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RESEARCH ARTICLE

Simultaneous Event-Based and Emergent Timing: Synchronization, Continuation, and Phase Correction

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ABSTRACT. It has been claimed that rhythmic tapping and circle drawing represent fundamentally different timing processes (event-based and emergent, respectively) and also that circle drawing is difficult to synchronize with a metronome and exhibits little phase correction. In the present study, musically trained participants tapped with their left hands, drew circles with their right (dominant) hands, and also performed both tasks simultaneously. In Experiment 1, they synchronized with a metronome and then continued on their own, whereas in Experiment 2, they synchronized with a metronome containing phase perturbations. Circle drawing generally exhibited reliable synchronization, although with greater variability than tapping, and also showed a clear phase-correction response that evolved gradually during the cycle immediately following a perturbation. When carried out simultaneously in synchrony, with or without a metronome, the two tasks affected each other in some ways but retained their distinctive timing characteristics. This shows that event-based and emergent timing can coexist in a dual-task situation. Furthermore, the authors argue that the two timing modes usually coexist in each individual task, although one mode is often dominant.

Keywords: circle drawing, phase correction, synchronization, tapping, timing

Research on the timing of repetitive movements and time perception conducted in the 1980s and early 1990s revealed that individual differences in timing precision were stable across different tasks, which led to the hypothesis of a general timing ability (Franz, Zelaznik, & Smith, 1992; Ivry & Hazeltine, 1995; Keele & Hawkins, 1982; Keele & Ivry, 1987; Keele, Ivry, & Pokorny, 1987; Keele, Pokorny, Corcos, & Ivry, 1985; Treisman, Faulkner, & Naish, 1992). However, the tasks that were compared generally involved discrete movements, such as tapping, or discrete perceptual events. When Robertson et al. (1999) for the first time compared individual timing precision in tapping and circle drawing, a continuous movement, they failed to find a significant correlation between tasks. (See also Zelaznik, Spencer, & Doffin, 2000.) Zelaznik, Spencer, and Ivry (2002) subsequently demonstrated that intermittent circle drawing (i.e., with pauses between circles) correlates with tapping, but not with continuous circle drawing. These results led Zelaznik et al. (2002) to distinguish between two forms of timing: *explicit timing* and *implicit timing*, later renamed *event-based timing* and *emergent timing* (Ivry, Spencer, Zelaznik, & Diedrichsen, 2002).[1] The distinction is closely related to that between discrete and continuous rhythmic movements (Hogan & Sternad, 2007; Huys, Studenka, Rheaume, Zelaznik, & Jirsa, 2008), and also to that between information-processing and dynamic systems approaches to rhythmic timing (see Pressing, 1999; Schöner, 2002; Torre & Balasubramaniam, in press).

Event-based timing is thought to require an explicit internal representation of the temporal interval(s) to be produced (as postulated in Wing & Kristofferson's [1973] well-known model), whereas emergent timing is believed to arise incidentally from dynamic control of nontemporal movement parameters such as stiffness (Turvey, 1977). The distinction is supported by a variety of empirical results. Zelaznik et al. (2005) showed that the variability of the first cycle in circle drawing does correlate with tapping variability, whereas the variability of subsequent cycles does not. They interpreted this finding as reflecting a rapid transition from an initial explicit representation of the target interval to the appropriate nontemporal task dynamics required for movement at the prescribed rate. The negative lag-1 autocovariance or autocorrelation of cycle durations, a hallmark of self-paced tapping, is typically absent from self-paced circle drawing, which shows a positive value instead (Robertson et al., 1999; Studenka & Zelaznik, 2008). Spencer and Zelaznik (2003) analyzed the linear relationship between period duration and variability in tapping and circle drawing and found steeper slopes for tapping. (See also Robertson et al.; Studenka & Zelaznik.) Spencer, Zelaznik, Diedrichsen, and Ivry (2003) found that patients with cerebellar damage were more variable than were controls when tapping or drawing intermittent circles but not when drawing continuous circles. Kennerley, Diedrichsen, Hazeltine, Semjen, & Ivry (2002) reported that callosotomy patients were able to coordinate their hands temporally in bimanual tapping but not in bimanual circle drawing. Thorough analyses of the different statistical signatures of event-based and emergent timing have been conducted by Delignières and colleagues (Delignières, Lemoine, & Torre, 2004; Delignières, Torre, & Lemoine, 2008; Lemoine & Delignières, 2009), although the continuous movement in their studies was not circle drawing but forearm oscillation performed with a joystick.

Several recent studies have uncovered conditions under which circle drawing, although carried out continuously, appears not to be emergently timed, or at least emergently timed to a lesser degree than in other conditions. Studenka and Zelaznik (2008) found that circle drawing with the nondominant hand, even after some practice, exhibited a negative lag-1 autocovariance, like tapping. Zelaznik and Rosenbaum (submitted) provided auditory feedback whenever a particular target point in circle drawing was passed; this resulted in a

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significant correlation with tapping with regard to individual differences in variability, suggesting a common event-based timing process. Conversely, Repp (2008) proposed that tapping, the prototypical event-based activity, has an emergent timing component that becomes stronger as the tempo increases, because the movement becomes less discrete and begins to resemble an oscillation. Thus, we may be dealing with a continuum of task-dependent mixtures of control modes rather than with two categorical alternatives. The two timing modes (and the corresponding theoretical approaches) could be viewed as complementing each other because they pertain to different levels of temporal organization (Semjen, 1996).

