9th International Conference on Music Perception and Cognition

Alma Mater Studiorum University of Bologna, August 22-26 2006

Detecting changes in timing: Evidence for two modes of listening

J. Devin McAuley[1] Deborah Frater Kellie Janke

Nathaniel S. Miller

ABSTRACT

This study contrasted interval- and entrainment (beat-based) perspectives of timing. Participants listened to sequences of tones and decided at the end of the sequence if they felt the sequence was speeding up or slowing down. Findings supported two distinct modes of listening. Some participants appeared to base their judgments on the relative synchrony/asynchrony of events with an internally-generated beat (a beat mode of listening) while others appeared to base their judgments on a comparison of the duration of the time intervals comprising each sequence (an interval mode of listening). A consequence of individual differences in mode of listening was that there were particular stimulus instances that yielded opposite perceptions. For some stimulus sequences, a beat-based mode provided listeners with a strong sense that the sequence was speeding up, while an interval-based mode suggested that the same sequence was slowing down. Implications of this work for understanding the neural mechanisms underpinning time and rhythm perception are discussed.

Keywords

Temporal processing, tempo, rhythm, entrainment

In: M. Baroni, A. R. Addessi, R. Caterina, M. Costa (2006) Proceedings of the 9th International Conference on Music Perception & Cognition (ICMPC9), Bologna/Italy, August 22-26 2006.

INTRODUCTION

A range of human behaviors require accurate and flexible judgments about sequence timing. An important unanswered question in research on timing concerns the nature of the mechanism(s) involved in the perception and/or production of time intervals that make up a temporally extended sequence of events, such as a melody. In the area of music perception, a behavioral example that illustrates the this capacity is the ability to determine with a relatively high degree of precision whether a piece of music is accelerating ('speeding up') or decelerating ('slowing down'). Many researchers have proposed formal models to account for various aspects of sequence timing, such as the detection of tempo changes in the above example. In general, these models derive from one of two theoretical perspectives: an interval-based perspective or an entrainment (beat-based) perspective.

The Interval View

Interval models of timing appeal to information-processing theories with distinct clock, memory and decision stages (Church & Broadbent, 1990; Gibbon, 1977; Gibbon, Church & Meck, 1984). The clock stage typically involves a pacemaker, which emits over time a continuous stream of pulses that flow into an accumulator via a switch, which is controlled by attention. The number of pulses accumulated during a target time interval, T, provides a representation of the duration of that interval (an interval code). Interval models assume that judgments about the timing of a sequence are based on a comparison of the interval codes derived from that sequence (Drake & Botte, 1993; Ivry & Hazeltine, 1995; Keele, Nicoletti, Ivry & Pokorny, 1989; Pashler, 2001).

Consider an application of an interval model to the example sequence in Figure 1A. This figure depicts a tone sequence that marks out a series of inter-onset-intervals (IOIs); all of the IOIs in this sequence are equal to 600 ms, except for the final 500 ms IOI, which is shorter than the preceding IOIs of the sequence. Most listeners would perceive that this sequence speeds up at the end. From an interval perspective, detecting that this sequence speeds up at the end requires a comparison of the interval codes generated for each IOI in the sequence. An interval code representation of durations is essentially a pulse 'count'. The perception of speeding up occurs because the accumulated 'count' associated with the 500-ms IOI is less than the stored 'count' associated with the preceding 600 ms IOIs.

[1] All authors are affiliated with the Department of Psychology, Bowling Green State University. Correspondence about this article should be addressed to Dr. J. Devin McAuley, Department of Psychology, Bowling Green State University, Bowling Green, OH 43403 USA (email: mcauley@bgnet.bgsu.edu).

