is perhaps most clearly evident in musical sequences in which the underlying beat, which typically communicates the tempo (rate) of the sequence, marks out salient points in time at approximately equal time intervals (Drake & Palmer, 1993; Parncutt, 1994; Povel & Essens, 1985). This article addresses factors affecting sensitivity to tempo for simple isochronous tone sequences.

There have been a number of previous studies addressing questions pertaining to tempo sensitivity, involving both auditory and visual stimuli (Drake & Botte, 1993; Grondin, 2001a; Ivry & Hazeltine, 1995; McAuley & Kidd, 1998; Michon, 1964; Monahan & Hirsh, 1990; Schulze, 1978, 1989; Vos, van Assen, & Franek, 1997). Nonetheless, basic questions about the nature of mechanism(s) used to detect changes in tempo and to make judgments about relative tempo remain unanswered (see Grondin, 2001b, for a recent excellent review). The focus of the present research is on tempo sensitivity and the multiple-look model proposed by Drake and Botte.

Drake and Botte (1993) considered effects of sequence length on listeners' ability to judge the relative tempo of pairs of isochronous tone sequences. Listeners heard an isochronous standard sequence, followed by an isochronous comparison, as illustrated in Figure 1. They were asked to judge the tempo of the comparison, relative to the standard. As the number of sequence tones increased, the listeners' ability to judge the faster of the two sequences improved. Relative just noticeable differences (JNDs) in tempo averaged 6% for single-interval sequences, in accord with earlier work (Abel, 1972; Allan, 1979; Creelman, 1962; Getty, 1975; Small & Campbell, 1962; Woodrow, 1951), whereas JNDs for multiple-interval sequences were sometimes less than about 2% (Drake & Botte, 1993; Friberg & Sundberg, 1995; Michon, 1964).

To explain these improvements, Drake and Botte (1993) proposed a multiple-look model whereby each time interval between tone onsets (interonset interval [IOI]) in the standard sequence provides an independent but variable estimate of sequence tempo. They hypothesized, as have others, that listening to the standard sequence leads to separate interval-based estimates of the standard's tempo, which are averaged to form an aggregate memory trace (Drake & Botte, 1993; Ivry & Hazeltine, 1995; Keele, Nicoletti, Ivry, & Pokorny, 1989; Schulze, 1989). As the number of independent "looks" at the same standard IOI increases, the average sampling error between the estimated and the actual tempo decreases, leading to lower discrimination thresholds. Drake and Botte predicted that the JND in tempo, taken as the standard deviation of the sampling distribution, should decrease inversely to the square root of the number of sequence intervals, as follows:

$$\mathrm{JND}_n = \frac{\mathrm{JND}_1}{\sqrt{n}}. \qquad (1)$$

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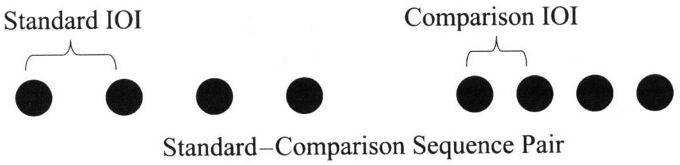

Figure 1. Diagram illustrating the tempo discrimination task examined by Drake and Botte (1993). Participants heard pairs of isochronous tone sequences and judged the tempo of the second (comparison) sequence relative to the first (standard) sequence. The tempo of each sequence was defined by the constant time interval between tone onsets, labeled in the diagram as the standard interonset interval (IOI) and the comparison IOI, respectively. The standard and the comparison sequences always contained the same number of tones.

In this equation, JND_1 is the observed JND for a single-interval standard sequence, and JND_n is the predicted JND for an n-interval standard sequence.

A number of studies have reported results consistent with a multiple-look model. Multiple-interval advantages have been reported for both auditory and visual sequences for tasks involving time interval perception, as well as production (Grondin, 2001a; Ivry & Hazeltine, 1995; McAuley & Jones, 2003; McAuley & Kidd, 1998; Rousseau & Rousseau, 1996; ten Hoopen & Akerboom, 1983). There are notable exceptions, however. Some studies have reported mixed results (Grondin, 2001a; Hirsh, Monahan, Grant, & Singh, 1990; Schulze, 1989), whereas others have shown no multiple-interval advantage (Pashler, 2001; ten Hoopen et al., 1994). One factor preventing a clear interpretation of some of this research is that the numbers of standard and comparison intervals have sometimes covaried, making the precise reason for improvements in tempo sensitivity unclear (Drake & Botte, 1993; Grondin, 2001a; McAuley & Kidd, 1998). That is, the multiple-interval advantage may occur because of multiple intervals in the standard sequence, in the comparison sequence, or in both.

Some indication that the multiple-interval advantage may be partially due to the number of comparison intervals comes from Grondin (2001a). Grondin (2001a) examined the detection of time changes in visual sequences, using a constant (fixed) standard interval, and found a multiple-interval advantage for what he termed a *discontinuous task* (in which the standard and the comparison sequences were separated by a gap and the number of standard and comparison intervals always covaried), but no multiple-interval advantage for a continuous task (in which the standard and the comparison sequences were not separated by a gap and there was only a single comparison interval). Grondin (2001a) suggested that these results identify a potentially important task distinction. Alternatively, the differences may simply be due to the number of comparison intervals available to participants.

Here, we propose that the number of intervals in standard and comparison sequences (notated here as n_1 and n_2) make distinct contributions to tempo discrimination thresholds. The generalized multiple-look model incorporates the potential contributions of the standard and comparison sequences by extending the original multiple-look model to measure average sampling error for two independent samples, rather than for a single sample:

$$\mathrm{JND}_{n_1:n_2} = \sqrt{\frac{w\left(\mathrm{JND}_{1:1}\right)^2}{n_1} + \frac{(1-w)\left(\mathrm{JND}_{1:1}\right)^2}{n_2}}. \quad (2)$$

As in the original multiple-look model, predicted tempo JNDs (notated here as $\mathrm{JND}_{n_1:n_2}$ for isochronous n_1-interval standard and n_2-interval comparison sequences) are based on the observed JND for the single-interval case ($\mathrm{JND}_{1:1}$). Thresholds are similarly predicted to have an inverse relationship with the number of sequence intervals, but unlike in Drake and Botte (1993), the relative contribution of each sequence to thresholds varies through a relative weight parameter w.