Synchronizing a Continuous Movement with a Metronome

Empirical and theoretical studies comparing event-based and emergent timing have focused almost exclusively on self-paced activities. However, several recent studies have investigated synchronization of continuous movements with a metronome. Torre and Delignières (2008) had participants perform eight tasks resulting from the crossing of three variables: tapping versus oscillation, unimanual versus bimanual movement (of the same kind), and synchronization with an auditory metronome versus self-paced movement at a tempo indicated by a preceding video clip. Like others before them, these authors found a (rather small) negative lag-1 autocorrelation (AC-1) of intervals for self-paced tapping, but a positive AC-1 for self-paced oscillations. During synchronization with a metronome, the negative AC-1 of tapping was larger and the positive AC-1 of oscillation was smaller than during self-paced activity, probably because of phase error correction. Asynchronies of taps or oscillation endpoints witl the metronome had positive ACs that decreased gradually with increasing lag for both movements but were about twice as large for oscillation than for tapping. This indicates fractal variability in the pattern of asynchronies, particularly with oscillatory movement. Torre and Balasubramaniam (in press) conducted additional analyses showing that during synchronization with a metronome phase correction in oscillation is implemented late in the movement cycle, whereas it is implemented early in tapping. Torre, Balasubramaniam, and Delignières (in press) found that the results obtained by Torre and Delignières for synchronization of an oscillatory movement with a metronome could be modeled by adding a continuous coupling function to a nonlinear oscillator equation.

Studenka (2008) focused on synchronization of unimanual tapping and circle drawing with an auditory sequence containing a small phase shift (a shortened or lengthened interval). In tapping, an automatic response to a phase shift is observed in the subsequent tap(s), known as the *phase correction response* (PCR; Repp, 2005). Studenka replicated this finding but had some difficulty eliciting a clear PCR in circle drawing. Part of the difficulty was getting participants to synchronize the designated circle target point (north [N]) crossings with the metronome; they usually had drifted away from the metronome by the time the phase shift occurred. Studenka tried to overcome this problem by asking participants to start drawing, then adding a metronome in synchrony with a target point crossing, and introducing the phase shift soon thereafter. Although a PCR was obtained, it was distinctly smaller than in tapping and superimposed on considerable drift in asynchronies. Also, phase correction was still far from complete after four cycles. Studenka obtained a larger PCR when participants received tactile feedback at the target point, which suggested to her that event-based timing had come into play in circle drawing.

The Present Study

Because emergent timing by definition has no explicit temporal goal, we submit that synchronization with a metronome must be event-based, even when the movement is continuous and thus ostensibly subject to emergent timing. It is hardly surprising that circle drawing is harder to synchronize with a metronome than is tapping because circle drawing (unlike the forearm oscillation investigated by Delignières, Torre, and their colleagues) does not offer a highly distinctive event that can be aligned with the metronome tones. Nevertheless, the apparent inability of Studenka's (2008) participants to maintain a designated phase relationship between circle drawing and metronome is puzzling because participants could see and feel when the top of each circle (marked by a large dot and maximally distant from their body) was reached. Factors that may have contributed to poor synchronization are relatively high movement velocity, short trial lengths, and possibly low motivation of participants. One purpose of the present study was to attempt to obtain better synchronization performance by using highly motivated participants, presenting longer pacing sequences, and choosing a circle size and metronome tempi that made participants move more slowly than in most previous circle drawing research. It stands to reason that the crossing of the target point becomes better defined visually and kinesthetically if the movement velocity is slower, thus facilitating event-based timing. Given more stable event-based synchronization, we expected the PCR to phase shift perturbations to be enhanced, relative to Studenka's data, while at the same time we expected characteristics of circle drawing suggesting emergent timing to persist. The predictions regarding the PCR were investigated in the second of the two experiments reported in this article.

Experiment 1 investigated basic characteristics of tapping and circle drawing in synchrony with a metronome and in self-paced continuation. Its most novel aspect was the inclusion of a condition in which tapping and circle drawing were performed simultaneously. Although there is previous research on bimanual tapping (e.g., Helmuth & Ivry, 1996; Torre & Deligniéres, 2008) and bimanual circle drawing (e.g., Spencer & Ivry, 2007; Summers, Maeder, Hiraga, & Alexander, 2008), not to mention a voluminous literature on bimanual finger and limb oscillation, we are not aware of any previous study in which participants tapped with one hand while drawing circles with the other. This dual task (which may seem challenging but was not particularly difficult for our participants, perhaps because they were trained musicians) enabled us to ask several interesting questions about event-based and emergent timing. If event-based and emergent timing engage different neural processes (cognitive and motor, respectively), they should retain their distinctive characteristics without interacting or interfering with each other. However, if the requisite timing or motor control processes overlap, circle drawing might assume characteristics of event-based timing (e.g., in the autocorrelation structure of the time series) when it is accompanied by tapping, and tapping might become more like emergent timing in some respects. There could also be interactions due to shared attentional resources, resulting in greater variability of one or both tasks in the dual-task than in the single-task conditions. Consequently, we searched for possible interactions between the two tasks in asynchronies and cycle durations, their variability, and their autocorrelation structure.

Interactions between the two activities during self-paced timing were of special interest. As long as both tasks are coordinated with a metronome, they need not be coordinated directly with each other (although they might be). However, when the metronome stops, the two activities must either be synchronized with each other or drift apart. If they remain synchronized, there are four theoretical possibilities: Tapping may be synchronized with circle drawing as the reference; circle drawing may be synchronized with tapping as the reference; both activities may be paced by the same cognitive timer and therefore be synchronized with each other; or they may be coupled somehow at a lower, motoric level. The first two possibilities imply that one activity will track the other and thereby tend to copy its interval time series, which implies unidirectional interactions. By contrast, if the two activities retain their distinctive timing properties but nevertheless stay in synchrony with each other, this would suggest that they are controlled by the same cognitive timing process. Although coupling at a more peripheral level is a fourth theoretical possibility, this is perhaps unlikely in view of the different kinematics of tapping and circle drawing.

EXPERIMENT 1

In this experiment, musically trained participants carried out three tasks at two tempi in a synchronization–continuation paradigm. We used musicians because they were readily available and motivated to do well. The tasks were circle drawing with the right hand (the dominant hand for all participants), tapping with the left hand, and both of these activities simultaneously. We did not include the reverse hand assignments because smooth circle drawing with the nondominant hand is difficult, whereas tapping with the left hand at a moderate tempo is not challenging and yields results similar to right-handed tapping (Studenka & Zelaznik, 2008).

