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Comfortable synchronization of cyclic drawing movements with a metronome

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Continuous circle drawing is considered a paragon of emergent timing, whereas the timing of finger tapping is said to be event-based. Synchronization with a metronome, however, must to some extent be event-based for both types of movement. Because the target events in the movement trajectory are more poorly defined in circle drawing than in tapping, circle drawing shows more variable asynchronies with a metronome than does tapping. One factor that may have contributed to high variability in past studies is that circle size, drawing direction, and target point were prescribed and perhaps outside the comfort range. In the present study, participants were free to choose most comfortable settings of these parameters for two continuously drawn shapes, circles and infinity signs, while synchronizing with a regular or intermittently perturbed metronome at four different tempi. Results showed that preferred circle sizes were generally smaller than in previous studies but tended to increase as tempo decreased. Synchronization results were similar for circles and infinity signs, and similar to earlier results for circles drawn within a fixed template (Repp & Steinman, 2010). Comparison with tapping data still showed drawing to exhibit much greater variability and persistence of asynchronies as well as slower phase correction in response to phase shifts in the metronome. With comfort level ruled out as a factor, these differences can now be attributed more confidently to differences in event definition and/or movement dynamics.

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1. Two tasks and two modes of timing control

Comparisons between two rhythmic movement tasks, circle drawing and finger tapping, have played an important role in recent theorizing about two modes of timing control, respectively called emergent and event-based (Ivry, Spencer, Zelaznik, & Diedrichsen, 2002; Zelaznik, Spencer, & Ivry, 2002, 2008). Circle drawing is perfectly continuous and thus offers no salient visual, tactile, or kinesthetic event along its trajectory that could serve as a reference point for interval timing. Therefore, its timing is said to be implicit (Zelaznik et al., 2002) or emergent (Ivry et al., 2002), which means it is not controlled by repeatedly producing an event-delimited interval (the period) but rather by setting non-temporal parameters of arm and hand muscles to values that result in the desired frequency of the circular movement. Gauging whether the produced frequency matches a target frequency given by a metronome does require a comparative perceptual judgment of frequency or period duration, followed by necessary adjustments. However, this process may be transitory, and as soon as the desired frequency is established, timing may no longer be controlled directly (Zelaznik et al., 2005).

Finger tapping, by contrast, is essentially a discontinuous movement, except at high frequencies, when it becomes quasi-oscillatory. Because its trajectory is unidimensional (up-down), it has two points at which the movement abruptly reverses direction (maximal flexion and extension). Of these, the point of maximal flexion (the tap proper) is far more salient perceptually because it occurs in contact with a surface, which results in tactile, kinesthetic, visual, and often also auditory sensations, whereas the point of maximal extension only provides kinesthetic and visual feedback. Even when finger movements are carried out without touching a surface ("air tapping" or finger wiggling), the point of maximal flexion tends to be more salient than the point of maximal extension (Carson & Riek, 1998). Given such a salient reference point in each movement cycle, it seems natural to conceptualize tapping as the serial production of inter-tap intervals, governed by an internal timekeeper (Wing & Kristofferson, 1973). Certainly, intervals are perceptually more salient in tapping than in circle drawing, because the delimiting events are both non-arbitrary and well-defined in tapping, whereas they are arbitrary (with regard to phase) and indefinite (having no clear sensory marker) in circle drawing. This does not mean, however, that the timing of tapping could not also be controlled implicitly, by setting non-temporal parameters of the motor system. Indeed, Repp (2008) has argued for dual control of tapping, with the relative contribution of implicit timing increasing as tempo increases. Nor should the possibility of cognitively controlled timing in tasks such as circle drawing be ruled out a priori.

The claim that rhythmic circle drawing and tapping rely on different modes of timing control rests in part on correlational evidence. Zelaznik and colleagues (Robertson et al., 1999; Zelaznik, Spencer, & Doffin, 2000; Zelaznik et al., 2002, 2005, 2008) have amassed data showing that individual differences in timing variability do not correlate significantly between the two tasks, whereas they often do correlate across variants of the same task (e.g., across different tempi), though less so for circle drawing than for tapping. Intermittent circle drawing, which comes to a full stop in each cycle, correlates with tapping, not with continuous circle drawing (Zelaznik et al., 2002). Persons with cerebellar lesions tend to be impaired in tapping and intermittent circle drawing, but not in continuous circle drawing, which points to a neural dissociation of the two forms of timing control (Spencer, Zelaznik, Diedrichsen, & Ivry, 2003). Recently, Zelaznik and Rosenbaum (2010) have found that auditory feedback provided at a particular point in the circle drawing trajectory boosts correlations between that task and tapping, presumably making circle drawing more event-based. It has also been argued that the different movement trajectories of tapping and circle drawing necessarily imply different regimes of timing control (Huys, Studenka, Rheaume, Zelaznik, & Jirsa, 2008). Another piece of evidence that has been brought to bear on the issue is that tapping is easier to synchronize with a metronome than is circle drawing (Studenka, 2008). Studenka also found that synchronization of circle drawing improves when tactile feedback is provided at one point in the trajectory, whereas synchronization of tapping deteriorates when no surface is contacted.

In another important line of research, Delignières and colleagues have investigated the distinction between event-based and emergent timing using joystick oscillation rather than circle drawing as the emergently timed activity to be contrasted with tapping (Delignières, Lemoine, & Torre, 2004; Delignières, Torre, & Lemoine, 2008; Lemoine & Delignières, 2009; Torre & Delignières, 2008). They showed that the interval time series of the two activities have different power spectra, indicating that tapping contains differenced white noise whereas joystick oscillations contain plain white noise, and different autocorrelation functions, with tapping exhibiting a negative lag-1 correlation and near-zero correlations at higher lags (as already shown by Wing & Kristofferson, 1973), whereas joystick oscillation is characterized by positive correlations that slowly decrease as lag is increased. The latter pattern indicates interval persistence in the form of slow undulations or drift. More recently, these researchers also studied synchronization of joystick oscillation with a metronome and found a slowly decaying positive autocorrelation function for asynchronies (Torre, Balasubramaniam, & Delignières, 2010). Comparisons with earlier data for synchronized tapping (Balasubramaniam, Wing, & Daffertshofer, 2004) enabled Torre and Balasubramaniam (2009) to show that phase correction occurs earlier in the tapping cycle (namely, during the extension movement) than in the joystick oscillation cycle. A direct comparison of two-dimensional (circle drawing) and unidimensional (joystick) oscillatory movements has not yet been conducted in the context of a synchronization task.

2. Synchronization with a metronome

Tapping in synchrony with a metronome has been investigated in many studies (see Repp, 2005, for a review). Synchrony is maintained by means of phase error correction, and it is commonly assumed that the perceptual input to that process is the perceived asynchrony between previous taps and metronome tones. However, much evidence suggests that phase correction operates regardless of whether asynchronies have been consciously perceived or not (Hary & Moore, 1987; Repp, 2000, 2001; Thaut, Tian, & Azimi-Sadjadi, 1998), and indeed someone tapping in synchrony with a metronome is usually only dimly aware of any asynchronies. This leaves open two possibilities: Either phase correction operates on subliminally registered asynchronies, or it relies not on asynchronies (at least not when they are not consciously perceived) but on tones and taps as independent temporal reference points from which the next action is timed (Hary & Moore, 1987; Repp, 2005). There is considerable evidence in favor of the second scenario, which can be seen as the interaction of two timing processes: One process resets the tapping phase with reference to the preceding tone, which requires timing an interval between the perceived time of occurrence of that tone and the intended time of occurrence of the next tap. The other process governs the timing from one tap to the next, which can be conceptualized as being governed by an internal timekeeper or oscillator that ensures relative constancy of the period. This second process becomes increasingly important as movement frequency increases because the tapping movement increasingly resembles an oscillation; thus the process can be equated with emergent timing – that is, timing governed by autonomous movement dynamics (Repp, 2008). This emergent timing inhibits phase resetting, which explains why phase correction is typically non-instantaneous and extends over several taps. Recent research has demonstrated that phase correction is slower when finger movement is more oscillatory (Elliott, Welchman, & Wing, 2009), and that synchronization with a metronome increases the asymmetry of movement trajectories (Balasubramaniam et al., 2004), which is likely to facilitate phase correction because it reduces the emergent timing component.

Synchronization of circle drawing with a metronome is often employed to induce self-paced drawing at a particular frequency, but is usually not analyzed. Only recently have two studies focused specifically on synchronization of drawing movements with a metronome. Studenka (2008), already mentioned, found poor synchronization due to phase drift. She also introduced phase shifts in the metronome and examined the ensuing phase correction in the series of drawing cycles, which seemed irregular, slow, and incomplete. By contrast, Repp and Steinman (2010) found considerable variability of asynchronies but few failures to synchronize. When they introduced phase shifts in the metronome, they found a systematic and quite large phase correction response during the immediately following drawing cycle, though not as large as in tapping. They also showed that circle drawing and tapping could be carried out simultaneously without difficulty, either in synchrony with a metronome or self-paced in synchrony with each other, and that timing interactions between the two simultaneous movements were small. Repp and Steinman concluded that event-based and emergent timing could not only coexist in one activity but also in two different activities that are carried out simultaneously.

Several methodological differences between these two synchronization studies may account for their different findings with regard to synchronization success and variability. One is the length of trials. Studenka used short trials and was struck by the large phase drift that was evident in their course.