In the proposed model, thresholds decrease inversely to both n_1 and n_2, with the parameter w modulating the contribution of each sequence, in a manner similar to a weighted average. Note that when $w = 1$, the predicted JND in tempo, $\mathrm{JND}_{n_1:n_2}$, is determined by the number of standard intervals only. In this case, the model reduces to the original multiple-look model depicted in Equation 1. In contrast, when $w = 0$, thresholds are determined by the number of comparison intervals only, a possibility that was not explicitly considered by Drake and Botte (1993). Finally, when w takes on intermediate values, thresholds are influenced by a weighted combination of the number of intervals in both sequences. Thus, the relative contribution of the number of standard and comparison intervals to tempo thresholds varies with w. Values of w greater than .5 indicate that thresholds are determined more by the number of standard intervals than by the number of comparison intervals, whereas values less than .5 indicate the opposite.

The proposed generalized version of the multiple-look model was tested in two experiments that clarified the factors responsible for the multiple-look effect. Participants were presented with standard–comparison pairs of sequences and judged the tempo of the comparison sequence (*faster* or *slower*), relative to the standard. Different sequence conditions independently varied (1) the number of intervals in the standard and comparison sequences and (2) the participants' uncertainty about the number of sequence intervals. The uncertainty manipulation explored the possibility that participants are less adept at using multiple looks for either the standard or the comparison sequence if they are unable to predict how many intervals there will be in the sequence on a given trial. Some evidence that uncertainty may mediate the strength of the multiple-look advantage has come from Schulze (1989), who failed to find a multiple-look advantage for conditions of high uncertainty about the number of standard intervals. In Experiment 1, the participants experienced a constant (fixed) 500-msec standard on all trials, whereas in Experiment 2, the participants experienced a variable (roving) standard of 400, 500, or 600 msec.

EXPERIMENT 1

The four sequence conditions in Experiment 1 are shown in Figure 2. Conditions independently varied the number of standard and comparison intervals (n_1, n_2 = 1 or 3); n_1:n_2 indicates an isochronous n_1-interval standard sequence followed by an isochronous n_2-interval comparison sequence. If the number of standard intervals affects tempo discrimination thresholds, but not the number of comparison intervals, thresholds should be lower in the 3:1 and 3:3 conditions than in the 1:1 and 1:3 conditions, with no difference between conditions sharing the same number of *standard* intervals. On the other hand, if the number of comparison intervals affects tempo discrimination thresholds, but not the number of standard intervals, thresholds should be lower in the 1:3 and 3:3 conditions than in the 1:1 and 3:1 conditions, with no difference between conditions sharing the same number of *comparison* intervals. If both the standard and the comparison sequences affect tempo discrimination thresholds, thresholds should be lowest in the 3:3 condition, highest in the 1:1 condition, and intermediate in the 1:3 and 3:1 conditions.

Method

Design. Experiment 1 implemented a 2 × 2 × 2 × 2 mixed factorial design. Two standard sequences (n_1 = 1, 3) were crossed with two comparison sequences (n_2 = 1, 3), yielding the four within-subjects sequence conditions depicted in Figure 2. Two levels of uncertainty about the number of standard intervals (certain or uncertain) were then crossed with two levels of uncertainty about the number of comparison intervals (certain or uncertain), yielding four between-subjects blocking conditions. In the *neither-blocked* condition, the number of intervals in the standard and comparison varied randomly from trial to trial. In the *standard-blocked* condition, the number of intervals in the standard sequence was constant within a trial block, whereas the number of comparison intervals varied. In the *comparison-blocked* condition, the reverse was true; the number of intervals in the comparison sequence was constant within a trial block, whereas the number of standard intervals varied. In the *both-blocked* condition, the number of intervals in both the standard and the comparison sequences was held constant in a trial block, with the order of presentation of the sequence conditions counterbalanced between participants.

Participants. Seventy-eight undergraduate students at Bowling Green State University, with self-reported normal hearing, participated in return for extra credit in an introductory psychology course. The participants were randomly assigned to one of the four blocking conditions. The data from 3 participants were discarded due to inattention or failure to comply with task instructions. Final numbers for the neither-blocked, standard-blocked, comparison-blocked, and both-blocked conditions were 17, 20, 22, and 16, respectively.

Materials. All the stimulus tones were 50 msec in duration and had a fundamental frequency of 440 Hz. The IOI of the standard sequence was always 500 msec, with the gap separating the standard and the comparison sequences equal to 1,000 msec (twice the standard IOI). The gap between sequences was defined by the time interval between the onset of the last tone of the standard sequence and the first tone of the comparison sequence. The comparison IOI varied randomly from

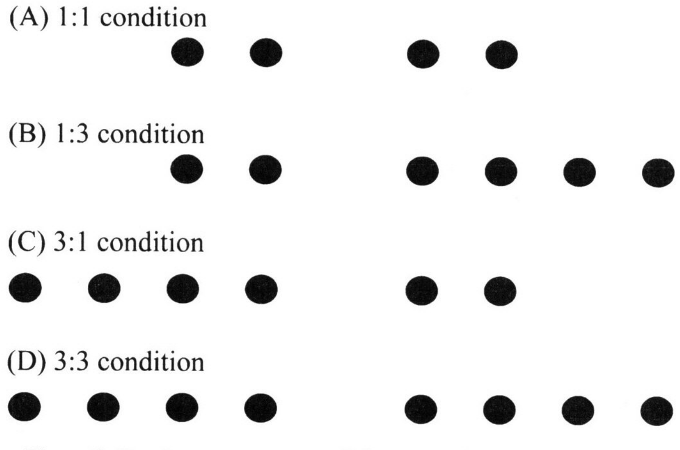

Figure 2. The four sequence conditions examined in Experiments 1 and 2. The different conditions are labeled (n_1:n_2) to specify the number of equal intervals in the standard sequence (n_1) and the number of equal intervals in the comparison sequence (n_2). Consistent with previous research, the gap between the standard and the comparison sequences was defined as the time interval between the onsets of the last tone of the standard sequence and the first tone of the comparison sequence and was always equal to twice the duration of the standard interonset interval.

trial to trial and, during test trials, took on one of six values that were yoked to the standard IOI (±2%, ±6%, or ±10%).