Our methodology in the circle-drawing task differed in several respects from previous studies. To enable us to record movement timing without using motion tracking equipment and software, which we did not have readily available, we had participants draw circles with a pen on a graphics tablet. Moreover, instead of freely tracing a circle, which permits spatial deviations, participants moved the pen inside the raised rim of a plastic circle drawing template, thereby moving in a perfectly circular trajectory and controlling only movement velocity. Finally, the target point for synchronization was not N on the circle, as in most earlier research, but west (W), and participants moved in a counterclockwise direction so that the moving hand did not obstruct the participant's view of the target point.[2] We did not expect any of these differences to efface the emergent timing characteristics of circle drawing.

Method

Participants

The participants included nine graduate students from the Yale School of Music (six women, three men; age range = 22–28 years) who were paid for their services, and the first author (age 64 years). The musicians' primary instruments were piano (2), violin (2), viola, double bass, clarinet, bassoon, and harp; Repp is an amateur pianist. All had some experience with perception and synchronization experiments but, except for Repp in a few pilot runs, had never performed a rhythmic circle drawing task and had rarely tapped with their left hand. All were right-handed by self-report.

Materials and Equipment

Tone sequences were generated online by a program written in MAX 4.0.9 (Cycling '74, San Francisco, CA), running on an Intel iMac computer. The tones (piano timbre) were produced by a Roland RD-250s digital piano according to musical instrument digital interface (MIDI) instructions from the MAX program and were presented over Sennheiser HD540 II headphones. All tones had the same pitch (C4, 262 Hz), the same nominal duration (40 ms, with rapid decay after the nominal offset), and the same intensity (MIDI velocity). Each sequence contained 30 tones with constant interonset intervals (IOIs) of either 600 or 800 ms. The last tone was followed by a silent interval of either 18 or 24 s (= 30*IOI) whose end was marked by a single low tone.

Participants tapped on a Roland SPD-6 electronic percussion pad and drew circles on an Adesso CyberTablet Z12 (report rate = 125 Hz) to whose surface two Pickett Circle Master No. 1204I Inking Templates had been affixed on top of each other. Participants used a battery-powered pen to move within the centrally located circle template, which had a diameter of 44.5 mm and a rim height of approximately 2 mm that prevented escape of the pen. The four cardinal points (N, W, south [S], east [E]) were marked on the template by ticks. Cardinal point crossings and tap times were recorded by the MAX program with a temporal resolution of 2 ms.

Procedure

Participants sat at a table facing the computer. The percussion pad (on the left) and the graphics tablet (on the right) were placed near the edge of the table in front of the computer keyboard. When tapping, participants rested their left wrist on the pad and moved their hand or finger. The taps produced an audible thud but no auditory feedback over the earphones. To draw circles, participants were instructed to hold the pen vertically or at a slight angle, to position it at N at the beginning of each trial, and to move around the circle smoothly and at a constant speed in a counterclockwise direction, with W being the target point for synchronization with the metronome. The trace made by the pen was visible on the computer screen, but participants' gaze was generally focused on the pen and the drawing template. Moving the pen inside the template created an audible swishing sound.

After a few minutes of informal practice with simultaneous tapping and circle drawing, participants completed 8 blocks of 6 randomly ordered trials each in a session lasting about 1 hr. The trials in each block represented tapping, circle drawing, and both tasks together at each of the two tempi. Participants initiated each trial by pressing the space bar. This made a message appear on the screen that told the participant which task to perform. The auditory pacing sequence started 2 s later, and participants started moving with the third tone, trying to synchronize with the tones as closely as possible. After the sequence ended, they continued their rhythmic movements at the same tempo until they heard the low tone that marked the end of the continuation phase.

Analysis

Asynchronies between taps and tones during synchronization were computed by subtracting the programmed time of each tone onset from the registered time of the nearest tap, so that a negative asynchrony signified that the tap preceded the tone. Because previous acoustic measurements had revealed an electronic processing delay of about 15 ms (SD $\approx$ 1 ms) between finger impact on the pad and a tap-triggered tone onset, a constant of 15 ms was subtracted from all registered asynchronies. Intertap intervals, referred to in this article as cycle durations, were also computed.

For circle drawing, the MAX program registered the times when the pen passed the cardinal points by immediately differencing the x- and y-coordinate values arriving from the tablet and saving the times of the appropriate zero crossings. The stream of raw tablet data was not saved. Asynchronies with regard to the target point (W) were calculated as for tapping, and 15 ms were likewise subtracted.[3] Cycle durations were calculated from each target point crossing to the next, and quarter-cycle durations were calculated from one cardinal point crossing to the next. Asynchronies between tapping and circle drawing were calculated such that a negative asynchrony indicates that the tap preceded the circle target point crossing.

In addition to means and standard deviations of asynchronies, cycle durations, and quarter-cycle durations, we calculated autocorrelation functions up to lag-10 for asynchronies and cycle durations, as well as lag-0 and lag-1 crosscorrelations (CCs) between the cycle durations of simultaneous tapping and circle drawing. All measures were calculated for individual trials, separately for synchronization and continuation phases, and then averaged across repetitions and, for display in graphs, across participants. The first two data points of the synchronization and continuation phases were omitted in all calculations, as well as the final data point(s) in continuation, because of the somewhat variable number of data points for the continuation phase. As a result, each phase comprised 26 target events.[4]

The statistical analyses were generally repeated measures analyses of variance (ANOVAs) with the independent variables selected from among the following: tempo (target intervals of 600 vs. 800 ms), activity (tapping vs. circle drawing), task (single vs. dual), phase (synchronization vs. continuation), and circle quarter-cycle (W–S, S–E, E–N, N–W). In tests of quarter-cycle effects, the Greenhouse–Geisser correction was applied. In the *Results* section we be use abbreviations for tapping (T), circle drawing (CD), T with simultaneous CD (T [and CD]), and CD with simultaneous T (CD [and T]).