Repp and Steinman used much longer trials, which revealed that phase drift, while often large, rarely led to phase wrapping but simply reflected large variability and persistence of asynchronies. Thus, Studenka may have underestimated her participants' ability to synchronize. Also, because the trials were so short, phase shifts always occurred early in Studenka's trials, when entrainment may have been weaker; this may have attenuated the phase correction response. A second factor is participants' musical training and motivation. Studenka's participants were unpaid college students with a wide range of years of music training (0–20), whereas Repp and Steinman's participants were highly trained musicians who were regular participants in synchronization experiments. This certainly could have contributed to their (apparently) better performance.

A third factor, and the one the present study is concerned with, is the manner and speed of circle drawing. Studenka's participants moved their fingertip, presumably in a counterclockwise direction, along the circumference of a visual template drawn on a plastic sheet. The circle diameter was 7 cm, and a small 1 cm diameter circle at its top marked the target point (“North”, N) that participants were instructed to pass through in synchrony with the metronome tones. The baseline metronome interval was 500 ms. By contrast, Repp and Steinman had their participants draw with a graphics pen in counterclockwise direction inside a raised circle drawing template that was only 4.5 cm in diameter. The target point was “West” (W), marked visually by a small tick, and metronome intervals were 600 and 800 ms. It is clear that Studenka's participants moved at a much faster speed, due to the larger circle size and the shorter metronome period. This made the passing through the target point less distinct visually and seems a possible reason for poorer synchronization performance. Moreover, circle size and movement speed may not have been at comfortable levels, and the position of the target point may not have been optimal. It is unclear whether the physical template used by Repp and Steinman, which did not allow spatial deviation from the circular trajectory, had an impact on synchronization variability and phase correction.

3. The present study

The present study had three purposes. One was to re-examine synchronization of circle drawing with a metronome under conditions in which participants could choose their own most comfortable circle sizes and target points, without any constraining templates. It was expected that participants would choose larger circle sizes at slower metronome tempi and would prefer target points in the south-western circle quadrant. It was assumed that synchronization and phase correction would be optimal under these comfortable conditions. The range of metronome tempi was expanded to match that employed in a recent study of synchronized finger tapping with the same participants (Repp & Keller, submitted for publication). Some of these participants had also performed in Repp and Steinman (2010), and the others were likewise highly trained musicians, which facilitated comparisons of results across these studies. Comparisons with finger tapping were expected to confirm differences between the two tasks that cannot be attributed to differences in comfort level, while comparisons with the previous circle drawing data were expected to reveal to what extent the physical template, the prescribed circle size, and the prescribed target point may have affected synchronization.

The second purpose was to extend the research to a second type of continuous drawing movement, the infinity sign (∞). It basically consists of two connected circles and thus invites two target points for synchronization. Thus it is intermediate between circle drawing and one-dimensional oscillatory movements such as finger or joystick oscillation (Balasubramaniam et al., 2004; Torre et al., 2010). The question was whether the synchronization results obtained with this new drawing shape would resemble those for circle drawing or whether they would be situated somewhere between circle drawing and tapping. Robertson et al. (1999) used a similar task, Figure-8 drawing, in an unpaced continuation paradigm and found that individual timing variability was unrelated to that in both circle drawing and tapping tasks.

The third purpose of the study was further to investigate phase correction in response to unexpected phase shifts in the metronome. Repp and Steinman (2010) only analyzed the immediate phase correction response (PCR) during the cycle following a phase shift. The results showed that phase correction gradually evolves during that cycle as a nonlinear (quadratic) function of time. The present study pursued the progress of phase correction during five consecutive cycles, thus extending the previous observations and providing an estimate of how many cycles are needed to complete the correction. As has been found in tapping (Repp, 2008), the PCR was expected to increase at slower metronome tempi, so that a smaller number of cycles would be needed for complete phase correction.

4. Methods

4.1. Participants

The 10 participants included 8 graduate students and one postgraduate of the Yale School of Music (5 men, 4 women, ages 22–26), who were paid for their efforts, and the author (age 65). All were regular participants in experiments in the author's lab. Their primary musical instruments were piano (2), violin (3), viola, cello, oboe, and bassoon, which they had studied for 13–21 years. The author is a lifelong amateur pianist with 10 years of lessons in childhood. One participant was left-handed (by self-report) and drew with his left hand.

4.2. Materials and equipment

Tone sequences were generated on-line by a program written in MAX 4.0.9, running on an Intel iMac computer. The tones (piano timbre) were produced by a Roland RD-250s digital piano according to instructions from the MAX program and were presented over Sennheiser HD280 pro headphones. All tones had the same pitch (C4, 262 Hz), the same nominal duration (40 ms), and the same intensity. The experiment consisted of two sessions. In Session 1, each sequence contained 62 tones separated by one of four constant inter-onset intervals (IOIs): 400, 700, 1000, or 1300 ms. In Session 2, each sequence contained a variable number of tones, with the same four IOIs constituting the baseline (unperturbed) IOIs. Each sequence in Session 2 contained phase shifts (i.e., changes of a single IOI) at each of 10 magnitudes ranging from −10% to 10% of the IOI in steps of 2% (not including zero). The 10 phase shifts in each sequence occurred in random order and were separated by 5–8 unchanged IOIs, this number also being a random variable; hence the variable number of tones in each sequence.

Participants drew with a battery-powered graphics pen on an Adesso CyberTablet Z12 (active area 25.5 × 15.8 cm; report rate = 125 Hz). The movement of the pen on the tablet made a swishing sound that was attenuated considerably by the circumaural headphones; it is not believed to have played a role in participants' timing and synchronization. The MAX program immediately calculated the differences between successive *x* and *y* coordinate values of the pen and saved the times at which one of the differences changed sign, which occurred after crossings of the cardinal points in the drawing trajectories. The circle trajectory had four cardinal points (W, S, E, N), whereas the infinity trajectory had six (W, S(*l*), N(*r*), E, S(*r*), N(*l*); the *l* and *r* indices stand for left and right, respectively). This is illustrated schematically in Fig. 1. The movement trajectory between cardinal points was not recorded because it did not seem essential, and the data reduction made analysis in a spreadsheet program (still the author's preferred mode) feasible.

4.3. Procedure

Participants came for two one-hour sessions on different days, usually at least one week apart. As described above, the first session used isochronous pacing sequences, whereas the second session used sequences containing phase shifts. Each session comprised 6 blocks of 8 randomly ordered trials each. The 8 trials resulted from the combination of two drawing shapes and four tempi (IOIs). Which shape was to be drawn in a given trial was conveyed by a verbal message on the computer screen.

At the beginning of the first session, the author described the two drawing shapes and asked the participant to decide in which direction s/he would prefer to draw them, and what point(s) on the trajectory (one in the circle, two in the infinity sign) they wished to synchronize with the metronome. Subsequently participants tried out their choices in a few practice trials. Participants were asked to maintain these choices throughout the experiment. They were also told that they could adjust the size of the drawn shapes from trial to trial as they saw fit, so as to be most comfortable. Furthermore, they were asked to start drawing in each trial with the third tone they heard, to draw as smoothly as

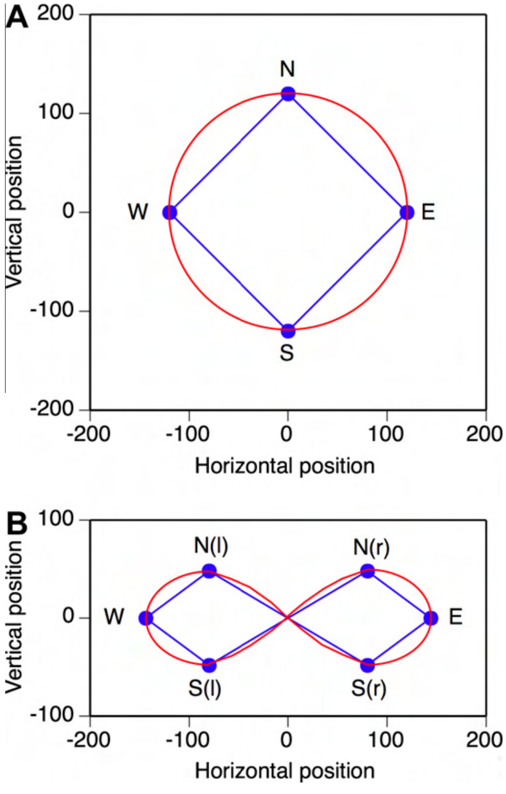

Fig. 1. Schematic diagrams of the (A) circle and (B) infinity sign shapes. Dots mark cardinal points at which the movement reversed direction along one of the coordinates.

possible, not to rest their wrist on the tablet, to stay in the right half of the tablet (or in the left half, for the left-hander), to look at their hand while drawing, and to maintain synchrony with the metronome at all times.

In the second session, participants were informed that small deviations from regularity would occur in the metronome and were told to adjust smoothly to these deviations, so as to stay in synchrony. They were asked to use the same preferred drawing strategies as in the first session.

5. Results

5.1. Missing data

In Session 1, 56 trials (11.7% of all expected data) were lost to analysis for various reasons. It was discovered at the analysis stage that one participant had failed to understand that each loop of the infinity shape was to be synchronized with the metronome and consequently had drawn the shape much too fast, which often resulted in phase drift. These data (24 trials) were excluded from analysis. Also excluded were the data from 16 other trials (9 circle, 7 infinity) that exhibited phase drift whose magnitude exceeded half a cycle. In addition, two trials had been skipped inadvertently, and two trials were excluded because the participant had not drawn the correct shape. Finally, 12 trials, mostly from one participant, were excluded because of inconsistent drawing direction for the infinity shape (see below).