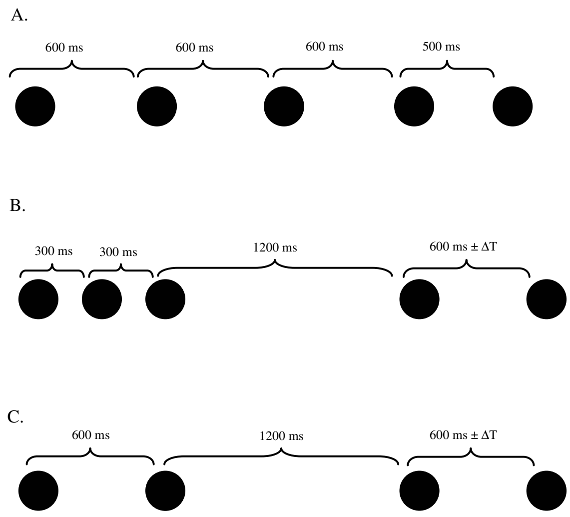

Figure 1. Three sequence examples: A. Isochronous 600-ms sequence with a shortened (500-ms) final IOI; B. Test sequence consisting of a pair of 300 ms IOIs followed by a 1200-ms IOI and a variable final IOI; C. Control sequence consisting of a 600-ms IOI followed by a 1200-ms IOI and a variable final IOI.

Figure 1B illustrates a slightly more complicated example. For this example, the sequence begins with two short IOIs (each 300 ms) followed by a longer 1200 ms IOI and a final IOI that is of intermediate duration (≈ 600 ms). On what basis would listeners make judgments about the timing of the end of this sequence? Would listeners perceive that the sequence 'speeds up' at the end or that it 'slows down'? From an interval perspective, there are at least two alternatives. First, listeners could base their judgments on an interval code associated with the beginning 300 ms interval. In this case, they would be expected to hear the sequence as slowing down because the ≈ 600 ms final IOI is longer than 300 ms. Alternatively, listeners could base their judgments on the interval code associated with the 1200 ms interval that immediately precedes the final IOI. In this case, listeners would be expected to hear the sequence as speeding up because the final IOI is shorter than 1200 ms. In some ways, this second alternative might be expected to be more likely because it involves the comparison of adjacent interval codes at the end of the sequence, whereas the first alternative does not.

The Entrainment View

Entrainment (beat-based) models of timing appeal to dynamic systems account of behavior as well as to biology. From a biological standpoint, entrainment is a ubiquitous process whereby some internal periodic activity (i.e., an oscillation) becomes synchronized with an external rhythm (Winfree, 2000). The most familiar examples of biological entrainment involve the entrainment of human circadian rhythms, such as our internal sleep-wake cycle, with various environmental 'zeitgebers' (time-givers) (Moore-Ede, Sulzman & Fuller, 1982). Entrainment models of timing, consider a different role for entrainment, namely in guiding overt perceptual-motor tracking of events on a time-scale commensurate with speech and music.

A key assumption of the entrainment approach to timing is that temporally extended sequences, as exemplified by music, engage people on a moment-to-moment basis through attentional synchrony (Jones, 1976; Jones & Boltz, 1989; Large & Jones, 1999; McAuley, 1995; McAuley & Jones, 2003; McAuley, Jones, Holub, Johnston & Miller, in press). From an entrainment perspective, individuals make judgments about sequence timing by detecting the synchrony/asynchrony of successive events (tones) with an internally generated beat (or pulse) that is induced by the temporal structure of the stimulus sequence. Events (tones) that arrive unexpectedly 'early' (i.e., *before* the predicted occurrence of a beat) provide evidence that a sequence is speeding up, while events that arrive unexpectedly 'late' (i.e., *after* the predicted occurrence of a beat) imply that a sequence is slowing down. McAuley and Jones (2003; see also Jones & Boltz, 1989) refer to this discrepancy between expected and actual onset times as temporal contrast.

Consider an application of the entrainment model to the sequences in Figure 1A and 1B. For the example in Figure 1A, participants would be expected to develop expectations for a recurring beat every 600 ms based on the repeating 600-ms interval marked out by the initial tones of the se-

ISBN 88-7395-155-4

quence. The final tone in the sequence, which marks a 500 ms interval, arrives 'early' relative to the expected onset based on the predicted beat and thus from an entrainment perspective (similar to the interval perspective), the sequence is slowing down.