Equipment. Tone sequences were presented to the participants on an IBM PC compatible computer at a comfortable listening level through Koss TI/65 headphones attached to a Yamaha PSR-270 MIDI keyboard that was set to a grand piano voice. The experiment was controlled by the MIDILAB software package, with a time resolution of ≈1 msec (Todd, Boltz, & Jones, 1989).

Procedure. At the start of the experiment, the participants studied a diagram of the four sequence conditions. The participants were told they would hear pairs of tone sequences (a fixed standard followed by a variable comparison) and would be asked to judge the tempo (rate) of the comparison sequence, relative to the standard, by pressing buttons labeled *faster* and *slower* on a response box. The participants were then given a practice block of 16 trials, during which they were exposed to each of the four sequence conditions, using tempo differences between the standard and the comparison sequences that were judged to be well above threshold (±15% or ±30%). Feedback was given after each practice trial to ensure that the participants understood the task.

Four 60-trial test blocks were then administered without feedback, with 10 observations obtained at each level of the comparison IOI in each sequence condition. All the trials were presented in a random order with the order of trial blocks counterbalanced between participants, depending on blocking condition. All the blocks were presented within a single session that lasted ≈90 min. All the trials had a maximum 5-sec response period and an additional 2-sec pause between trials. Between blocks, the participants were given a short break and received instructions about the sequence conditions in the next block; a background survey that contained questions about musical experience was administered about halfway through the experiment.

Data analysis. Proportions of faster responses were determined for each participant for each sequence condition for each of the six comparison IOI values averaged over the four test blocks. JNDs and points of subjective equality (PSEs) were determined from the resulting psychometric curves, using the method prescribed by Macmillan and Creelman (1991, pp. 219–220). JND is a measure of the slope of the curve and equals half the distance between the 25th and the 75th percentiles. We converted JND to a relative measure by dividing it by the standard IOI. PSE is a measure of the intercept corresponding to the stimulus duration judged *faster* 50% of the time. We converted PSE to a directional constant error (CE) score by subtracting standard IOI: CE = PSE − standard IOI. Positive values for CE mean that slower comparison sequences were perceived as equal in tempo to the standard sequence (overestimation), whereas negative values for CE mean that faster comparison sequences were perceived as equal in tempo to the standard sequence (underestimation). Separate four-way mixed measures ANOVAs were performed on relative JNDs and CEs to assess contributions of the number of standard and comparison intervals to tempo sensitivity and the role of uncertainty.

Quantitative model fits were performed using an exhaustive search of the one parameter space, defined by w. Fits were performed to the observed JND values at each level of uncertainty, using the observed $\mathrm{JND}_{1:1}$ value to predict the threshold values in the remaining conditions. All model fits minimized the root-mean square error of approximation (RMSEA) between the observed and the predicted relative JNDs for the four sequence conditions (1:1, 1:3, 3:1, and 3:3). Estimates of w provided a quantitative interpretation of the relative contribution of the number of standard and comparison intervals to tempo thresholds in each condition.

Results

Figure 3A shows mean relative JNDs, with standard error bars, for the four sequence conditions collapsed over the four uncertainty levels (blocking conditions). Thresholds were highest in the 1:1 and 3:1 conditions and lowest in the 1:3 and 3:3 conditions. A 2 × 2 × 2 × 2 mixed measures ANOVA on relative JNDs revealed a main effect of the number of comparison intervals [$F(1,71) = 52.13$, $MS_e = 1.77, p < .01$], but not a main effect of the number of standard intervals [$F(1,71) = 0.97$, $MS_e = 0.719, p = .33$] or a significant interaction between these two factors [$F(1,71) = 0.22$, $MS_e = 0.87, p = .64$].

Mean relative JNDs in each blocking condition are shown in Table 1. Overall, relative JNDs were lower when listeners were certain about the number of standard intervals ($M = 3.33\%$, $SE = 0.18$) than when they were uncertain about the number of standard intervals ($M = 3.97\%$, $SE = 0.17$). Table 1 also shows the obtained fits of the generalized multiple-look model for each of the blocking conditions. Overall, w estimates were less than .5, indicating that the number of comparison intervals has a greater role in determining thresholds than does the number of standard intervals. A comparison of w estimates across blocking conditions supports the view that the number of standard intervals has a larger effect on tempo discrimination thresholds when listeners know how many intervals there will be in the standard sequence (standard blocked, $w = .35$; both blocked, $w = .34$) than when they do not know (neither blocked, $w = .14$; comparison blocked, $w = .1$).

This interpretation was supported by the ANOVA on relative JNDs, which revealed a main effect of uncertainty in number of standard intervals [$F(1,71) = 6.87$, $MS_e = 4.36, p < .01$] but no main effect of uncertainty in number of comparison intervals [$F(1,71) = 0.58, MS_e = 4.36$, $p = .45$]. Moreover, there was an interaction between levels of uncertainty in number of standard intervals and number of comparison intervals [$F(1,71) = 7.94$, $MS_e = 1.77, p < .01$]. The effect of uncertainty in the number of standard intervals appeared to be more pronounced when there was a single comparison interval ($M = 4.75\%$, $SE = 0.26$ vs. $M = 3.67\%$, $SE = 0.27$) than when there were three comparison intervals ($M = 3.20\%$, $SE = 0.12$ vs. $M = 3.00\%$, $SE = 0.12$). One possible explanation may be that thresholds were already so low with three intervals in the comparison sequence that the effect of uncertainty in number of standard intervals was minimal. There were no other significant interactions (all $ps > .1$).