Results

Asynchronies

Figures 1A and 1B show mean asynchronies in synchronization with the metronome for T and CD. As expected, asynchronies were negative, indicating that taps and CD target crossings generally preceded the pacing tones. In addition to a main effect of task, $F(1, 9) = 14.42, p = .004$, there was a strong interaction between activity and task, $F(1, 9) = 32.76$, $p < .001$: Simultaneous T reduced CD asynchronies substantially, $F(1, 9) = 27.34$, $p = .001$, whereas simultaneous CD had no significant effect on T asynchronies. As can be seen in Figure 1C, the mean asynchrony between T and CD in the dual task was small during synchronization and remained small during continuation. It did not vary significantly with task or tempo.

Variability of Asynchronies

Figures 2A and 2B show the mean within-trial standard deviations of T and CD asynchronies with the metronome during the synchronization phase. It is clear that variability was much greater for CD than for T, $F(1, 9) = 132.82, p <$ .001, as was fully expected. Variability was also larger at the slower than at the faster tempo, $F(1, 9) = 37.93, p < .001$, and more so for CD than for T, as reflected in a significant interaction, $F(1, 9) = 9.83, p = .012$. Finally, variability was greater in the dual task than in the single tasks, $F(1, 9) =$

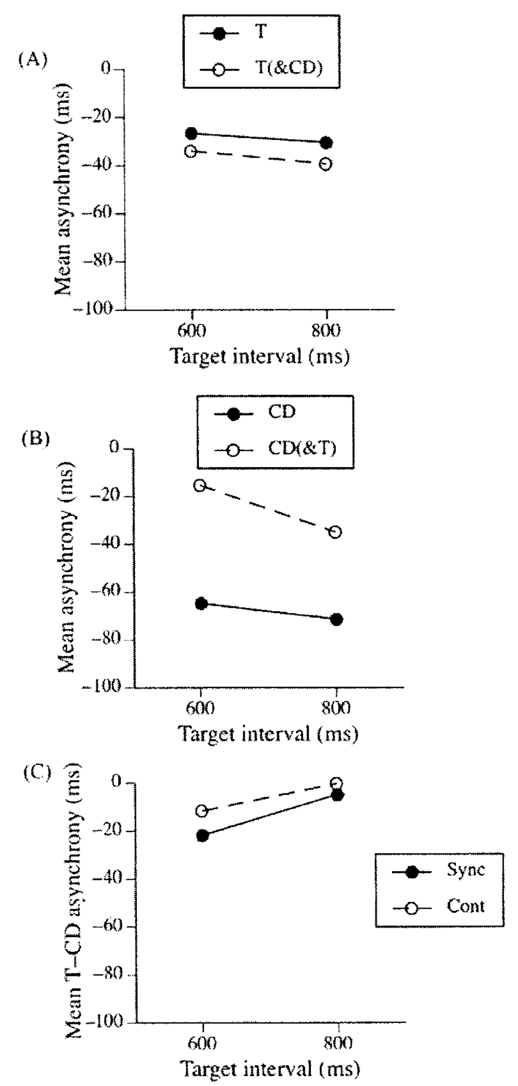

FIGURE 1. (**A** and **B**) Mean asynchronies of tapping (T) and circle drawing (CD) with the pacing sequence during the synchronization phase, at two tempi (target intervals). T (and CD) refers to T with simultaneous CD, and CD (and T) to CD with simultaneous T. (**C**) Mean asynchronies between T and CD during synchronization (sync) and continuation (cont).

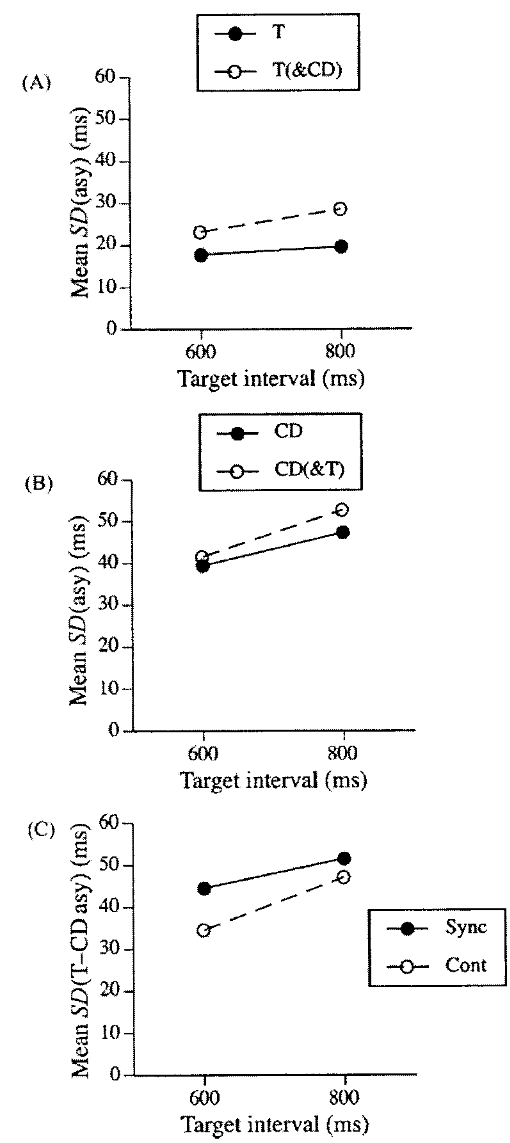

FIGURE 2. (**A** and **B**) Mean standard deviations of asynchronies (asy) of tapping (T) and circle drawing (CD) with the metronome. (**C**) Mean standard deviations of asynchronies between tapping (T) and circle drawing (CD) during synchronization (sync) and continuation (cont).