For the example in Figure 1B, entrainment model predictions are somewhat different from those generated from an interval perspective. From an entrainment (beat-based) perspective, the initial two 300-ms IOIs followed by the longer 1200-ms IOI are consistent with the perception of a periodic beat every 300 or 600 ms. The latter possibility is a likely outcome because in a group of three tones, listeners tend to hear subjective accents on the first and last tones even when there are no explicit acoustic markings (Povel & Essens, 1985; Povel & Okkerman, 1981). If listeners pick up on the recurring 'beat' implied by these rhythmic grouping accents (which are spaced by 600 ms) and project these beats through to the end of the sequence, then final intervals shorter than 600 ms will be perceived as 'early' and convey the sense that the sequence is speeding up, whereas final intervals longer than 600 ms will be perceived as 'late' and covey the sense that the sequence is slowing down.

Overview

Overall, interval- and entrainment-models of timing have met with mixed success (Ivry & Hazeltine, 1995; Keele et al., 1989; McAuley & Kidd, 1998; Pashler, 2001; McAuley & Jones, 2003). In general, interval models have been more successful when applied to investigations of isolated interval timing, whereas entrainment models have been more successful when applied to investigations of sequence timing; see McAuley & Jones (2003) for a review.

The present research considers the possibility that the mixed success of these two approaches may be at least part due to individual differences in mode of listening. Some individuals may listen in an 'interval mode', while others may listen in an entrainment or 'beat mode'. To consider this possibility, we had individuals listen to monotone sequences and judge whether at the *end of the sequence*, they felt these sequences were 'speeding up' or 'slowing down'. Sequences were constructed in order to investigate various predictions of interval and entrainment models.

The test sequences of interest were identical in structure to Figure 1B. If individuals listen to test sequences in an interval mode, they could either use the 300 ms initial IOI as the basis for their judgments, in which case they should hear all of the sequences as slowing down, or they could use the 1200 ms IOI as the basis for their judgments, in which case they should hear all of the sequences as speeding up. On the other hand, if individuals listen to the test sequences in a beat mode, then the rhythmic grouping accents are likely to lead people to perceive a recurring beat every 600 ms. Extrapolating the beat though the end of the sequence should yield the perception that the sequence is slowing down whenever the final tone is 'late' (i.e., when the final IOI is longer than 600 ms) and should yield the perception that the sequence is speeding up whenever the final tone is 'early' (i.e., when the final IOI is shorter than 600 ms). Results for test sequences were compared to control sequences (with an explicit 600 ms initial IOI); see Figure 1C.

METHOD

Participants

Forty-three students at Bowling Green State University, with self-reported normal hearing and a range of musical experience (M = 4.49 years, SD = 4.47) participated in the experiment in return for extra credit in an introductory psychology course or monetary compensation. Participants were assigned to either a test group (n = 27) or a control group (n = 16). Participants in the test group heard sequences that were structured as in Figure 1B (test sequences), while participants in the control group heard sequences that were structured as in Figure 1C (control sequences).

Apparatus

Stimulus generation and response collection was controlled by an IBM PC compatible computer running the MIDILAB software package, with a time resolution of ≈ 1 millisecond (Todd, Boltz, & Jones, 1989). Auditory sequences were presented to participants at a comfortable listening level through Grado SR-80 headphones attached to a Yamaha PSR-270 MIDI keyboard set to a piano voice.

Stimuli and conditions

Figure 1B and 1C illustrate the general structure of the test and control sequences, respectively. Test sequences consisted of five tones that delineated an initial pair of 300 ms IOIs followed by a 1200 ms IOI and a variable final IOI equal to 600 ms ±2%, ±6%, ±10%, or ±14%. Control sequences consisted of four, rather than five tones, which specified an initial 600 ms IOI, rather than a pair of 300 ms IOIs; otherwise, control sequences were identical to test sequences. All stimulus tones were 50 ms in duration and had a fundamental frequency of 440 Hz.