Finally, to assess the potential impact of the number of standard and comparison intervals and level of uncertainty on directional distortions in perceived tempo, a second 2 × 2 × 2 × 2 mixed measures ANOVA was performed on CE scores. Although CE was, overall, very close to zero, the ANOVA revealed two main effects. There was a main effect for the number of standard intervals [$F(1,71) = 7.47, MS_e = 4.82, p < .01$]; CE scores (reported here as a percentage of the 500-msec standard IOI) were very slightly positive when there was only a single interval in the standard sequence ($M = 0.74\% \pm 0.22$) but not different from zero ($M = 0.04\% \pm 0.18$) when there were three intervals in the standard sequence. There was an opposite main effect for the number of comparison intervals [$F(1,71) = 8.28$, $MS_e = 5.96, p < .01$]; CE scores were not different from zero when there was

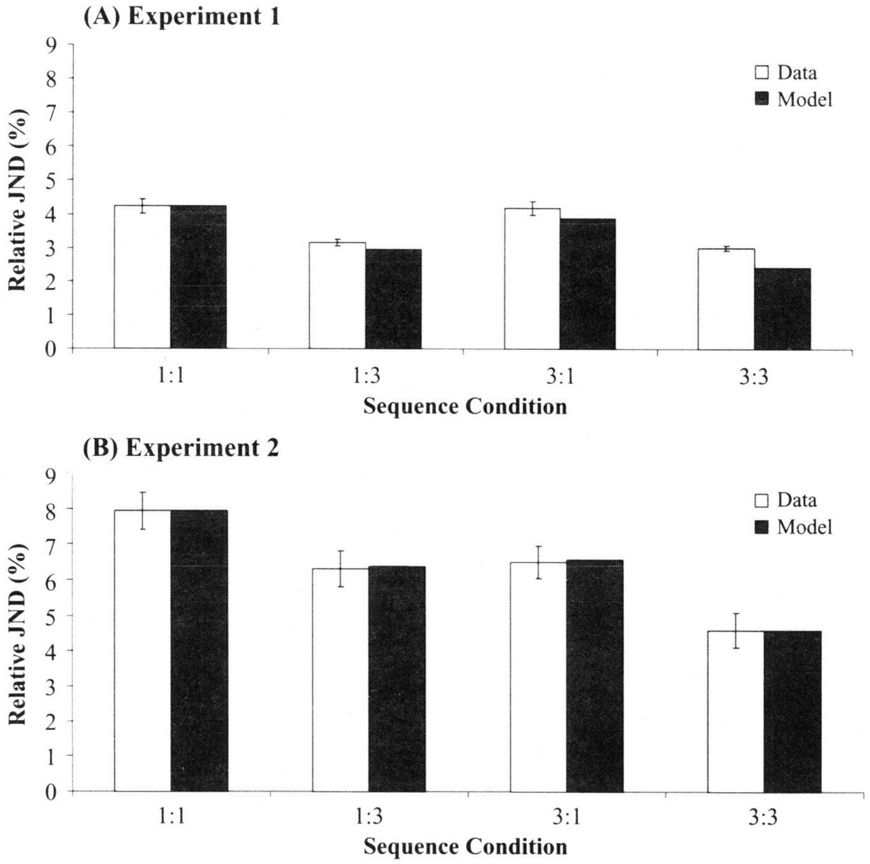

Figure 3. Mean observed and predicted relative just noticeable differences (JNDs) in tempo, with standard error bars, for the four sequence conditions: 1:1, 1:3, 3:1, and 3:3. (A) Experiment 1 data for a fixed 500-msec standard interonset interval (IOI) averaged over the four uncertainty conditions. (B) Experiment 2 data for a roving standard averaged over the three standard IOI values of 400, 500, and 600 msec. Mean predicted values reported in panels A and B were obtained by averaging the corresponding values reported for the model fits in Tables 1 and 2, respectively.

one interval in the comparison sequence ($M = 0.01 \pm 0.24$) but were very slightly positive with three intervals in the comparison sequence ($M = 0.80 \pm 0.18$). There were no significant interactions (all $ps > .1$).

Discussion

Mean relative JNDs for Experiment 1 were similar to those previously reported by Drake and Botte (1993) for the same 500-msec standard IOI. For the identical

Table 1
Observed and Predicted Mean Relative Just Noticeable Differences (Reported as a Percentage of the 500-msec Standard Interonset Interval; With Standard Errors of the Means) for the Four Sequence Conditions (1:1, 1:3, 3:1, and 3:3) for the Four Levels of Uncertainty

	Blocking Condition (Level of Uncertainty)											
	Neither			Standard			Comparison			Both		
Sequence	Data			Data			Data			Data		
Condition	*M*	*SEM*	Model	*M*	*SEM*	Model	*M*	*SEM*	Model	*M*	*SEM*	Model
1:1	4.51	0.46	4.51	4.11	0.42	4.11	4.91	0.40	4.91	3.43	0.47	3.43
1:3	3.32	0.21	2.95	3.32	0.19	3.09	3.14	0.18	3.11	2.89	0.21	2.57
3:1	4.75	0.41	4.29	3.79	0.38	3.60	4.83	0.36	4.74	3.38	0.43	3.02
3:3	3.15	0.17	2.60	3.03	0.16	2.37	3.18	0.15	2.83	2.73	0.18	1.98
Mean	3.93	0.25	3.59	3.56	0.23	3.23	4.01	0.22	3.90	3.11	0.26	2.75

Note—Model estimates of *w* for the neither-blocked, standard-blocked, comparison-blocked, and both-blocked conditions were .14, .35, .1, and .34, respectively.

1:1 sequence condition, mean relative JND was 4.5% in the present study, which compares with 5% in Drake and Botte's study. Similarly, our mean relative JND of approximately 3% for the 3:3 sequence condition was intermediate to those observed for the 2:2 and 4:4 sequence conditions in Drake and Botte's study. However, in contrast to Drake and Botte's multiple-look model, which posited that thresholds should decrease inversely to the number of standard intervals, tempo discrimination thresholds appeared to be affected by the number of comparison intervals, but not by the number of standard intervals.

This finding was qualified somewhat by the uncertainty manipulation. Overall, thresholds were generally lower when the participants knew how many intervals there would be in the standard sequence than when they did not know. In contrast, uncertainty about the number of comparison intervals appeared to have very little effect on thresholds. Consistent with this interpretation, fits of the generalized multiple-look model to each blocking condition showed that w estimates were larger (suggesting a greater contribution of the number of standard intervals to thresholds) when the participants were certain about the number of standard intervals (standard-blocked/both-blocked conditions) than when they were uncertain (comparison-blocked/neither-blocked conditions) and that there was very little difference in the obtained w values when uncertainty about the number of comparison intervals varied.