The 9 circle trials with phase drift included all 6 trials of one participant drawing at the fastest tempo (IOI = 400 ms). This resulted in a missing data point that, for the purpose of statistical analysis, was filled in by substituting that participant's values from the IOI = 700 ms condition or, if there was a clear trend across the three slower tempi, by extrapolating from that trend to IOI = 400 ms.

In Session 2, 72 trials (15% of all expected data) were lost to analysis. About half of them were due to a programming error that resulted in occasional failures to play a sequence. The participant who drew infinity signs too fast again did so, resulting in the loss of 24 trials, and the participant who failed to synchronize circles at the fastest tempo again had difficulties in that condition. However, the participant who had previously shown inconsistent drawing direction for infinity signs was consistent now. In all, 8 trials (all of them circles) were omitted because of phase drift, and 3 trials because of inconsistency of target points with other trials in the same condition.

5.2. Drawing direction

All right-handed participants preferred to draw circles in the counterclockwise direction, whereas the single left-handed participant drew in the clockwise direction. Preferences for drawing infinity signs varied. Five participants (including the left-hander) drew the left loop clockwise and the right loop counterclockwise, three drew the opposite way (one of them drew two early trials in Session 1 the other way; they were excluded), and one participant changed from the second to the first drawing style about halfway through Session 1; only the later trials were analyzed. All participants drew consistently with regard to direction in Session 2, six one way and three the other way.

5.3. Shape size

To determine shape sizes, the distance from one cardinal point to the next along each coordinate axis was computed, and these distances were then averaged across movement cycles and trials for each participant. In that way, spatial translations of the drawn shape on the tablet in the course of a trial were largely filtered out. An average shape, centered on the origin of the coordinate system, was reconstructed from the average x and y distances. The recorded coordinate values were converted to metric units after determining through measurements that 100 coordinate units equaled approximately 1.9 cm on the tablet in both horizontal and vertical directions.

Fig. 2 shows the results, averaged across the two sessions. It emerged that there were two distinct groups of participants with regard to shape size. One small group ($N = 3$ for circles, $N = 2$ for infinity signs because one participant's data were excluded, as mentioned above) drew very small shapes and barely changed their size with tempo (open symbols in Fig. 2). It seems likely that these participants drew the shapes by rotating their wrist, which limited the spatial range of their movements. The other group ($N = 7$) drew larger shapes that systematically increased with IOI duration, as predicted (filled symbols in Fig. 2). These participants, who included the author, most likely rotated their shoulder as they drew.

Fig. 2 also shows that the shapes were not drawn perfectly. The average circles were not quite round: Their horizontal (W–E) axis was tilted, indicating a slightly elliptic shape. (The left-handed participant, who drew circles small and clockwise, showed a tilt in the opposite direction.) The infinity signs, too, were not perfect: Their vertical axes were tilted inward, especially on the left side, which indicates that the loops were not perfectly circular. There were also considerable individual differences in the relative height and width of the shape, with some participants drawing flatter infinity signs than others. A few who drew very round loops produced inflection points (i.e., extra cardinal points) in the inner trajectory; these data points were filtered out before analysis. The shapes drawn by each participant were similar across the two sessions.[1]

To assess whether the distortions of target shapes were significant, the distances between adjacent cardinal points for each shape were expressed as percentages of the cumulative distance (linear circumference) and subjected to a three-way repeated-measures ANOVA with the variables of session,

[1] Some participants were encouraged by the author during instruction not to draw the infinity signs too flat. Only one participant, who was not a native speaker of English, was shown a drawing of the infinity shape during instructions. In hindsight, it might have been a good idea to show a drawing to all participants, to reduce individual differences. Evidently, there are individual differences in people's mental template of the infinity sign.

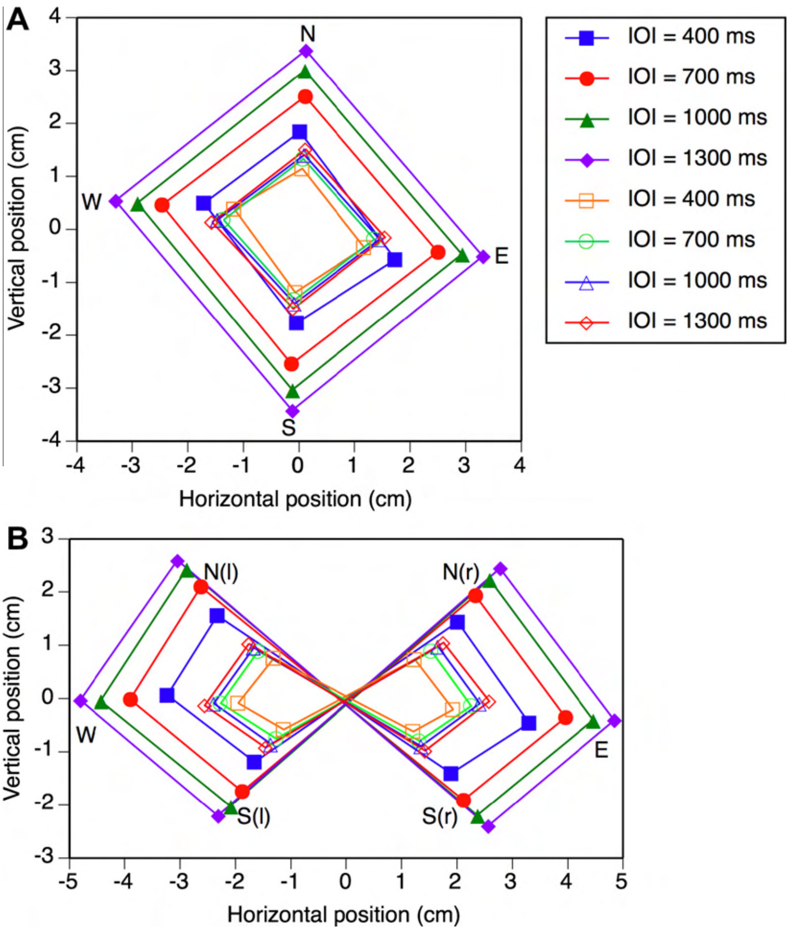

Fig. 2. Average cardinal point coordinates of (A) circles and (B) infinity signs at the four metronome tempi (IOI = inter-onset interval) for two groups of participants who drew large and small shapes respectively. (Large shapes: filled symbols, $N = 7$ for circles, $N = 6$ for infinity; small shapes: open symbols, $N = 3$ for circles, $N = 2$ for infinity.).

segment, and tempo. For circles, there was a significant difference among segments, $F(3, 27) = 20.95$, $p = .001$ (Greenhouse-Geisser corrected), with W–S and E–N being longer than S–E and N–W. (This despite a contrary trend in the left-handed participant who drew circles clockwise.) This difference also interacted with tempo, $F(9, 81) = 14.56$, $p < .001$, because it was most pronounced at the fast tempo.

For infinity signs, first the four outer (short) segments were compared. At first, drawing direction was included as a between-participant variable, but as it did not generate any significant effects, the ANOVA was repeated without it. There was a significant difference among segments, $F(3, 24) = 4.04$, $p = .037$, which interacted with tempo, $F(9, 72) = 3.81$, $p = .028$. The lower segments, S(l)–W and S(r)–E, tended to be shorter than the upper segments, W–N(l) and E–N(r), and this difference was again more pronounced at the fast tempo. In addition, the main effect of tempo reached significance, $F(3, 24) = 5.40$, $p < .044$: The percentage of the linear circumference due to the four short segments increased slightly as the tempo decreased, which implies that the loops became somewhat rounder. A comparison of the two long segments, N(l)–S(r) and N(r)–S(l), also revealed a difference, $F(1, 8) = 15.50$, $p = .004$, with the former being somewhat longer than the latter. The interaction with tempo fell short of significance here, $F(3, 24) = 4.29$, $p = .060$. There was no effect of drawing direction.

To compare the sizes of the shapes drawn at different tempi, their diameters were estimated. Circle diameters were estimated by calculating the mean of the Euclidean W–E and N–S distances. Diameters of the infinity loops were estimated roughly by adding the N(l)–S(l), N(r)–S(r), and W–E distances and dividing by four. (On average, as can be seen in Fig. 2, infinity signs were about twice as wide as they were tall.) Fig. 3 shows the mean diameters as a function of tempo, separately for the two participant groups that differed in shape size. It is evident that shape size increased with IOI duration, even a little for those participants who drew very small shapes. A two-way repeated-measures ANOVA on the data for all participants combined revealed reliable effects of IOI duration for circles, $F(3, 27) = 16.48$, $p = .002$, and for infinity signs, $F(3, 24) = 17.98$, $p = .001$. There was no significant difference between sessions.