Procedure

Participants in both test and control groups were instructed to listen to each auditory sequence and judge whether they felt that the end of the sequence was 'speeding up' or 'slowing down.' Responses were made by pressing one of two labeled buttons on a response box. Participants were not shown a diagram of the task or told anything about the sequence other than the number of tones. The experimenter emphasized to participants that we were simply interested in their perception of the sequence and that if they heard all sequences in one particular way, then they should indicate so throughout the experiment. That is, it was 'ok' for them to respond that the sequence was always 'speeding up', 'slowing down' or a combination of 'speeding up' and 'slowing down.'

Participants first completed a familiarization block of eight trials, where the final IOI was 600 ms ±15% or ±30%. Three test blocks, with 32 trials each, were administered with short rest breaks between blocks. The final IOI varied randomly from trial to trial. Twelve total responses were obtained for each level of the final IOI. After the experiment, participants completed a musical experience questionnaire and a short survey that solicited feedback about any strategies used during the experiment.

RESULTS

A preliminary inspection of the data showed that thirteen (out of 16) participants in the control group made relative tempo judgments about the end of the sequence based on the initial 600-ms IOI. As expected, final IOIs that were shorter than 600 ms tended to elicit judgments that the sequence sped up, while final IOIs that were longer than 600 ms tended to elicit judgments that the sequence slowed down. Of the remaining three participants in the control group, only one appeared to make judgments based on the 1200 ms IOI (responding that all sequences sped up at the end), while two others showed no clear response pattern (classified as mixed).

With respect to the participants in the test group who experienced an initial pair of 300-ms IOIs, we observed two dominant response patterns. First, nine (out of 27) participants appeared to make tempo judgments about the end of the sequence using the initial 300-ms IOI; because all final IOIs were longer than 300 ms, these participants tended to hear all sequences as slowing down. This first response pattern is consistent with the interval perspective on timing. Second, consistent with an entrainment perspective of timing, twelve (out of 27) participants in the test group appeared to make tempo judgments about the end of the sequence using an implied 600-ms beat period. These participants performed very similarly to participants in the control group; final IOIs that were shorter than 600 ms tended to elicit judgments that the sequence sped up at the end, while final IOIs that were longer than 600 ms tended to elicit judgments that the sequence slowed down at the end. Of the remaining six participants that heard the test sequences, one appeared to base their judgments on a comparison of the final two IOIs (i.e., they used a 1200 ms IOI consistent with an interval model), while the other five showed no clear response pattern ('mixed').

A summary of the distribution of response patterns for the participants in the control and test groups is reported in Table 1. Overall, the most striking aspect of these data concerns individual differences. The data provide evidence for two modes of listening. In making tempo judgments about the end of each sequence, some participants in the test group appeared to listen to the sequences in an 'interval mode' and base their judgments on the explicit 300-ms initial IOI while others appeared to listen to the sequences in a 'beat mode' and base their judgments on an implicit 600-ms initial IOI (that was not explicitly present, but implied by the beat). From an entrainment perspective, it is possible that some of the participants that used an explicit 300-ms interval heard beats every 300 ms and thus were listening in a beat mode. We return to this issue in the discussion. For comparison purposes, we refer to participants that used an explicit 300-ms interval as 'interval' listeners and those that used an implicit 600-ms interval as 'beat' listeners.

Table 1. Relative distribution of response strategies for participants in the control and test groups

Response Strategy	Control (%)	Test (%)
600 ms	81.25	44.40
300 ms	0.00	33.30
1200 ms	6.25	3.70
Mixed	12.50	18.50

The remainder of the presentation of the results focuses on comparisons of the response patterns of participants in the test group that appeared to be listening in either an 'interval mode' or a 'beat mode', with those of participants in the control group. We were particularly interested in whether the response patterns of participants in the test group who were listening in a beat mode (that provided an *implicit* 600 ms initial IOI) would be similar to those of control group (who were given an *explicit* 600 ms initial IOI).