Finally, although the number of standard intervals did not reliably affect thresholds, the number of standard intervals did reliably affect CE scores, although the magnitude of the effect was very small. There appeared to be slightly less distortion in perceived tempo with more intervals in the standard sequence, whereas the opposite was true with more intervals in the comparison sequence. Combined, the findings from Experiment 1 suggest that multiple intervals in the standard sequence produce a slightly more accurate temporal memory, but not a less variable one.

One possible reason that the number of standard intervals contributed very little to thresholds is that the participants may have developed a stable memory for the 500-msec standard over the course of the experimental session; indeed, CEs were practically negligible. Forming a stable long-term referent for the standard tempo may have eliminated the advantage conferred by multiple standard intervals. Experiment 2 directly tested this possibility, using a roving standard. A roving standard should make it more difficult to form a stable referent and more likely that increasing the number of standard intervals will reduce tempo discrimination thresholds.

EXPERIMENT 2

In Experiment 2, the standard IOI took on one of three values (400, 500, or 600 msec) and varied randomly from trial to trial. If the null effect of the number of standard intervals found in Experiment 1 was due to the participants' developing a long-term referent for the 500-msec standard tempo, we hypothesized that the number of intervals in the standard should have a larger effect on tempo thresholds when the standard IOI varied from trial to trial. If, however, the roving versus fixed standard distinction is not important, we would expect to find a pattern of performance in Experiment 2 similar to that in Experiment 1. The latter possibility would permit us to conclude more generally that the multiple-look advantage is due to the number of intervals making up the comparison sequence, not the number of intervals making up the standard sequence.

One additional possibility we considered was that the number of intervals in the standard sequence might effectively reduce tempo discrimination thresholds for the 400- and 600-msec standards, but not for the 500-msec standard. The reasoning here was that the participants might form a stable referent for the 500-msec standard by picking up on the average tempo conveyed by the time intervals making up the experimental session, which also was 500 msec. Some evidence that participants form a stable referent for the session mean comes from Jones and McAuley (2005). If this occurred in Experiment 2, we should find an effect of the number of standard intervals for both the 400- and the 600-msec conditions, but not for the 500-msec condition. For the 500-msec standard, we would expect to find results similar to those in Experiment 1. In terms of the generalized multiple-look model, this hypothesis implied that separate fits to each of the standard IOI conditions should produce larger w values for the 400- and 600-msec standards than for the 500-msec standard, with the w value for 500 msec potentially similar in both experiments.

Method

Design. Experiment 2 implemented a 2 × 2 × 3 mixed factorial design. Two standard sequences ($n_1 = 1, 3$) were crossed with two comparison sequences ($n_2 = 1, 3$) and three standard IOIs (400, 500, and 600 msec). Sequence condition was manipulated between subjects, and standard IOI was manipulated within subjects.

Participants. Seventy-seven undergraduate students at Bowling Green State University, with self-reported normal hearing, participated in the experiment in return for extra credit in an introductory psychology course. The participants were randomly assigned to one of the four standard–comparison sequence conditions. The data from 9 participants were discarded due to inattention or failure to follow task instructions or because preliminary threshold estimates were $\gg 2$ *SD*s above the mean.[1] Final numbers for the 1:1, 1:3, 3:1, and 3:3 conditions were 16, 16, 19, and 17, respectively.

Materials. Stimulus tones were 50 msec in duration and had a fundamental frequency of 440 Hz. The gap separating the standard and the comparison sequences, defined as the time interval between the onset of the last tone of the standard sequence and the first tone of the comparison sequence, was always equal to twice the standard IOI.

Equipment. The same experimental setup was used as that in Experiment 1.

Procedure. The same general procedure was followed as that in Experiment 1. Prior to testing, the experimenter presented instructions for the tempo judgment task, while the participants studied a diagram of the appropriate sequence condition. The participants were given a practice block of 24 trials with feedback, during which they were exposed to each of the three standard IOIs. For the practice block, tempo differences between the standard and the comparison sequences were well above threshold (±15% or ±30%). Following practice, the participants were administered five test blocks of 36 trials. During these blocks, both standard and comparison IOIs varied randomly from trial to trial; as in Experiment 1, the comparison IOIs were ±2%, ±6%, or ±10% of the standard IOI. Ten observations were obtained for each standard–comparison pair. The order of trials was randomized within each block, and the order of blocks was counterbalanced between participants. The experiment lasted ≈90 min, with short breaks between test blocks.

Results and Discussion

Figure 3B shows mean relative JNDs, with standard error bars for the four sequence conditions, averaged over the three standard IOI values. By comparing Figures 3A and 3B, it can be seen that relative JNDs were generally higher in Experiment 2 than in Experiment 1; for the 500-msec standard IOI in the matching both-blocked condition, mean relative JNDs for Experiments 1 and 2 were 3.12 ± 0.10 and 6.83 ± 0.52, respectively. Moreover, in relation to Experiment 1, the use of a roving, rather than a fixed, standard appeared to produce effects of number of standard intervals *and* number of comparison intervals on tempo discrimination thresholds; thresholds were highest in the 1:1 condition, next highest in the 1:3 and 3:1 conditions, and lowest in the 3:3 condition.

Consistent with independent contributions of number of standard and comparison intervals to tempo thresholds, an ANOVA on relative JNDs showed main effects of number of standard intervals [$F(1,64) = 10.35$, $MS_e = 12.24$, $p < .01$] and number of comparison intervals [$F(1,64) = 12.92$, $MS_e = 12.24$, $p < .01$] but no interaction between these two factors [$F(1,64) = 0.09$, $MS_e = 12.24$, $p = .76$]. Overall, there was no main effect of tempo [$F(2,128) = 2.24$, $MS_e = 8.37$, $p = .11$], but the interaction between tempo and number of comparison intervals approached significance [$F(2,128) = 2.57$, $MS_e = 8.37$, $p = .08$]. No other interactions were significant (all $ps > .1$).