10.61, $p = .010$. Although the Activity × Task interaction was not significant, separate ANOVAs on T and CD revealed that the increase in variability in the dual task was reliable only for T, $F(1, 9) = 37.71$, $p = .001$, not for CD, $F(1, 9) = 1.71$, $p = .224$. For T, the increase was also larger at the slower tempo, $F(1, 9) = 5.30$, $p = .047$. The mean standard deviation of T–CD asynchronies in the dual task is shown in Figure 2C. During synchronization this variability was similar to that of CD asynchronies with the pacing sequence, but it decreased during continuation, $F(1, 9) = 5.55$, $p = .043$. Variability was larger at the slower tempo than at the faster tempo, $F(1, 9) = 22.24$, $p = .001$.

For CD, the standard deviation of asynchronies with the metronome during synchronization was calculated not only for the W target point but also for the three other cardinal points (whose asynchronies were much larger, of course),

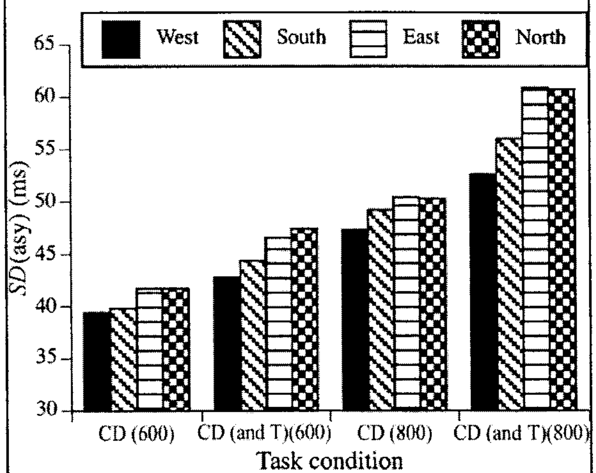

FIGURE 3. Mean standard deviations of circle drawing (CD) cardinal point asynchronies (asy). T = tapping.

with the expectation that variability would be smallest at the target point if W constituted an anchor point for CD timing (cf. Roerdink, 2008; Roerdink, Ophoff, Peper, & Beek, 2008; Torre et al., in press). The results, shown in Figure 3, confirmed this prediction. Variability differed significantly across cardinal points, $F(3, 27) = 11.68, p < .001$, increasing from W to S to E, with little difference between E and N. The difference among cardinal points was more pronounced at the slower tempo than at the faster tempo, $F(3, 27) = 5.27$, $p = .013$, and also more pronounced in the dual task than in the single task, $F(3, 27) = 10.00$, $p = .003$. Of course, variability was also greater at the slower than at the faster tempo, $F(1, 9) = 35.04, p < .001$. Although mean variability was clearly greater in the dual than in the single tasks, the main effect of task surprisingly did not reach significance, $F(1, 9) = 4.06$, $p = .075$, which indicates that the increase was due to a minority of participants who showed very large effects.

Cycle and Quarter-Cycle Durations in Circle Drawing

The mean W–W cycle durations confirmed that participants generally adopted and maintained the target tempi. During synchronization, mean cycle durations were very close to the target intervals. During continuation, they were 0–10 ms shorter, depending on the condition, indicating a very slight acceleration. Quarter-cycle durations reflect the smoothness of the CD movement. If participants had followed instructions to move at a constant speed, all quarter-cycle durations should have been equal. In fact, however, there was a marginally significant tendency for N–W to be longest and for W–S to be shortest, $F(3, 27) = 3.34$, $p = .050$, suggesting that some participants slowed down when approaching the W target and accelerated after passing it. The tendency was more pronounced in the dual than in the single task, $F(3, 27) = 3.74, p = .035$, and also tended to be larger at the slower tempo, $F(3, 27) = 3.36$, $p = .051$. The triple interaction was also significant, $F(3, 27) = 4.50$, $p = .023$. It appears that at the slower tempo participants slowed down when they approached the target in single-task CD, whereas in CD(&T) they slowed down gradually throughout the cycle.

Variability of Cycle Durations

Figure 4 shows the within-trial standard deviations of cycle durations (W–W for CD). As expected, variability was generally larger at the slower tempo than at the faster tempo, $F(1, 9) = 30.46$, $p < .001$, and more so for CD than for T, $F(1, 9) = 16.79$, $p = .003$. However, there was much less of a difference in variability between T and CD in this case than in the case of asynchronies (Figure 2). Although CD showed somewhat higher variability than T overall, $F(1, 9) = 11.27, p = .008$, this difference was apparent only between the single-task conditions; in the dual-task condition, T and CD variability were similar, $F(1, 9) = 18.04$, $p = .002$, for the interaction. Also, although variability was greater overall in the dual than in the single-task conditions, $F(1, 9) = 12.67$, $p = .006$, only T showed this task difference. This was confirmed by separate ANOVAs on T and CD, which revealed a significant task effect only for T, $F(1, 9) = 46.26$, $p < .001$, not for CD, $F(1, 9) = 0.05, p = .831$. In the combined analysis of T and CD, the task effect also was larger during synchronization than during continuation, $F(1, 9) = 6.42$, $p = .032$, and tended to be larger at the slower than at the faster tempo, $F(1, 9) = 4.65, p = .059$.

We further calculated the standard deviations of CD cycle durations between different cardinal points (i.e., W–W, S–S, E–E, and N–N), with the expectation that W–W would exhibit the lowest variability. The results confirmed these expectations, $F(3, 27) = 7.99, p = .006$. The difference among cycle durations was more pronounced in the dual than in the single task, $F(3, 27) = 4.42, p = .023$. Naturally, variability was larger at the slower than at the faster tempo, $F(1, 9) = 54.19$, $p < .001$, and also somewhat larger during synchronization than during continuation, $F(1, 9) = 8.14$, $p = .019$.