Figure 2 shows mean proportion of 'speeding up' responses as a function of the final IOI for participants in the control group (filled symbols) and test group (open symbols). For the test group, separate lines depict interval and beat listeners, respectively. From this figure it is clear that participants classified as beat listeners responded to the sequences very similarly to participants in the control group, but very differently from the participants classified as interval listeners, even though interval listeners heard the same sequences as the beat listeners. Supporting this interpretation of the data, a two-way mixed measures ANOVA on P('speeding up') comparing participants classified as beat listeners with control participants at each of the eight levels of the final IOI revealed a main effect of the final IOI [$F(7,161) = 257.08$, $MS_e = 0.014$, $p < 0.001$], but no overall group difference (beat listeners versus control) [$F(1,23) = 1.87$, $MS_e = 0.051$, $p = 0.19$] or significant interaction [$F(7,161) = 0.245$, $MS_e = 0.014$, $p = 0.97$]. Confirming that beat and interval listeners were indeed responding differently, a two-way mixed measures ANOVA on P('speeding up') comparing beat and interval listeners revealed a main effect of the final IOI [$F(7, 133) = 75.26$, $MS_e = 0.011$, $p < 0.001$], a main effect of group [$F(1,19) = 166.72$, $MS_e = 0.077$, $p < 0.001$], as well as a significant interaction between the two factors [$F(7,133) = 61.393$, $MS_e = 0.011$, $p < 0.001$].

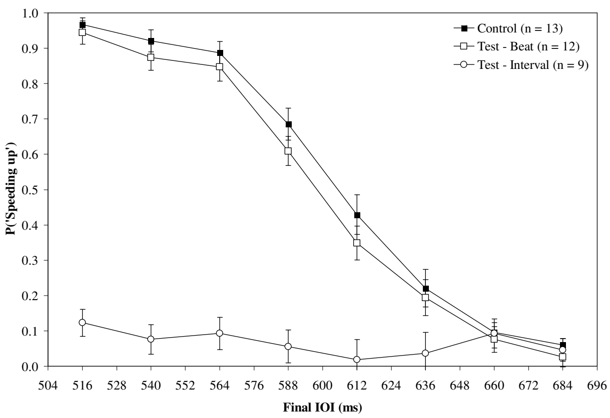

Figure 2. Proportion of 'speeding up' responses as a function of the final IOI for participants in the control group (filled symbols) and for participants in the test group (open symbols).

To further examine the similarity of the performance of beat listeners and participants in the control group, we determined just-noticeable difference (JND) in tempo for each participant in both groups using the method prescribed by MacMillan & Creelman (1991; pp. 219 - 220). JND data (expressed as a percentage of 600-ms) were then subjected to a one-way between-subject's ANOVA. Overall, there was no difference between JNDs for beat listeners ($M = 4.74$, $SE = 0.33$) and participants in the control group ($M = 4.82$, $SE = 0.40$) [$F(1,23) = 0.019$, $MS_e = 1.69$, $p = 0.89$]. The JND results suggests that even though beat listeners never heard an explicit 600-ms IOI, their discrimination performance was as accurate as control participants who experienced a 600-ms initial IOI on every trial.

Finally, we considered potential similarities and differences in reaction times. Figure 3 shows mean reaction time (RT) in milliseconds as a function of final IOI for participants in the control group (filled symbols) and test group (open symbols). As in Figure 2, separate lines are shown for interval and beat listeners, respectively. Similar to the response proportion data, RT patterns for beat listeners were very similar to the control participants, but very different from interval listeners. Supporting this interpretation, a two-way mixed measures ANOVA on mean RT comparing beat listeners versus control at each of the eight levels of the final IOI revealed a main effect of the final IOI [$F(7,161) = 20.24$, $MS_e = 36743$, $p < 0.001$], but no overall group difference [$F(1,23) = 1.39$, $MS_e = 544050$, $p = 0.25$] or significant interaction [$F(7,161) = 1.11$, $MS_e = 36743$, $p = 0.36$]. Confirming the RT differences between beat and interval listeners, a two-way mixed measures ANOVA on mean RTs revealed a main effect of the final IOI [$F(7, 133) = 2.84$, $MS_e = 36344$, $p < 0.01$] and a significant interaction between final IOI and group [$F(7,133) = 8.25$, $MS_e = 36344$, $p < 0.001$]. Unlike the response proportion data for the beat/interval comparison, there was no main effect of group [$F(1,19) = 0.109$, $MS_e = 1210848$, $p = 0.745$].