To investigate the marginal interaction between tempo and number of comparison intervals, separate 2 × 2 ANOVAs and model fits were performed on relative JNDs at each standard IOI. Summary data and corresponding model fits are reported in Table 2. Model fits were obtained using a single average JND value in the 1:1 condition (collapsed over standard IOI) to predict the 12 observed threshold values shown in the table. Most notably, the number of intervals in the standard sequence had the largest impact on thresholds in the 400- and 600-msec conditions. This conclusion was supported by both the separate ANOVAs and the model fits.

For both the 400- and the 600-msec standards, ANOVAs revealed main effects of number of standard intervals [$F(1,64) = 3.82$, $MS_e = 4.96$, $p < .05$, and $F(1,64) = 15.51$, $MS_e = 7.33$, $p < .01$, respectively] and somewhat weaker effects of number of comparison intervals [$F(1,64) = 3.12$, $MS_e = 4.96$, $p = .08$, and $F(1,64) = 3.82$, $MS_e = 7.33$, $p < .05$, respectively]. In contrast, for the 500-msec standard, the ANOVA showed no reliable effect of number of standard intervals [$F(1,64) = 1.2$, $MS_e = 16.71$, $p = .28$] but a strong main effect of number of comparison intervals [$F(1,64) = 9.45$, $MS_e = 16.71$, $p < .01$]. None of the three standard IOI conditions revealed an interaction between number of standard and number of comparison intervals (all $ps > .1$), suggesting that these factors make independent contributions to thresholds.

The model fits of *w* for the 400-, 500-, and 600-msec standard conditions were .50, .20, and .69 for 400-, 500-, and 600-msec IOI values, respectively. This suggests that the number of standard intervals contributed more to tempo thresholds for the 400- and 600-msec standard IOIs than for the 500-msec standard IOI. For the 500-msec standard IOI, the *w* value of .20 was somewhat less than the value of .34 reported for the matching both-blocked condition in Experiment 1, indicating an even stronger contribution of the number of comparison intervals than in Experiment 1. Overall, results from the statistical analysis and model fits to JND data are consistent with the hypothesis that participants form a stable referent for the 500-msec standard by detecting the average tempo conveyed by time intervals in the experimental session, but not for the two extreme standard IOIs (400 and 600 msec).

Additional support for this interpretation was found in analyses of CEs. Figure 4 shows CEs reported as a percentage of standard IOI for 400-, 500-, and 600-msec standards for the four sequence conditions. CEs were positive for the 400-msec standard, negative for the 600-msec standard, and closest to zero for the 500-msec standard,

Table 2
Observed and Predicted Mean Relative Just Noticeable Differences (Reported as a Percentage of the Standard Interonset Intervals [IOIs]; With Standard Errors of the Means) for the Four Sequence Conditions (1:1, 1:3, 3:1, and 3:3) for the Three Standard IOIs

	Standard IOI (msec)								
Sequence	400			500			600		
Condition	*M*	*SEM*	Model	*M*	*SEM*	Model	*M*	*SEM*	Model
1:1	6.37	0.57	7.93	9.41	0.99	7.93	8.02	0.68	7.93
1:3	6.27	0.56	6.48	5.36	0.99	5.42	7.34	0.68	7.07
3:1	6.16	0.51	6.48	7.33	0.94	7.38	6.02	0.62	5.83
3:3	4.36	0.54	4.58	5.27	0.99	4.58	4.14	0.66	4.58
Mean	5.79	0.27	6.37	6.84	0.49	6.34	6.38	0.33	6.35

Note—Model estimates of *w* for the 400-, 500-, and 600-msec standards were .50, .20, and .69, respectively.

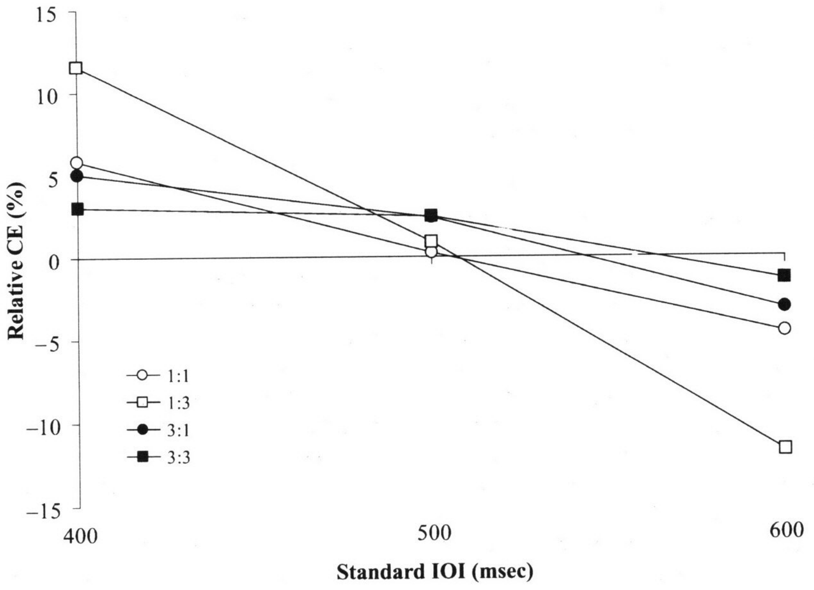

Figure 4. Relative constant errors (CEs) in Experiment 2 (reported as percentages of the standard interonset interval [IOI]) for the 400-, 500-, and 600-msec standards for the four sequence conditions.

reminiscent of Vierordt's law and the concept of an indifference interval (Vierordt, 1868; Woodrow, 1934, 1951; see Jones & McAuley, 2005, for a review). A 2 × 2 × 3 mixed measures ANOVA revealed a main effect of tempo [$F(2,128) = 79.26$, $MS_e = 28.85$, $p < .01$] but also significant two-way interactions between tempo and number of standard intervals [$F(2,128) = 16.53$, $MS_e = 28.85$, $p < .01$] and between tempo and number of comparison intervals [$F(2,128) = 3.20$, $MS_e = 28.85$, $p < .01$] and a significant three-way interaction between tempo, number of standard intervals, and number of comparison intervals [$F(2,128) = 10.12$, $MS_e = 28.85$, $p < .01$].