5.4. Target points

Each participant had been instructed to choose a target point or area on the shape trajectory for synchronization with the metronome. Because the target point was not prescribed, its mean asynchrony with the metronome was not known. Therefore, an exact target point could not be identified. Instead, an ideal target point was defined as the point on the (linear) trajectory that, on average, showed a zero asynchrony with the metronome. An expected electronic processing lag of 15 ms for

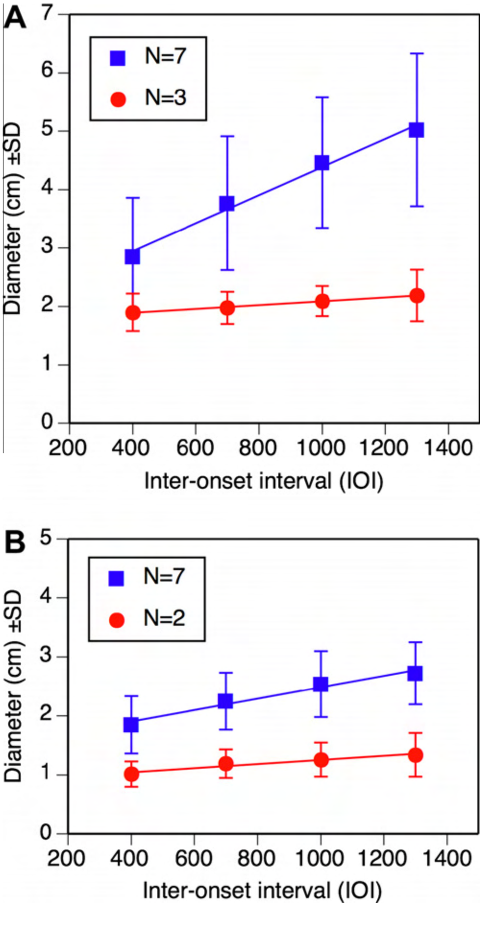

Fig. 3. Average diameter of (A) circles and (B) infinity sign loops for two participant groups as a function of metronome inter-onset interval, with standard deviation bars.

tablet input and sound output combined (not including the delay due to tablet report rate) was taken into account. To estimate the ideal target point, the normalized mean relative phases (expressed as values between 0 and 1, or between −1 and 0 if negative) of the cardinal point crossings at each tempo were plotted as a function of the normalized mean cumulative Euclidean distance from a reference point (i.e., they were expressed as a proportion of the total linear circumference). That distance stood in for the distance along the curvilinear drawing trajectory, which was not known exactly but could be assumed to be roughly proportional to the linear distance between cardinal points (see Fig. 1). Such graphs for a single participant (the author) are shown in Fig. 4.

In these fairly representative data, the functions for circles (Fig. 4A) are strikingly linear, suggesting that drawing velocity was rather constant. Fitted regression lines have slopes close to 1, which follows

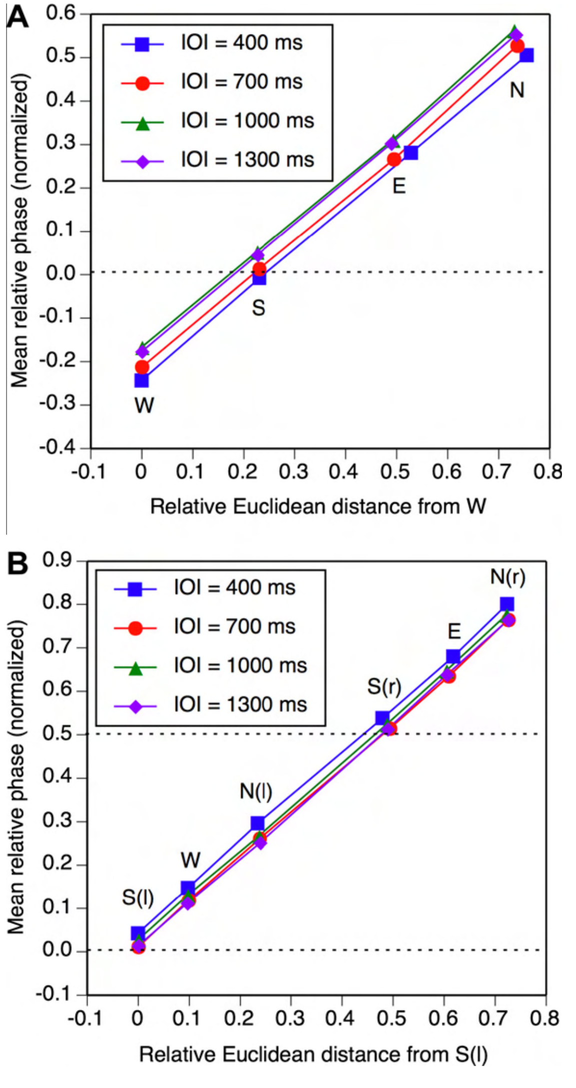

Fig. 4. Mean relative phase (normalized to cycle duration) of cardinal points for each metronome IOI as a function of cumulative linear distance (normalized to cycle duration) from a reference point. Data from a single participant (the author). (A) Circles, with W as the reference. (B) Infinity signs, with S(*l*) as the reference. Dotted horizontal lines indicate exact synchrony with the metronome.

from the fact that both axes are normalized. Thus, the intercept of each regression line with the *x*-axis at *y* = 0 (dotted horizontal line in Fig. 4), which is the desired estimate of the target point, can be calculated simply as 1 minus the *y*-axis intercept. For this one participant, the circle target point is close to *S* and seems to vary but slightly with IOI duration. The corresponding functions for infinity shapes (Fig. 4B) are also very linear and have slopes close to 1, so that the target points can be calculated in the same way. Given the method of calculation, the two target points for infinity signs are exactly half a movement cycle (= a full metronome cycle) apart. Again, they are close to S for this participant, and a small shift with tempo is evident.

The estimated target point locations for all participants and their changes with tempo in Session 1 are shown in Fig. 5. Except when mentioned, these results were closely replicated in Session 2. All participants had highly linear phase-distance functions (as in Fig. 4A) for circles. The target points (Fig. 5A) show considerable individual differences. At the slower tempi, however, they tended to be near cardinal points: Five participants clustered around S, two around W, and three (including the left-hander, who drew in the clockwise direction) around N. At the fast tempo, there was greater variability, but no clear trend in one or the other direction. Two-way repeated-measures ANOVA did not reveal a significant effect of tempo or session. Nevertheless, some individual participants did seem to show an effect of tempo because they showed the same tendency in both sessions. Note, however, that this could be due either to a shift of the target point itself or a change in asynchrony between target point and metronome, or both.

The results for infinity shapes (Fig. 5B) are shown only for one half of the shape, as they are identical for the other half. Here individual differences were smaller, and most participants targeted a point in the vicinity of S. The single exception, with a target point near N, was one of the three participants who drew

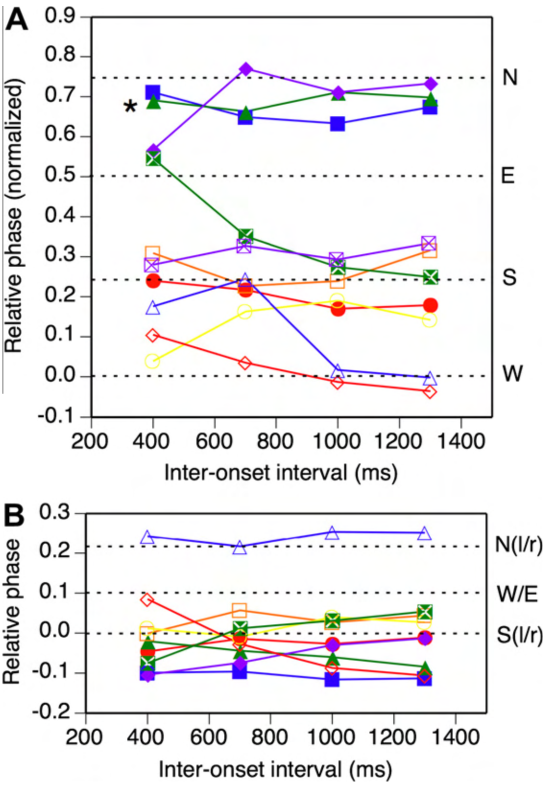

Fig. 5. Estimated target points for synchronization as a function of IOI duration in (A) circles and (B) infinity signs. Each symbol represents an individual participant. The asterisk near a filled triangle indicates a missing data point that was filled in.

the left loop counterclockwise and the right loop clockwise; in Session 2, however, his target point was near S. There was no significant effect of tempo or session. The general preference for S as the target point seemed to be independent of drawing direction and handedness. However, two of the three participants who drew the left loop counterclockwise and the right loop clockwise showed clear deviations from linearity in the phase-distance functions (unlike Fig. 4B), indicating that they did not draw with constant velocity but slowed down during the downward movement from N to E or W.

5.5. Segment durations

To examine the temporal characteristics of the drawing movements, the durations of the trajectories between successive cardinal points were calculated. To facilitate comparisons across tempi, the durations were expressed as percentages of IOI duration. This analysis was conducted only on the data of Session 1.

In the analysis of circle segments, the data of the left-handed participant, who drew circles clockwise, were entered in reverse order. Fig. 6A shows mean segment durations as a function of IOI duration. (The *x*-axis labels pertain to the right-handed participants; for the left-handed participant, they would be E–S, S–W, W–N, N–E.) It is evident that segment durations were rather uneven at the fastest tempo, with the W–S and E–N segments being much shorter than the S–E and N–W segments. This was confirmed in a two-way repeated-measures ANOVA, which showed a significant main effect of segment, $F(3, 27) = 18.50$, $p < .001$, and a significant Segment $\times$ Tempo interaction, $F(9, 81) = 9.71$, $p < .001$. When the data for the fastest tempo were omitted from the ANOVA, however, only the main effect of segment was significant, $F(3, 27) = 11.75$, $p < .001$: At each of the slower tempi, the W–S segment (E–S for the left-hander) was shorter than the other three segments. For all but one participant (the one with a target point near N), this was the part of the trajectory that moved toward the target point. The participant with the N target point did not show a marked acceleration toward that point.