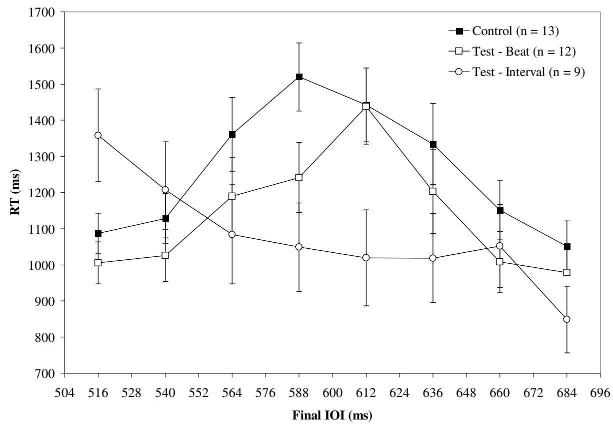

Figure 3. Mean reaction time (ms) as a function of the final IOI for participants in the control group (filled symbols) and participants in the test group (open symbols).

DISCUSSION

The present study considered individual differences in the perception of sequence timing for a task which had participants listen to simple monotone sequences and judge whether they felt the sequences they heard were speeding up or slowing down at the end. Sequences were constructed in order to investigate various predictions of interval and entrainment perspectives on timing. There were two groups of participants: control and test. Participants in the control group heard sequences patterned after Figure 1C where there was a 600 ms initial IOI and a variable final IOI that was centered on 600 ms (i.e., $600 \pm \Delta T$). Participants in the test group heard sequences patterned after Figure 1B where there was a 300 ms initial IOI and a variable final IOI that was manipulated in an identical fashion to the control sequences.

We were particularly interested in what information participants would use to judge the timing of the end of the sequence. For the control sequences, the answer to this question seemed likely to be relatively straightforward. From both an interval- and entrainment- perspective on timing, we expected that most participants would base their judgments on the initial 600-ms interval. However, an interval perspective on timing also raises the possibility that participants might use the 1200-ms IOI adjacent to the final IOI as the basis for their judgment. Consistent with the first possibility, most participants in the control group based their tempo judgments using the initial 600 ms IOI; final IOIs shorter than 600 ms resulted in judgments that the sequence was speeding up, while final IOIs longer than 600 ms resulted in judgments that the sequence was slowing down. Moreover, threshold estimates for these participants yielded a relative just-noticeable difference of approximately 4.5%, which is similar to what would be observed if participants were asked to explicitly judge the duration of the final IOI relative to the initial IOI (Miller & McAuley, 2005).

For participants that heard the test sequences, response strategies were more variable. However, there were two dominant response patterns, which seemed to correspond to two modes of listening. Some participants appeared to base their judgments on a 300 ms interval that was derived from the initial 300 ms IOI of the sequence and thus were listening in an 'interval mode'; other participants appeared to base their judgments on an extrapolated beat that recurred every 600 ms and thus were listening in a 'beat mode'. In general, distinct modes of listening were supported by both response patterns and reaction time patterns. The beat mode of listening was especially noteworthy because the test sequences did not contain an explicit 600 ms interval. Moreover, threshold estimates for these participants were not significantly different from control participants (who did hear an explicit 600 ms interval). Perhaps the most striking consequence of individual differences in mode of listening was that there were particular stimulus instances that yielded *opposite* perceptions. For some stimulus sequences, a beat-based mode provided listeners with a strong sense that the sequence was speeding up, while an interval-based mode suggested that the *same sequence* was slowing down.