The three-way interaction suggested that overestimation of the 400-msec standard and underestimation of the 600-msec standard were larger for the 1:3 sequence condition than for the other three sequence conditions. There was no main effect of the number of standard intervals [$F(1,64) = 1.36$, $MS_e = 39.19$, $p = .25$], no main effect of the number of comparison intervals [$F(1,64) = 0.03$, $MS_e = 39.19$, $p = .85$], and no interaction between these two factors [$F(1,64) = 0.01$, $MS_e = 39.19$, $p = .91$].

GENERAL DISCUSSION

Previous studies of tempo discrimination in isochronous sequences have reported greater tempo sensitivity with increased sequence length (Drake & Botte, 1993; Grondin, 2001a; McAuley & Kidd, 1998; Michon, 1964). This multiple-interval advantage in tempo discrimination has been attributed to the number of "looks" participants have at the time interval defining the tempo of the first (standard) sequence in a standard–comparison pair of sequences (Drake & Botte, 1993; Keele et al., 1989; Schulze, 1989). One problem with this interpretation is that some designs have covaried the number of intervals in the standard and comparison sequences, making the precise reason for the observed improvements unclear. The general aim of this study was to clarify the factors responsible for the multiple-look effect. Is the reported multiple-look effect due to having more standard intervals, more comparison intervals, or a combination of the two?

Experiment 1 showed that with a fixed standard interval, there are improvements in tempo sensitivity (as measured by JNDs) with multiple intervals in the comparison sequence, but not with multiple intervals in the standard sequence. Experiment 2 extended this result by showing that with a roving, rather than a fixed, standard, tempo discrimination thresholds are affected by the number of intervals in *both* the standard and the comparison sequences, especially for standard IOI values differing from the session mean (e.g., 400 and 600 msec in Experiment 2). Combined, these results are consistent with the view that with a fixed standard interval, participants develop a stable long-term referent for the standard tempo that overrides any advantage conferred by multiple presentations of the standard interval, but that with a roving standard, they are less able to form such a stable tempo referent.[2]

Overall, the proposed generalized multiple-look model provides a much better fit to data from both experiments than does the original multiple-look model. Data consistent with the original multiple-look model would have yielded w estimates close to 1.0, and in no case did that occur. With minor exceptions, w estimates were less than .5, indicating that the number of comparison intervals played a greater role in determining thresholds than did the number of standard intervals. Comparing model fits across experiments suggests that the relative contribution of number of standard intervals to tempo thresholds is generally larger when the standard is roving than when it is fixed.

These findings are qualified in two ways. First, w estimates obtained from each blocking condition in Experiment 1 suggest that the contribution of number of standard intervals to tempo thresholds is greater in conditions with low uncertainty for number of standard intervals (standard blocked, $w = .35$; both blocked, $w = .34$) than in conditions with high uncertainty for number of standard intervals (neither blocked, $w = .14$; comparison blocked, $w = .10$). Second, separate w estimates for 400-, 500-, and 600-msec standard IOIs in Experiment 2 suggest that the contribution of number of standard intervals is mediated by the relationship of standard IOI to session mean. Larger w estimates were found for the two extreme standard IOIs (400 msec, $w = .5$; 600 msec, $w = .69$) than for the 500-msec standard IOI ($w = .20$).

CE data complement these findings. In Experiment 1, CEs were almost negligible, suggesting that the participants developed a stable referent for the 500-msec standard. In contrast, Experiment 2 showed a clear pattern of CEs across the three standard interval conditions. CEs were positive for the 400-msec standard (corresponding to overestimation), negative for the 600-msec standard (corresponding to underestimation), and closest to zero for the 500-msec standard. In the broader timing literature, patterns of CEs of this sort are well established and have been linked historically to the concept of an indifference interval or preferred tempo (Fraisse, 1963; Vierordt, 1868; Woodrow, 1934, 1951).

Some recent evidence suggests that preferred tempi may be, in part, a relative, rather than an absolute, property of the timing system (Jones & McAuley, 2005). In a series of experiments, Jones and McAuley varied the global distributional properties of time intervals making up the extended temporal context of the experimental session and found that CEs gravitated toward the session mean, supporting the view that individuals develop a sense of the average pace of events in the environment. Both the JND and the CE results from Experiment 2 are consistent with this view.

The present research suggests the need to reevaluate claims made in at least four previous studies. First, the effect of number of comparison intervals in Experiment 1, plus the weak effect of number of standard intervals, is at odds with the dominant explanation of the multiple-interval advantage offered by Drake and Botte (1993, p. 284). Drake and Botte attributed improvements in tempo sensitivity to multiple "looks" at the time intervals making up the standard sequence, not to those for the comparison sequence. However, Drake and Botte also covaried the number of intervals in standard and comparison sequences and blocked the standard interval, so they did not rule out the possibility that the number of comparison intervals was the dominant factor. Indeed, the results of Experiment 1, which produced relative JNDs in the same range as that in Drake and Botte, suggest that the multiple-interval effect they reported was more likely due to the number of comparison intervals than to the number of standard intervals per se.

Second, a similar issue emerges in previous research by McAuley and Kidd (1998), who, like Drake and Botte (1993), reported a multiple-interval advantage in tempo discrimination attributed to the standard sequence. Rather than invoking a multiple-look mechanism to explain their data, McAuley and Kidd attributed observed improvements in tempo sensitivity to enhanced perceptual entrainment (synchronization). This interpretation suffers from the same problem as the multiple-look interpretation of Drake and Botte. McAuley and Kidd, like Drake and Botte, covaried the number of standard and comparison intervals, using a blocked standard. Thus, like Drake and Botte, they did not rule out the possibility that observed improvements were due to the number of comparison intervals, rather than to the number of standard intervals. The results from Experiment 1 suggest that the improvements in tempo sensitivity reported by McAuley and Kidd were most likely due to the number of comparison intervals and, thus, not specifically to enhanced perceptual entrainment (synchronization) with the standard sequence.