Shorter segment duration suggests acceleration, but that would be true only if the trajectory lengths were equal. The exact trajectory lengths were not known, so mean segment velocities could not be computed with any accuracy. However, it can be assumed that the curvilinear trajectories increased with the linear distances between cardinal points. Fig. 2A showed that, at the fastest tempo, the W–S and E–N distances were markedly *greater* than the S–E and N–W distances. This means participants traversed a greater distance in a shorter time and thus definitely moved faster along these segments. Because of the distorted (elliptic) shape of the circle, the trajectory of these long segments also must have been less curved than that of the short segments, a difference that probably also entailed greater movement velocity (Lacquaniti, Terzuolo, & Viviani, 1983). At the slower tempi, however, distances between cardinal points were more similar, and in particular the W–S and E–N distances were almost identical. Yet, W–S took less time to traverse than E–N, which suggests that participants did accelerate as they approached S, the lowest point on the circle. This seemed to be true regardless of individual target point location (Fig. 4A).

Fig. 6B shows the mean relative segment durations of infinity signs. Results are shown separately for the six participants who drew the left loop counterclockwise and the right loop clockwise (filled symbols) and the three who drew the opposite way (open symbols). As can be seen, their patterns were very different. While the first group drew the short segments quickly and took longer for the long N(*l*)–S(*r*) and N(*r*)–S(*l*) segments, as one should expect, the second group took almost as long with the N(*r*)–E and N(*l*)–W segments as with the long segments. (Note that for the second group the movement direction goes from right to left along the *x*-axis.) This indicates very different drawing strategies: Whereas the first group drew at what seems to be a fairly constant velocity, the second group accelerated as they moved downward toward S along the outer loop and slowed down as they passed N after moving upward from one loop to the other. Thus they emphasized the S target points in their kinematics. The observed segment duration differences clearly cannot be accounted for by differences in segment length (Fig. 4B).

A three-way repeated-measures ANOVA on the first group's data for the short segments, with the variables of side (left vs. right), segment (upper vs. lower), and IOI duration revealed a significant main effect of segment, $F(1, 5) = 30.48$, $p = .003$, due to a tendency to traverse the lower segment of the outer loop faster than the upper segment. The Side $\times$ Segment interaction fell short of significance, but the

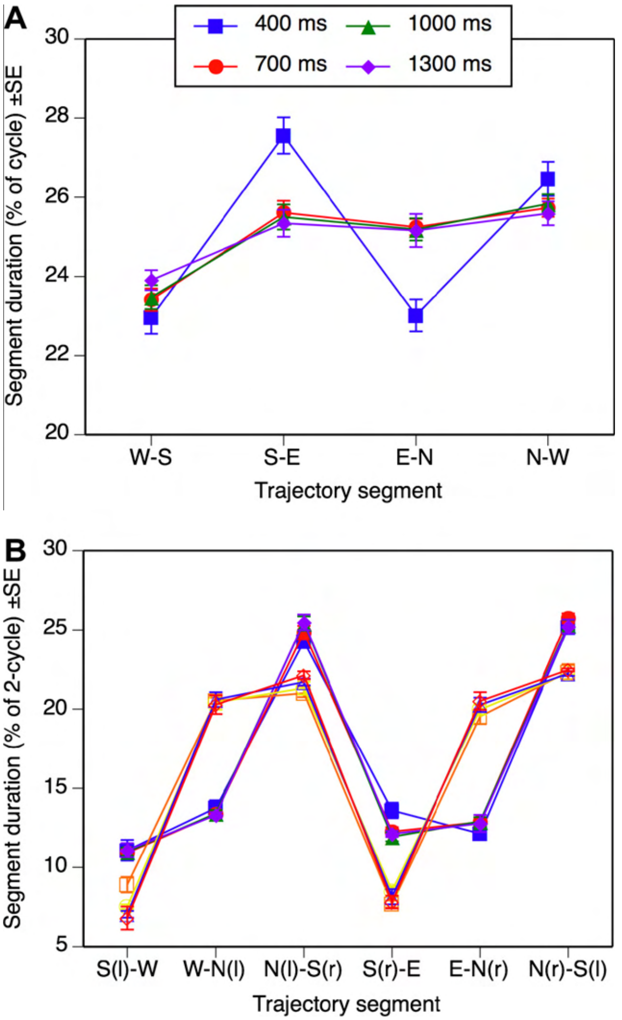

Fig. 6. Relative trajectory segment duration as a function of IOI duration for (A) circles and (B) infinity signs. Segment durations are shown as a percentage of cycle duration. In panel B, filled symbols represent participants who drew infinity signs "outside up, inside down" ($N = 6$), whereas open symbols represent participants who drew "outside down, inside up" ($N = 3$). For the latter, the *x*-axis labels should be read from right to left. Error bars are standard errors and in panel B are usually smaller than symbols.

triple interaction was significant, $F(3, 15) = 6.08$, $p = .025$, evidently due to the relatively slow traversal of S(*r*)–E at the fastest tempo. A two-way ANOVA on the two long segments did not reveal any significant difference. A three-way ANOVA on the second group's short segment data confirmed a significant main effect of segment, $F(1, 2) = 582.81$, $p = .002$. In addition, the Side × IOI Duration interaction reached significance, $F(2, 6) = 12.30$, $p = .045$, evidently due to slightly different durations at the fastest tempo (open squares). A two-way ANOVA on the long segments did not reveal any significant difference.

5.6. Variability

To assess variability, within-trial standard deviations of asynchronies (calculated relative to the same tone within each cycle) in Session 1 were calculated for each cardinal point and then averaged

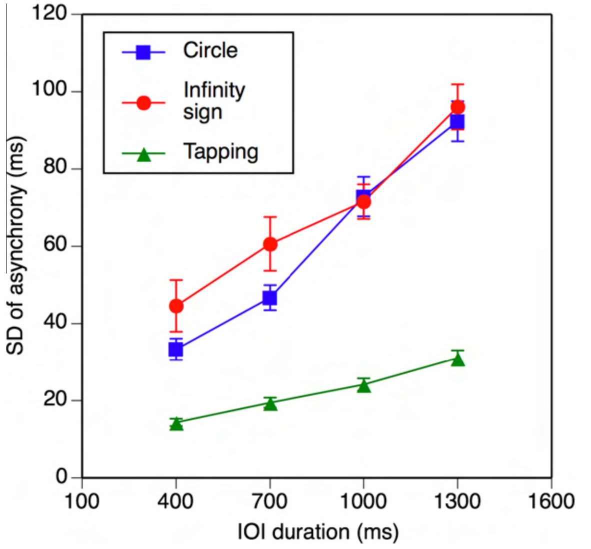

Fig. 7. Mean within-trial standard deviations of asynchronies as a function of IOI duration for circles, infinity signs, and tapping (data from Repp and Keller, submitted for publication). Error bars are between-participants standard errors.

across trials. Fig. 7 shows the standard deviations after averaging them also across cardinal points. As expected, variability increased with IOI duration. At the faster tempi, variability of circles was lower than of infinity signs, but this difference disappeared at the slower tempi. Also included in the figure are corresponding data for tapping from a recent experiment employing the same participants (with one exception), the same tempi, and the same trial lengths, with six trials per IOI duration (Repp & Keller, submitted for publication). It is clear that variability of asynchronies was much smaller for tapping than for drawing movements.

Variability in Session 2 (not shown) was quite similar to that in Session 1. Although phase correction in response to perturbations had been expected to increase variability, practice may have counteracted this effect. A three-way repeated-measures ANOVA on the drawing data from both sessions (without the participant for whom infinity shape data were not available) revealed a significant main effect of IOI duration, $F(3, 24) = 113.11$, $p < .001$, and a main effect of drawing shape, $F(1, 8) = 9.48$, $p = .015$, with lower variability for circles than for infinity signs. The interaction between these two variables was not significant. Separate ANOVAs were conducted on each shape, with cardinal point included as a variable. For circles, the main effect of cardinal point was significant, $F(3, 27) = 7.14$, $p = .007$, and surprisingly interacted with session, $F(3, 27) = 8.36$, $p = .003$. In Session 1, variability tended to be smaller at S than at the other cardinal points, $F(3, 27) = 3.81$, $p = .053$, but in Session 2, variability was smaller at S and N than at W and E, $F(3, 27) = 10.28$, $p = .001$. For infinity signs, data for the two sessions had to be analyzed separately because data for mirror-symmetric cardinal points from the two loops had been combined in Session 2 for the PCR analysis (see below). There was no significant difference among cardinal points in Session 1, but in Session 2 variability at S and N was smaller than at W and E combined, $F(3, 24) = 9.46$, $p = .004$, and it interacted with IOI duration, $F(3, 24) = 9.43$, $p = .001$, being most pronounced at the slow tempi.