Several issues are raised by this work. First, because participants had a range of formal musical training, it is reasonable to ask whether the distinction between beat and interval listeners may have simply been due to differences in musical experience. The answer to this question is no. Average number of years of formal musical training for participants classified as beat and interval listeners did not significantly differ [$t(19) = 1.25$, $p = 0.22$]. Moreover, there was no reliable correlation between musical training and relative JNDs [$r(23) = -0.07$, $p = 0.74$].

Second, it is not clear what flexibility there is in mode of listening. Perhaps participants heard the ambiguous test sequences both ways, but simply chose to respond in either a beat mode or an interval mode. Responses to a questionnaire (given at the end of the experiment) suggest that mode of listening was not purely a response strategy, per se, but that there were indeed differences in how participants *heard* these sequences. For example, in response to a question about response strategies, a number of the participants classified as beat listeners specifically stated that they based their judgments on 'the beat'. In contrast, a common questionnaire response for participants classified as interval listeners was that they used no particular strategy. Another possibility is that test sequences generated perceptions about sequence timing that were analogous to those found with visual illusions such as the Necker Cube. That is, it is possible that perceptions about sequence timing varied between interval and beat modes from trial to trial. This might explain the mixed response patterns of some participants, which were not clearly described by either mode of listening.

Third, from an entrainment perspective, it is possible that participants that used an explicit 300-ms interval heard beats every 300 ms and thus were listening in a beat mode, not an interval mode. In this respect, the only participants that unambiguously listened in an interval mode were those that based their judgments on the 1200 ms IOI that was adjacent to the final IOI. Moreover, this possibility suggests that individual differences in timing may be better described by differences in time scale of attending than by the distinction between interval and entrainment models (Jones, 1997; Large & Jones, 1999; McAuley et al., 2006). Further research is needed to clarify the nature of the two modes of listening.

Finally, we briefly speculate on the implications of this work for understanding the neural basis of timing. In the past decade, there has been a tremendous increase in neuroscience research on timing, which is in part due to significant advances in in-vivo imaging of the human brain. Despite the large number of neuroscience investigations of human timing, there is relatively little consensus on many issues. One concerns the location of a central 'clock' mechanism. Researchers have proposed the cerebellum and basal ganglia as potential candidates for a central clock and there is considerable evidence to support either as the locus of such a mechanism; see Diedrichsen, Ivry & Pressing (2003) for a review.

Recent neuroscience studies of timing have suggested a range of issues that may explain some of the disagreement about the relative roles if the cerebellum and basal ganglia to timing, including distinctions between short and long durations, discrete and rhythmic movements, and event and emergent timing (Schaal et al., 2004; Spencer et al., 2003). Part of the lack of consensus may also stem the assumption that there is only a single timing mechanism. It seems more plausible to us that timing engages multiple mechanisms, which in some cases have redundant function. Thus, both the cerebellum and basal ganglia may play central roles in timing and have overlapping functions. Similarly, the present research adds to this debate by suggesting that when individuals make judgments about sequence timing, they can engage in either an interval- or beat mode of listening to accomplish the same task. Thus, interval- and entrainment models of timing offer complementary, rather than competing perspectives on human timing.

ISBN 88-7395-155-4

ACKNOWLEDGMENTS

The authors are grateful to Molly Henry and Ann Mary Mercier for their assistance with data collection and their comments on various aspects of this project. Thanks are due also to Laren Conklin, Laura Dilley, Leslie Gulvas, Jessica Grahn, Jonathan Miller, Kevin Pang for their helpful comments at various stages of this project. Portions of this research were supported by Public Health Service Grant AG20560.

REFERENCES

Church, R. M. & Broadbent, H. A. (1990). Alternative representations of time, number, and rate. *Cognition, 37* (1-2), 55-81.

Diedrichsen, J., Ivry, R. B., & Pressing, J. (2003). Cerebellar and basal ganglia contributions to interval timing. W. H. Meck (Ed.), *Functional and neural mechanisms of interval timing*. Boca Raton, FL: CRC Press.