Autocorrelations

The autocorrelation (AC) functions for asynchronies with the metronome during the synchronization phase are shown Figures 5A and 5B. As expected (following Torre & Delignières, 2008), AC-1 values were positive for T and CD, but much larger for CD than for T. Moreover, the higher lag ACs were close to zero for T but slowly decreasing for CD, reaching zero at lag 5 at the faster tempo and around

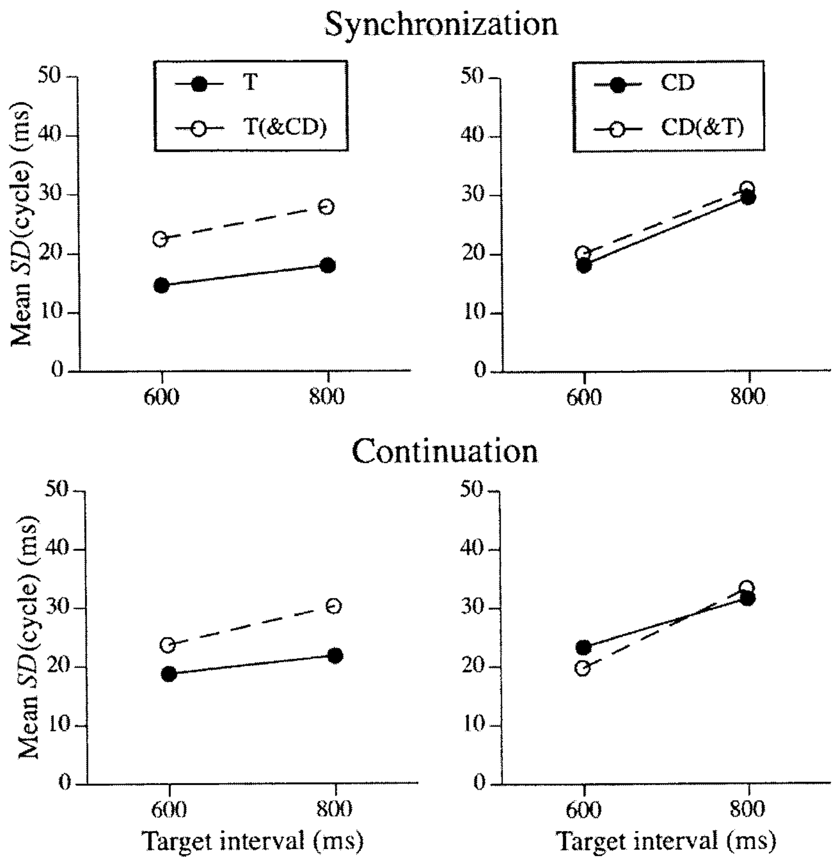

FIGURE 4. Mean standard deviations of cycle durations. CD = circle drawing; T = tapping.

lag 7 at the slower tempo. These patterns indicate medium-term dependencies in the time series of CD asynchronies, but only short-term dependencies among T asynchronies. An ANOVA on the AC-1 values confirmed a highly consistent difference between T and CD, $F(1, 9) = 151.77$, $p < .001$, and also indicated that AC-1 values were larger at the faster tempo, $F(1, 9) = 16.75$, $p = .003$. Although the Tempo × Activity interaction was not significant, separate analyses of T and CD showed the effect of tempo to be reliable only for CD, $F(1, 9) = 30.24$, $p < .001$, where it also extended to longer lags. There was no difference between single and dual tasks.

We further computed the autocorrelation functions for the asynchronies between simultaneous T and CD during the synchronization and continuation phases; they are shown in Figure 5C. These functions are lower than those for asynchronies of CD with the metronome, but clearly higher than those for asynchronies of T with the metronome. Also, the functions were slightly lower during continuation than during synchronization, especially at the faster tempo. This indicates some coordination between T and CD during continuation.

Figure 6 shows the AC functions for cycle durations during synchronization and continuation. Attention focuses here on the AC-1 values, as higher lag ACs were close to zero in most cases; only the AC-2 of T during synchronization seemed to be consistently negative (but small). AC-1 values were negative for T, as expected, but positive for CD, $F(1, 9) = 86.23$, $p < .001$. A small main effect of phase, $F(1, 9) = 6.08$, $p = .036$, is negligible in view of an extremely consistent Activity × Phase interaction, $F(1, 9) = 136.16$, $p < .001$: AC-1 values of T were more negative in synchronization than in continuation, whereas those of CD were more positive in synchronization than in continuation. The only other significant effect was an interaction between task and phase, $F(1, 9) = 7.45$, $p = .023$. It indicated that AC-1 was more negative in the dual than in the single task during continuation only. Although the Activity × Task × Phase interaction was not significant, the just-mentioned difference was due entirely to T rather than CD, as highlighted by the oval in Figure 6. A separate analysis on the T data confirmed a significant Task × Phase interaction, $F(1, 9) = 13.49$, $p = .005$, whereas this interaction was totally absent

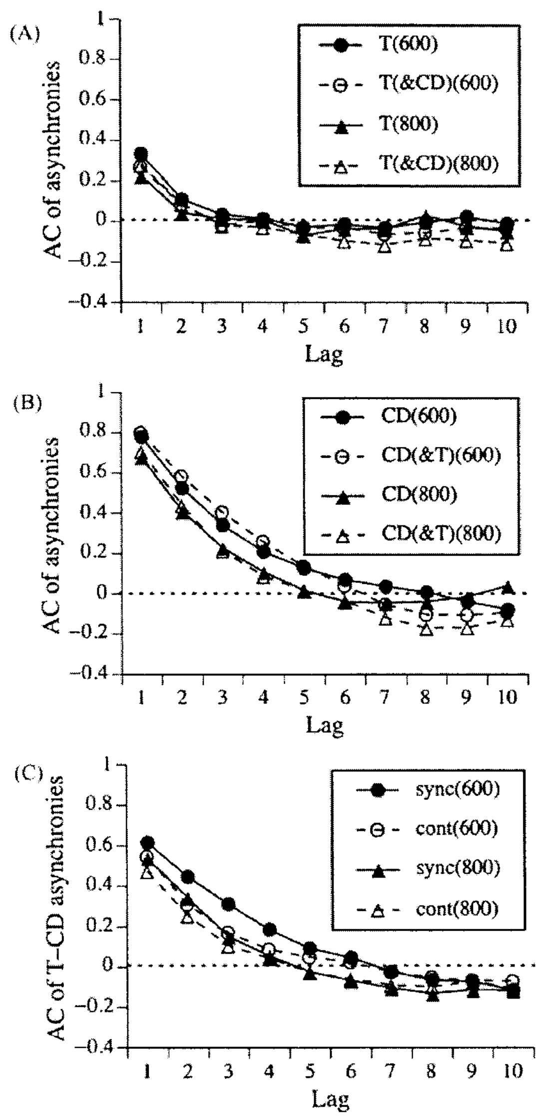

FIGURE 5. (A and B) Mean autocorrelation (AC) functions for asynchronies with the metronome during the synchronization phase. (C) Mean AC functions for asynchronies between taps and circles during the synchronization (sync) and continuation (cont) phases. CD = circle drawing; T = tapping.