5.7. Autocorrelations

To assess the degree of persistence of asynchronies from cycle to cycle in each task, autocorrelations from lag 1 to lag 10 were calculated for the asynchronies at cardinal point S within each trial of Session 1 and then averaged across trials, separately for each IOI duration. (Session 2 data were not considered because there persistence was conflated with phase correction in response to perturbations.) The autocorrelation functions are shown in Fig. 8 together with corresponding functions for tapping (data from Repp & Keller, submitted for publication). Circles and infinity signs both showed high positive correlations at lag 1 that decayed gradually as lag increased. The correlations also decreased as IOI duration increased. Infinity signs showed somewhat smaller correlations than circles, especially at long lags and slow tempi. In contrast to the drawing tasks, tapping showed much smaller positive correlations at lag 1 that depended strongly on IOI duration, reaching zero at an IOI of 1300 ms. These correlations decayed quickly, but at the two faster tempi small positive correlations extended to longer lags. A three-way repeated-measures ANOVA on the drawing data revealed, in addition to the obviously significant main effect of lag, significant main effects of drawing shape, $F(3, 24) = 6.59$, $p = .006$, and of IOI duration, $F(3, 24) = 16.17$, $p = .004$, with no significant interactions.

5.8. Phase correction

The main purpose of Session 2 was to assess the speed of phase correction in response to perturbations. The extent of phase correction was assessed at each cardinal point during five consecutive metronome cycles (= movement half-cycles for infinity signs) following each phase-shifted tone. The reference (baseline) asynchrony in each case was the asynchrony of the same cardinal point in the (half-)cycle preceding the perturbation. Phase correction was assessed as the slope of the linear regression line relating the difference between the current asynchrony and the reference asynchrony to phase shift magnitude, averaged across trials. The expected slope in the vicinity of the perturbation was −1 because an unexpected phase shift results in an equal shift of the asynchrony in the opposite direction. Phase correction is reflected in the subsequent increase of the slope towards zero: Phase correction is complete when the asynchrony no longer depends on the phase shift. The temporal relation between the first cardinal point at which phase correction was measured and the phase shift in the metronome varied somewhat among participants (due to different target points) and from trial to trial (due to local phase drift), so that the average slope for each cardinal point is actually based on a range of phase relationships.

These average slopes are shown in Fig. 9. For circles (Fig. 9A), they start out close to −1, as expected, and then increase gradually, starting within the first cycle. As predicted, phase correction was faster at

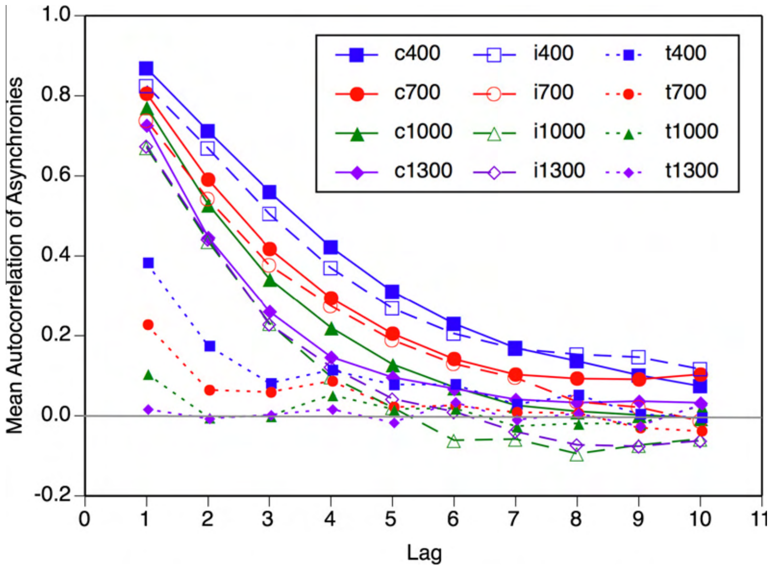

Fig. 8. Mean autocorrelation functions for asynchronies of circle (*c*) drawing, infinity (*i*) sign drawing, and tapping (*t*), each at four IOI durations (400, 700, 1000, 1300 ms). Tapping data are from Repp and Keller (submitted for publication).

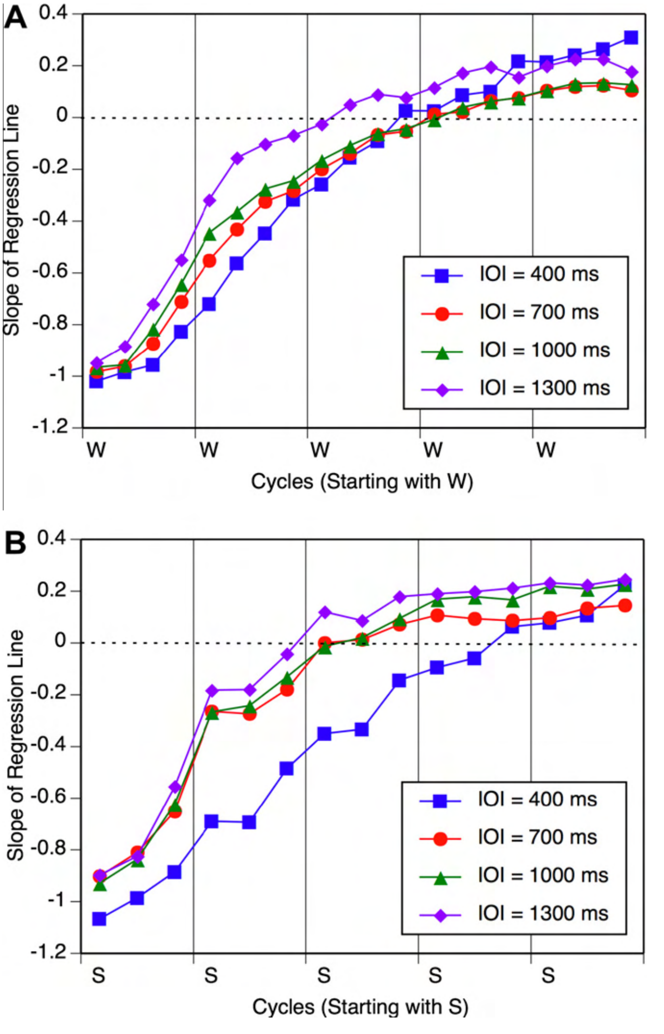

Fig. 9. Mean slopes of regression lines relating changes in asynchrony to phase shift magnitude during five cycles following a perturbation, for (A) circles and (B) infinity signs.

slower tempi. At the slowest tempo, it was complete within two cycles. At the other tempi, three cycles were needed, on average, to complete phase correction. In the fourth and fifth cycles, a tendency towards overcorrection can be seen. For infinity signs (Fig. 9B), phase correction was rather slow at the fastest tempo, requiring more than three cycles for complete correction, whereas at the other three tempi only two cycles were needed.[2] Overcorrection in the later cycles is also evident.

Fig. 10 compares the mean phase correction responses (PCRs) for the two drawing shapes and for tapping (Repp & Keller, submitted for publication). The PCR is defined as the proportion of the phase shift that is corrected one cycle later; thus it corresponds to 1 plus the slope shown at the beginning of the second cycle in Fig. 9. It is evident that the PCR was much larger in tapping than in drawing. It

[2] Steps in the functions are artifacts of cardinal point alignment due to the three participants who drew the infinity signs in the opposite direction from the others. The data were aligned so that the short segments (S–W/E–N) were within the cycle boundaries indicated by the vertical lines in Fig. 9B, and the long segments (N–S or S–N) straddled the boundaries.

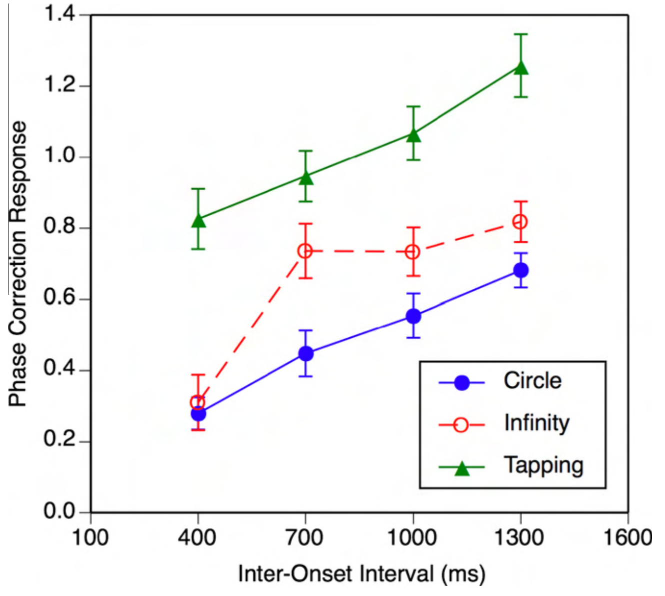

Fig. 10. Mean phase correction response as a function of inter-onset interval duration for the two drawing shapes and for tapping (data from Repp and Keller, submitted for publication), with standard error bars.

was also larger for infinity shapes than for circles, and it increased with IOI duration in all three tasks. A two-way ANOVA on the drawing data revealed significant main effects of shape, $F(1, 8) = 13.39$, $p = .006$, and of IOI duration, $F(3, 24) = 22.05$, $p < .001$, whereas the interaction was not significant.