Third, the results from Experiment 1 suggest a different interpretation of Grondin (2001a). Recall that Grondin (2001a) examined detection of time changes in visual sequences, using a fixed standard interval, and found a multiple-interval advantage for a discontinuous task (identical to the task examined by Drake & Botte, 1993, and McAuley & Kidd, 1998) but no multiple-interval advantage for a continuous task (where standard and comparison sequences were not separated by a gap). Like Drake and Botte (1993) and McAuley and Kidd, Grondin covaried the number of standard and comparison intervals, but only for the discontinuous task. The continuous task always involved a single comparison interval, so that multiple comparison intervals were available to participants who performed the discontinuous task, but not to those who performed the continuous task. Given the results of Experiment 1, which showed that threshold differences are due primarily to number of comparison intervals, time sensitivity likely improved for the discontinuous task in Grondin's (2001a) study because of multiple comparison intervals, but not because of multiple standard intervals. Moreover, no multiple-interval advantage was found for the continuous task because only a single comparison interval was tested, not because of a task difference per se.[3]

Finally, the present results suggest a slightly revised interpretation of Schulze (1989). Schulze, like Grondin (2001a), examined detection of time changes in isochronous sequences, using a continuous task, but for auditory rather than for visual stimuli. Like the present study, Schulze was interested in differentiating the effects of number of standard intervals on time sensitivity in fixed and roving standard conditions. In accord with the present research, Schulze found that listeners were better able to detect a time change when it occurred later in the sequence when the standard was variable (the roving standard condition), but not when it was held constant (the fixed standard condition).

One factor complicating the interpretation of Schulze's (1989) data is that the design also randomly varied the number of intervals in the standard sequence from trial to trial in the fixed standard condition, but not in the roving standard condition. This makes it unclear whether the fixed versus roving standard difference Schulze reported was indeed due to a distinction between the fixed and the roving standard conditions or to differences in participants' knowledge about the number of standard intervals on any given trial (i.e., whether or not they knew where the time change was going to occur within the sequence). The present results suggest that the fixed versus roving standard difference Schulze observed for the continuous task was partially, but not entirely, due to differences in listeners' knowledge about the number of standard intervals.

Overall, these findings contribute to the understanding of tempo sensitivity by showing that certain discrepancies in previous studies may be explained by three factors. The first factor is the confounding of the number of intervals in standard and comparison sequences. Some studies may have misattributed multiple-look effects to the number of intervals in the standard sequence, as opposed to the comparison sequence (Drake & Botte, 1993; Grondin, 2001a; McAuley & Kidd, 1998). A second factor is the use of a fixed versus a roving standard. These results suggest that with a fixed standard tempo, listeners develop a stable long-term referent for standard tempo that potentially overrides advantages afforded by multiple intervals in the standard sequence, whereas with a roving standard, this is much less likely to happen. There are cases, however, in which a long-term tempo referent may develop with a roving standard. These appear to reflect sensitivity to the average tempo (pace) of the extended temporal context of the listener's environment. The third factor is listeners' uncertainty about the number of intervals. The present results suggest that listener uncertainty about the number of standard intervals affects tempo sensitivity, but not uncertainty about the number of comparison intervals.

The primary theoretical contribution of this work is the development of the generalized multiple-look model. This model has been applied in a descriptive manner to quantify the relative contribution of number of standard and comparison intervals to tempo sensitivity in the different conditions tested. As such, the model is neutral with respect to the ongoing debate between the proponents of interval and entrainment theories of timing (Ivry & Hazeltine, 1995; McAuley & Jones, 2003; Pashler, 2001). However, it is possible to conceive of advantages afforded by multiple intervals in standard and comparison sequences in terms of either an interval model or an entrainment model.

In an entrainment model, time judgments are based on the magnitude and sign of the relative phase difference between tone onsets in the stimulus sequence and expected tone onsets generated by the underlying oscillatory timer (McAuley, 1995; McAuley & Jones, 2003; McAuley & Kidd, 1998). For standard–comparison pairs of isochronous sequences, judgments about the relative tempo of the comparison sequence are based on the relative phase of *only* the ending tone of the comparison sequence. One way that current entrainment approaches might be modified to account for an effect of number of comparison intervals would be to permit the relative phase of *each* tone onset in the comparison sequence to contribute to tempo judgments. Some physiological support for this view comes from a recent ERP study of tempo perception involving the measurement of contingent negative variation, or CNV (Pfeuty, Ragot, & Pouthas, 2003). In this study, decreases in CNV amplitude were observed during the presentation of the comparison sequence, but not during the presentation of the standard sequence, leading the authors to conclude that participants were using a beat-based (oscillatory) process to check whether the tone onsets of the comparison sequence occurred at the anticipated times on the basis of an extrapolation of the standard sequence.

In conclusion, the present research contributes to the current debate between interval and entrainment theorists by offering the following general constraints for future models. Extensions of current models of tempo perception must be able to account for (1) the effect of the number of comparison intervals, as well as that of the number of standard intervals, (2) the development of a long-term stable tempo referent that is also sensitive to the global distributional properties of the session context, and (3) a role for uncertainty about the number of standard intervals.

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NOTES

1. The relatively high attrition rate in Experiment 2 is consistent with our general observation that students seeking research participation credit toward the end of the academic semester tend to be less compliant and attentive than students who choose to participate earlier in the semester. Most of the subjects dropped were end-of-the-semester subjects.

2. One possibility we did not directly consider in the present set of experiments is that the 500-msec standard represents an absolute tempo referent. We feel that this possibility is very unlikely in light of Jones and McAuley (2005, Experiment 2), where 500 msec served as a diagnostic standard interval, which was embedded in eight different session context conditions. Across the eight context conditions, the 500-msec standard produced both positive and negative CEs that depended on its relationship to the session mean.

3. To directly test for a possible effect of task, we ran a continuous task version of Experiment 1 (not reported here). Thirteen participants were tested on the same four sequence conditions, using a fixed 500-msec standard IOI, with the gap separating the standard and the comparison sequences eliminated. Consistent with the results of Experiment 1, an ANOVA on JND revealed a significant main effect of the number of comparison intervals [$F(1,12) = 11.2$, $MS_e = 60.28$, $p < .01$] but not a significant main effect of the number of standard intervals [$F(1,12) = 0.18$, $MS_e = 112.7$, $p = .63$] or a significant interaction [$F(1,12) = 0.06$, $MS_e = 2.67$, $p = .81$].

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