in the CD data. The negative AC-1 for T was surprisingly small in single-task continuation, where it is a hallmark of discrete timing. However, it grew much larger in the T (and CD) dual task.

Cross-Correlations

CCs between the cycle durations of simultaneously performed T and CD could be diagnostic as to whether one activity served as the temporal reference for the other, particularly during the continuation phase, in which case the lag-1 CC (either CC-1 or CC+1, as defined subsequently) should be positive and significant, or whether both activities were governed by a central cognitive timer, in which case the lag-0 CC (CC0) should be positive and significant. All CCs were rather small (< 0.20), but some were clearly larger than zero, whereas others were not. Results at the two tempi were similar. An ANOVA yielded a significant main effect of CC lag, $F(2, 18) = 8.02, p = .007$, as well as a CC Lag × Phase interaction, $F(2, 18) = 4.93, p = .044$. The relatively largest values were obtained for CC0 during synchronization with the metronome, suggesting some degree of common timing control of T and CD. However, during continuation CC0 was significantly smaller, $F(1, 9) = 11.26, p = .008$, and not significantly different from zero. The values of CC-1 (CD lagging T) were all near zero, indicating that CD did not track the cycle durations of T. However, three of the four values of CC+1 (T lagging CD) were significant (the fourth one was nearly significant, $p < .06$), indicating that T might have tracked CD to some extent. CC+1 did not differ significantly between synchronization and continuation.

Discussion

We discuss first the results of the single-task conditions, which largely replicate previous findings, and then turn to the results of the novel dual-task condition.

Tapping

Tapping, even though it was performed with the left hand, yielded results typically found in tapping tasks (see Aschersleben, 2002; Repp, 2005; Studenka & Zelaznik, 2008; Torre & Delignières, 2008). These include slight anticipation of pacing tones (negative mean asynchrony) during synchronization with the metronome, low variability of these asynchronies and of cycle durations (considering that the participants were musicians), a positive lag-1 autocorrelation of asynchronies, and a negative lag-1 autocorrelation of cycle durations, with near-zero autocorrelations at longer lags (as predicted by the Wing–Kristofferson [1973] model). Although both the mean negative asynchrony and variability typically increase with cycle duration (e.g., Mates, Radil, Müller, & Pöppel, 1994; Repp, 2003), these tendencies were weak in the present study. However, the two target-cycle durations, 600 and 800 ms, did not represent a large tempo difference. Variability of cycle durations was greater during continuation than during synchronization; this is as expected because self-paced tapping is less stable in tempo than is metronome-paced tapping.

The negative lag-1 autocorrelation of tapping cycle durations was larger in synchronization than in continuation (as in Torre & Delignières, 2008), which can be attributed to phase correction during synchronization. Phase correction may also be responsible for the slightly negative lag-2 autocorrelation during synchronization. The lag-1 autocorrelation during continuation seems rather small (only about −.05) but

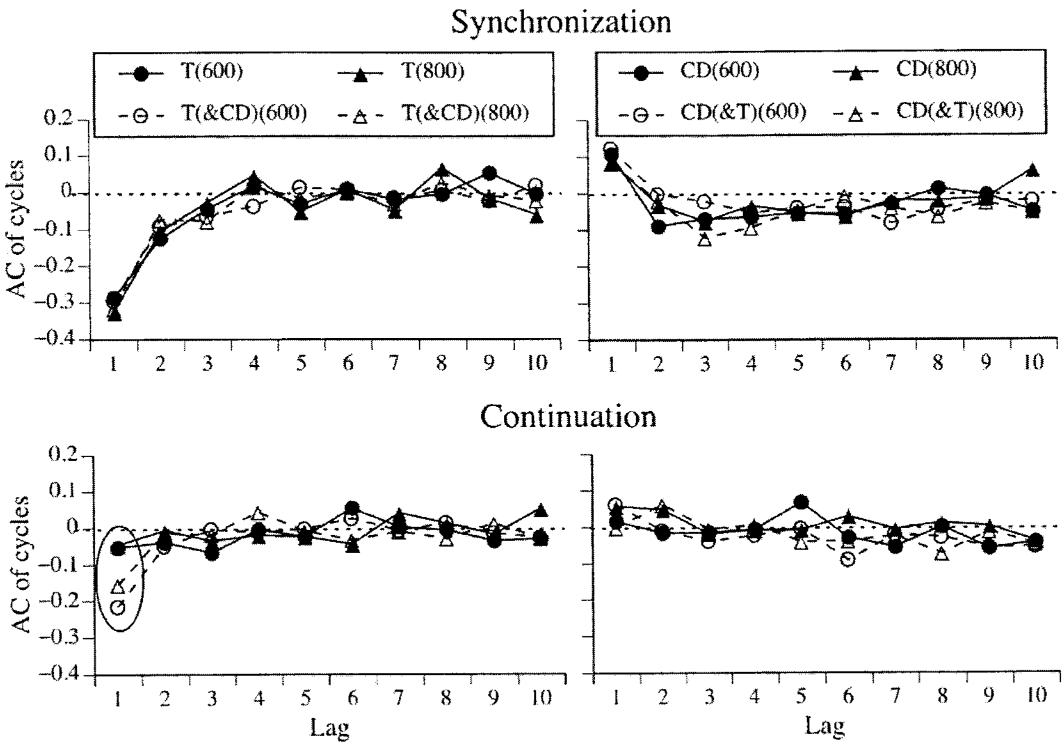

FIGURE 6. Mean autocorrelation (AC) functions for cycles. CD = circle drawing; T = tapping.