6. Discussion

This study examined synchronization of rhythmic drawing movements with a metronome when participants were free to choose shape size, drawing direction, and target points. Their choices and the dependence of the choices on tempo were of interest in themselves, but the main question was whether the increased comfort they afforded would aid synchronization and phase correction compared to earlier studies in which circle templates with prescribed target points were used (Repp & Steinman, 2010; Studenka, 2008). Furthermore, the present study compared circle drawing with infinity sign drawing, a task that combines aspects of circle drawing and joystick oscillation (investigated by Torre et al., 2010), and both drawing tasks with finger tapping (Repp & Keller, submitted for publication).

Participants were unanimous in their preferred direction of circle drawing: Right-handers drew counterclockwise, whereas the single left-hander drew clockwise. Thus they all drew such that they moved towards their body when they moved along the inner perimeter of the circle. Presumably, this is also the way in which participants drew circles in previous circle drawing studies, although the drawing direction was usually not reported. The reason for this preference is not immediately obvious. Intuitively, however, the preferred motion resembles pulling, whereas the contrary motion seems like pushing, which has a negative connotation. The preferred motion also matches the direction in which the letter O is commonly drawn in handwriting. With regard to drawing direction for infinity signs, however, participants were split almost evenly (5 vs. 4), considering that the left-hander drew like the right-handers and thus in the opposite direction relative to his dominant hand. Participants were consistent in maintaining their preferred direction across the two sessions, which were separated by at least one week; only one participant changed direction during Session 1. It would be interesting to know what led participants to draw either the left or the right loop of the infinity sign in the direction they preferred for a single circle.

As expected, the size of the drawn shapes depended on tempo. Three participants drew very small shapes, presumably because they used wrist rather than shoulder rotation, and showed only very small increases in diameter as the tempo decreased. The majority of participants presumably drew with shoulder rotation and showed clear increases in shape size. Their average preferred circle diameter ranged from roughly 3 cm at IOI = 400 ms to 5 cm at IOI = 1300 ms. At IOI = 700 ms, it was 3.8 cm, though one participant drew circles as large as 5.5 cm. Repp and Steinman (2010) used a circle template with a diameter of 4.5 cm at IOIs of 600 and 800 ms, which thus was within participants' comfort range. By contrast, Studenka's (2008) circle template was 7 cm in diameter and the IOI was 500 ms. These settings may have been outside participants' comfort zone and thus may have led to poor synchronization. However, it is possible that participants prefer larger circles when drawing with the finger, as they did in Studenka's experiments, than when drawing with a pen. Certainly it is unlikely that any participants would use wrist rotation when drawing with the finger, as several participants in the present study apparently did when drawing with a pen.

The larger the drawn shape is at a given metronome rate, the greater is the movement velocity, which results in poorer visual definition of the target point or area that is to be synchronized with the metronome, but in stronger kinesthetic sensations associated with the target area. Did the present participants adjust shape size so as to maintain a constant velocity across different tempi? In that case, the increase in circle diameter should have been proportional to the increase in metronome IOI. That was clearly not the case: Circle diameter increased by about 80% while IOI increased by more than 200%. Thus, participants drew with slower velocities at the slower metronome tempi. This reflects a conservative strategy, perhaps due to a trade-off between visual and kinesthetic cues.

As for the choice of target point, there was less consistency among participants for circles than for infinity signs. For circles, five participants chose a point or region near S, two a point near W, and three a point near N. For infinity signs, all participants chose target points near S in Session 2, and only one deviated by choosing N in Session 1. The distribution of target points suggests that they were mentally associated with cardinal points, but in general they did not coincide exactly with cardinal points. This is true even if it is considered that the mean asynchrony between target points and metronome tones was probably not zero in reality, but most likely negative, indicating anticipation. For circle drawing, Repp and Steinman (2010), who prescribed W as the target point, found mean asynchronies of about −70 ms at IOIs of 600 and 800 ms. This implies that, at least at IOI = 700 ms, the actual target points in the present study may have been lower than plotted in Fig. 5A by about 0.1 of normalized relative phase (and higher for the left-handed participant who drew clockwise with a target point near N). These adjustments, however, do not make the target points coincide any more closely with cardinal points. It is also possible that the anticipation tendency increased with IOI duration, as it does in tapping (e.g., Mates, Radil, Müller, & Pöppel, 1994). However, this should have resulted in rising functions in Fig. 5, which occurred in only one or two cases. Other participants showed falling functions, which indicate overshoot of target points at fast tempi, or actual shifts of target points in the movement direction. Ultimately, of course, target points are an abstraction; more realistically perhaps, they represent the center of a target area or tolerance zone on the circle circumference, and similarly for infinity signs.

In general, the circle drawing results support the informal observation of Repp and Steinman (2010) that W and S seem more natural than E and N as target points in counterclockwise drawing. The reasons for this may be better visibility and movement towards the body. Nevertheless, two participants spontaneously chose N. In studies of self-paced circle drawing with a visual template (e.g., Zelaznik, Spencer, & Doffin, 2000; Zelaznik et al., 2002, 2005), a target point is usually marked at N. Studenka (2008, Appendix A) compared synchronization of circle drawing with a metronome when target points were marked at either N or S and found no significant difference, although asynchronies tended to be larger at N. With regard to infinity signs, it is worth noting that drawing direction did not seem to matter much in the choice of target points. All participants (with one exception in Session 1) targeted a region near S, which is closest to the body. Some participants, however (the ones whose functions are lowest in Fig. 5B), may have targeted the central intersection of the N–S (or S–N) trajectories, which is not marked in the figure because it did not correspond to a movement reversal (cardinal point). These participants all drew the left loop counterclockwise, which means they always moved diagonally downward from N to S, towards the body.

Drawing direction had an effect on the shape of circles. Circles drawn counterclockwise tended to be slightly elliptic, with a tilted horizontal axis, whereas the tilt was in the opposite direction for the left-handed participants who drew clockwise. Drawing velocity, although it could not be estimated precisely, seemed rather smooth in all cases. Drawing direction did not affect the shape of infinity signs, but two of the three participants who drew the left loop counterclockwise drew with very uneven velocity, accelerating towards S and slowing down between N and W/E. These participants approached the S target region from the outside, moving along a path of high curvature, whereas other participants approached S along the almost straight inner path from N. Because movement naturally tends to slow down as curvature increases (Lacquaniti et al., 1983), the former participants may have felt it necessary to accelerate, so as to emphasize the target point. A tendency to accelerate into the target point was noted by Repp and Steinman (2010) in circle drawing, and conversely Luck and Sloboda (2008) found that perceived "beats" in a visual trajectory tend to be associated with points of maximum acceleration.

As expected, continuous drawing in synchrony with a metronome proved to be strikingly different from tapping with a metronome in several respects, despite the fact that the timing of synchronized drawing must to some extent be event-based. (If it were not, apparent target points would vary from trial to trial, and phase drift would probably occur within trials.) First, the variability of asynchronies was much larger in drawing than in tapping, even more so than in Repp and Steinman (2010). Second, the asynchronies were more persistent in drawing than in tapping, which in part accounts for their greater variability. Persistence implies slow drift that changes direction randomly from time to time. While variability increased with IOI duration, persistence decreased; this is likely to be due to increases in random variability with IOI duration. Third, phase correction was slower in drawing than in tapping, but increased similarly with IOI duration. The mean PCRs at IOI = 700, which were 0.45 for circle drawing and 0.95 for tapping, can be compared with those reported by Repp and Steinman for IOIs of 600 and 800 ms, which were similarly large for tapping but larger for circle drawing than in the present study (about 0.6). This suggests that the present efforts to optimize participants' comfort level in circle drawing did not help improve synchronization. On the contrary, performance was somewhat worse than in the Repp and Steinman study. This could be due to a difference in participants (though four participants were shared), but another relevant difference is the use of a raised template by Repp and Steinman, which provided tactile as well as some auditory feedback and thereby may have aided rather than hampered synchronization. Also, the fact that the W target point was visually marked in that study may have played a role. The present experiment loosened some of these constraints in the interest of comfort, but this may actually have increased variability and impeded synchronization.

Nevertheless, the present data confirm Repp and Steinman's (2010) results by showing that phase correction in circle drawing is much more systematic than suggested by Studenka (2008). Phase correction during the first cycle (Fig. 9A) shows the gradual nonlinear increase reported by Repp and Steinman (see also Torre et al., 2010). The results extend these previous findings by demonstrating that phase correction is complete within 2–3 cycles and tends to be followed by overcorrection. This suggests a slow drift that is initiated by the PCR and then persists for some time, which is probably due to period correction accompanying and outlasting phase correction. Indeed, there may not be any clear distinction between these two processes in the dynamics of continuous movement. Incidentally, it might also be noted that tapping shows overcorrection at slow tempi (see Fig. 10), but this occurs in the immediate PCR and may not persist.

A novel feature of the present research is its comparison of circle drawing and infinity sign drawing. Although both drawing movements are continuous, the latter is less uniform because of its binary structure and its periodic changes in curvature. Therefore, one might expect it to be easier to synchronize with a metronome. This was only partially borne out: Variability of asynchronies was actually somewhat greater than in circle drawing. However, persistence of asynchronies was smaller, and PCRs were larger, except at the fastest tempo. Still, the two drawing tasks were definitely more similar to each other than they were to tapping, which showed far superior synchronization performance. This result is in line with the findings of Torre et al. (2010), whose joystick oscillation task is even less continuous than infinity sign drawing because it is one-dimensional and thus has points of zero velocity (at reversals of movement direction). Nevertheless, Torre et al. demonstrated that it has all the characteristics of an emergently timed movement, like circle drawing.