Drake, C. & Botte, M. (1993). Tempo sensitivity in auditory sequences: Evidence for a multiple-look model. *Perception and Psychophysics*, *54* (3), 277-286.

Gibbon, J. (1977). Scalar expectancy theory and Weber's law in animal timing. *Psychological* Review*, 84* (3)*,* 279-325.

Gibbon, J., Church, R. M., & Meck, W. (1984). Scalar timing in memory. *Annals of the New York Academy of the Sciences, 423,* 52-77.

Ivry, R. B., & Hazeltine, R. E. (1995). Perception and production of temporal intervals across a range of durations: Evidence for a common timing mechanism. *Journal of Experimental Psychology: Human Perception and Performance, 21* (1), 3-18.

Jones, M. R. (1976). Time, our lost dimension: Toward a new theory of perception, attention, and memory. *Psychological Review, 83* (5)*,* 323-355.

Jones, M. R., & Boltz, M. (1989). Dynamic attending and responses to time. *Psychological Review, 96* (3)*,* 459-491.

Keele, S. W., Nicoletti, R., Ivry, R. B., & Pokorny, R. A. (1989). Mechanisms of perceptual timing: Beat-based or interval-based judgments. *Psychological Research, 50* (4), 251-256.

Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review, 106* (1)*,* 119-159.

Macmillan, N. A., & Creelman, C. D. (1991). *Detection theory: A user's guide*. New York, NY: Cambridge University Press.

McAuley, J. D. (1995). *Perception of time as phase: Toward an adaptive-oscillator model of rhythmic patter processing.* Unpublished doctoral dissertation, Indiana University, Bloomington.

McAuley, J. D., & Jones, M. R. (2003). Modeling effects of rhythmic context on perceived duration: A comparison of interval and entrainment approaches to short-interval timing. *Journal of Experimental Psychology: Human Perception and Performance, 29* (6), 1102-1125.

McAuley, J. D., Jones, M. R., Holub, S., Johnston, H. M., & Miller, N. S. (2006). The time of our lives: Life span development of timing and event tracking. *Journal of Experimental Psychology: General.*

McAuley, J. D., & Kidd, G. R. (1998). Effect of deviations from temporal expectations on tempo discrimination of isochronous tone sequences. *Journal of Experimental Psychology: Human Perception and Performance, 24* (6), 1786-1800.

Miller, N. S., & McAuley, J. D. (2005). Tempo sensitivity in isochronous tone sequences: The multiple-look model revisited. *Perception and Psychophysics, 67* (7), 1150-1160.

Moore-Ede, M. C., Sulzman, F. M., & Fuller, C. A. (1982). *The clocks that time us: Physiology of the circadian timing system.* Cambridge, MA: Harvard University Press.

Pashler, H. (2001). Perception and production of brief durations: Beat-based versus interval-based timing. *Journal of Experimental Psychology: Human Perception and Performance, 27* (2), 485-493.

Povel, D. J., & Essens, P. (1985). Perception of temporal patterns. *Music Perception, 2* (4), 411-440.

Povel, D. J., & Okkerman, H**.** (1981). Accents in equitone sequences. Perception &Psychophysics, 30 (6), 565-572.

Schaal, S., Sternad, D., Osu, R., & Kawato, M. (2004). Rhythmic arm movements are not discrete. *Nature Neuroscience, 7, 10*, 1136-1143.

Schulze, H. H. (1978). The detectability of local and global displacements in regular rhythmic patterns. *Psychological Research, 40* (2), 173-181.

Spencer, R. M. C., Zelaznik, H. N., Diedrichsen, J., & Ivry, R. B. (2003). Disrupted timing of discontinuous but not continuous movements by cerebellar lesions. *Science*, 300, 1437-1439.

Todd, R. E., Boltz, M., & Jones, M. R. (1989). The MIDILAB research system. *Psychomusicology, 8* (2), 83-96.

Winfree, A. T. (2000). *The Geometry of Biological Time* (Second ed. Vol. 12). New York: Springer-Verlag.