The crucial differences between tapping and drawing with regard to synchronization with a metronome presumably lie in the feedback received from the contact of the finger with a surface and in the actual interruption of the movement in tapping. Tactile and auditory feedback in tapping gives precise (multimodal) definition to the events that are to be synchronized with the metronome tones. Studenka (2008) and Elliott et al. (2009) have shown that removal of tactile feedback in tapping impairs phase correction, whereas discrete feedback during circle drawing improves phase correction (Studenka, 2008). Interruption means that the movement must be re-initiated in every cycle, which affords an opportunity for phase resetting. In continuous movements, even in those in which there are moments of zero velocity, there is greater inertia that inhibits phase adjustments and leads to persistence of asynchronies. An interesting intermediate case is intermittent circle drawing, where a pause is inserted between full circles (Zelaznik et al., 2002). Its variability has been shown to correlate more with that of tapping than with that of circle drawing (Zelaznik et al., 2002), but it has not yet been explored in a synchronization task. The fact that it is interrupted should facilitate phase correction, but at the same time it does not offer a clearly defined target event if the task is to synchronize the movement with the metronome. This paradigm offers an opportunity to investigate more systematically the relative importance of movement continuity and event definition, leaving room for further research.

Some of the theoretical notions underlying the present research seem to be at variance with the highly respected views of Delignières, Torre, and colleagues (Delignières et al., 2004; Torre & Balasubramaniam, 2009; Torre & Delignières, 2008; Torre et al., 2010). In particular, these authors argue that event-based and emergent timing are mutually exclusive and cannot occur simultaneously. They have also shown that emergent timing can be modeled as arising from a limit cycle dynamics, and that synchronization of an emergently timed movement with a metronome can be characterized by means of a continuous coupling of the limit cycle to the metronome frequency. It is interesting that joystick oscillation, a periodic movement containing two clear reversal points that would seem to be good candidates for event-based timing, seemed to be purely emergently timed in their analysis. This is consistent with the results for infinity sign drawing in the present study being essentially similar to those for circle drawing. Apparently, all these continuous movements represent a single category of emergently timed, limit-cycle governed activities, regardless of how distinct target events along the trajectory are. This is indeed problematic for the alternative view that most tasks represent a combination of event-based and emergent timing.

However, attributing movement timing entirely to a limit cycle amounts to reducing the human agent to an automaton. This seems too extreme a view. For one thing, any movement can be started and stopped at will, whereas a limit cycle will oscillate indefinitely. An agent can also decide not to synchronize a movement with a metronome and thus has at least control over coupling parameters. Choice of a preferred point or region on a movement trajectory for purposes of synchronization is also a cognitive strategy that is not predicted by a limit cycle. Some evidence exists showing that reinforcement of such target points through sensory feedback enhances their role in movement control (Studenka, 2008; Zelaznik & Rosenbaum, 2010). Autonomous regimes of movement control must coexist with cognitive processes that reinforce, modulate, or compete with them, as the case may be. There is no reason why event-based timing of, say, joystick oscillation could not coexist with its apparent emergent timing, even though the event-based timing is not reflected in the statistical properties of the time series. A human agent is certainly free to think about and judge the intervals between joystick reversals, and more complex experimental paradigms (e.g., involving interference between simultaneous tasks) might yet reveal dual processes in the timing of continuous movements. It is even possible that event-based timing of a continuous movement necessarily emerges as "emergent timing" because the movement is continuous, not because its timing is emergent. In other words, all timing may be event-based, but it may manifest itself in different ways depending on the movement dynamics. Similarly, phase correction in synchronization, which Torre and Balasubramaniam (2009) attribute to different processes in event-based and emergently timed tasks, may be a single process of sensorimotor coupling with different manifestations that depend on the movement dynamics. Systematic exploration of the boundaries between apparently event-based and emergent timing regimes might help resolve these issues.

Acknowledgments

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References

Balasubramaniam, R., Wing, A. M., & Daffertshofer, A. (2004). Keeping with the beat: Movement trajectories contribute to movement timing. *Experimental Brain Research, 159*, 129–134.

Carson, R. G., & Riek, S. (1998). The influence of joint position on the dynamics of perception-action coupling. *Experimental Brain Research, 121*, 103–114.

Delignières, D., Lemoine, L., & Torre, K. (2004). Time intervals [sic] production in tapping and oscillatory motion. *Human Movement Science, 23*, 87–103.

Delignières, D., Torre, K., & Lemoine, L. (2008). Fractal models for event-based and dynamical timers. *Acta Psychologica, 127*, 382–397.

Elliott, M. T., Welchman, A. E., & Wing, A. M. (2009). Being discrete helps keep to the beat. *Experimental Brain Research, 192*, 731–737.

Hary, D., & Moore, G. P. (1987). Synchronizing human movement with an external clock source. *Biological Cybernetics, 56*, 305–311.

Huys, R., Studenka, B. E., Rheaume, N. R., Zelaznik, H. N., & Jirsa, V. K. (2008). Distinct timing mechanisms produce discrete and continuous movements. *PLoS Computational Biology, 4*(4), e1000061.

Ivry, R. B., Spencer, R. M., Zelaznik, H. N., & Diedrichsen, J. (2002). The cerebellum and event timing. *Annals of the New York Academy of Sciences, 978*, 302–317.

Lacquaniti, F., Terzuolo, C., & Viviani, P. (1983). The law relating the kinematic and figural aspects of drawing movements. *Acta Psychologica, 54*, 115–130.

Lemoine, L., & Delignières, D. (2009). Detrended windowed (lag one) autocorrelation: A new method for distinguishing between event-based and emergent timing. *Quarterly Journal of Experimental Psychology, 62*, 585–604.

Luck, G., & Sloboda, J. (2008). Exploring the spatio-temporal properties of simple conducting gestures using a synchronization task. *Music Perception, 25*, 225–239.

Mates, J., Radil, T., Müller, U., & Pöppel, E. (1994). Temporal integration in sensorimotor synchronization. *Journal of Cognitive Neuroscience, 6*, 332–340.

Repp, B. H. (2000). Compensation for subliminal timing perturbations in perceptual-motor synchronization. *Psychological Research, 63*, 106–128.

Repp, B. H. (2001). Phase correction, phase resetting, and phase shifts after subliminal timing perturbations in sensorimotor synchronization. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 600–621.

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin & Review, 12*, 969–992.

Repp, B. H. (2008). Perfect phase correction in synchronization with slow auditory sequences. *Journal of Motor Behavior, 40*, 363–367.

Repp, B. H., & Keller, P. E. (submitted for publication). Estimating the phase correction parameter in sensorimotor synchronization: Empirical comparison of different methods.

Repp, B. H., & Steinman, S. R. (2010). Simultaneous event-based and emergent timing: Synchronization, continuation, and phase correction. *Journal of Motor Behavior, 42*, 111–126.

Robertson, S. D., Zelaznik, H. N., Lantero, D. A., Gadacz, K. E., Spencer, R. M., Doffin, J. G., et al (1999). Correlations for timing consistency among tapping and drawing tasks: Evidence against a single timing process for motor control. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 1316–1330.

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.

Studenka, B. E. (2008). *Error correction timing behavior in tapping and circle drawing.* Unpublished Ph.D. dissertation, Purdue University, West Lafayette, Indiana.

Thaut, M. H., Tian, B., & Azimi-Sadjadi, M. R. (1998). Rhythmic finger tapping to cosine-wave modulated metronome sequences: Evidence of subliminal entrainment. *Human Movement Science, 17*, 839–863.

Torre, K., & Balasubramaniam, R. (2009). Two different processes for sensorimotor synchronization in continuous and discontinuous rhythmic movements. *Experimental Brain Research, 199*, 157–166.

Torre, K., & Delignières, D. (2008). Distinct ways of timing movements in bimanual coordination tasks: Contribution of serial correlation analysis and implications for modeling. *Acta Psychologica, 129*, 284–296.

Torre, K., Balasubramaniam, R., & Delignières, D. (2010). Oscillating in synchrony with a metronome: Serial dependence, limit cycle dynamics, and modeling. *Motor Control, 14*, 323–348.

Wing, A. M., & Kristofferson, A. B. (1973). Response delays and the timing of discrete motor responses. *Perception & Psychophysics, 14*, 5–12.

Zelaznik, H. N., Rosenbaum, D. A. (2010). Timing processes are shared when tasks have the same goal. *Journal of Experimental Psychology: Human Perception and Performance*, doi:10.1037/a0020380.

Zelaznik, H. N., Spencer, R. M., & Doffin, J. G. (2000). Temporal precision in tapping and circle drawing movements at preferred rates is not correlated: Further evidence against timing as a general-purpose ability. *Journal of Motor Behavior, 32*, 193–199.

Zelaznik, H. N., Spencer, R. M., & Ivry, R. B. (2002). Dissociation of explicit and implicit timing in repetitive tapping and drawing movements. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 575–588.

Zelaznik, H. N., Spencer, R. M., & Ivry, R. B. (2008). Behavioral analysis of human movement timing. In S. Grondin (Ed.), *Psychology of time* (pp. 233–260). Bingley, U.K.: Emerald.
Zelaznik, H. N., Spencer, R. M., Ivry, R. B., Baria, A., Bloom, M., Dolansky, L., et al (2005). Timing variability in circle drawing and tapping: Probing the relationship between event and emergent timing. *Journal of Motor Behavior, 37*, 395–403.