is not unreasonable. According to the Wing–Kristofferson model, it represents the negative ratio of the motor variance to the total variance. With the total variance being about 400 ms^2 (Figure 4, lower left panel), the motor variance comes to about 20 ms^2, which is low but not implausible (e.g., Wing, 1980). Torre and Delignières found small positive autocorrelations of cycles at longer lags during self-paced tapping, which were not replicated here. Their finding reflects slow tempo fluctuations that were probably due to the great length of their trials (600 taps) and perhaps also to the lack of musical training of their participants. The same reasons probably explain also why Torre and Delignières found positive higher lag autocorrelations of asynchronies during synchronization, which were absent here.

Circle Drawing

Unimanual circle drawing showed a greater mean negative asynchrony with the metronome than did tapping; Studenka (2008) also found this in her first experiment, though not in her second one. Variability of asynchronies was much larger for circle drawing than for tapping and was also more affected by tempo. Thus, synchronization accuracy of circle drawing was relatively poor, suggesting weak and slow phase correction, consistent with Studenka's research. However, unlike Studenka's participants, who seemed to be unable to stay in synchrony with the metronome (though her trials were perhaps too short to demonstrate this conclusively), the present participants definitely were able to maintain approximate synchrony; only a few trials (excluded) exhibited phase wrapping. This means some phase correction must have occurred. This issue was addressed further in Experiment 2, described subsequently.

Asynchronies of circle drawing with the metronome tended to fluctuate slowly, and this is reflected in the autocorrelation function, which shows positive dependencies up to lag 5 or 7, depending on tempo. For oscillatory movement, Torre and Delignières (2008) found a similar decay across short lags but persistent positive autocorrelations at longer lags, which they attributed to fractal noise generated by an internal timekeeper. This long-term persistence was not replicated in the present study, probably due to the shorter trial durations combined with the extensive musical training of the participants in the present study.

Participants' cycle durations during continuation of circle drawing were close to the target values. Cycle variability was somewhat larger than in tapping, especially at the slower tempo, in the synchronization and continuation phases. This represents a difference from the results of Zelaznik and his colleagues who consistently report lower cycle variability in self-paced circle drawing than in self-paced tapping. One reason for this could be that the present participants, who were not only musicians but also moderately to highly experienced in tapping tasks (albeit using the dominant hand), were particularly stable in their tapping. Indeed, their mean coefficients of variation (CV) for self-paced tapping (3.1 and 2.7 at 600 and 800 ms, respectively) were quite low compared to those in earlier studies that compared tapping and circle drawing (e.g., Robertson et al., 1999; Studenka & Zelaznik, 2008), whereas the mean CVs of circle drawing were comparable. Indeed, there is no reason why musicians should differ from nonmusicians in their circle drawing ability.

Studenka and Zelaznik (2008) reported a lag-1 autocovariance close to zero for linearly detrended cycle durations of self-paced circle drawing with the dominant hand, whereas Torre and Delignières (2008) found persistent positive autocorrelations across a wide range of lags for the cycles of self-paced oscillations. The absence of a negative lag-1 autocorrelation is considered a hallmark of emergent timing. The present data agree more with Studenka and Zelaznik, even though no detrending was performed: The lag-1 autocorrelation of the cycle durations of self-paced circle drawing was positive but very small. The autocorrelations at longer lags were all close to zero, meaning that the continuation tempo of circle drawing was quite stable. During synchronization, the lag-1 autocorrelation of circle drawing was more clearly positive, without any increase in higher lag autocorrelations. Even though the lag-1 autocorrelation of tapping was more negative during synchronization than during continuation, presumably because of rapid phase correction, the opposite trend in circle drawing could have been due to slower phase correction that extended over several cycles. Such slow correction tends to introduce positive correlations between successive cycles, whereas rapid phase correction tends to introduce alternations between shorter and longer cycles and thus a negative correlation.

Ideally, circle drawing should be carried out with a constant tangential velocity, and that generally seems to have been the case in earlier studies, although the velocity profile or phase portrait has rarely been reported. In the present study, there was a tendency to slow down as the target point was approached (i.e., during the N–W quadrant). This velocity pattern was equally present in synchronization and continuation and thus was not specific to synchronization with the metronome. It suggests an anchor point in the trajectory (see Beek, Turvey, & Schmidt, 1992; Roerdink et al., 2008; Torre et al., in press) that served as a reference for cognitive timing. In the converse situation of synchronizing taps to the downbeat perceived in a continuous conducting gesture, Luck and Sloboda (2008) found that taps were synchronized most often to the point of maximum acceleration. Here, the point of maximum acceleration in the circle trajectory probably occurred near the target point and thus was synchronized, more or less closely, with the metronome. (Because of the coarse sampling of the movement trajectory during data collection, a more detailed analysis of velocity and acceleration profiles could not be performed.)

Another indicator of the presence of an anchor point is that timing variability is minimal at that point. Evidence for this was obtained in the synchronization phase, where the variability of asynchronies with the metronome tended to be smaller at the target point than at the other three cardinal points. (During continuation, this measure obviously was not available.) In both synchronization and continuation, there was also a tendency for the W–W cycle to be less variable than cycle durations measured between other cardinal points, at least at the faster tempo. These findings differ somewhat from previous circle drawing studies where such differences, if they were looked for at all, were not found (Spencer & Zelaznik, 2003). Differences in method, such as the present use of a pen, drawing within a raised template, or having W as the target point, might be responsible for the emergence of an anchor point in the trajectory.

Nevertheless, circle drawing continued to exhibit important hallmarks of emergent timing, namely a positive or near-zero lag-1 autocorrelation of cycle durations and high positive short-lag autocorrelations of asynchronies during synchronization, indicative of slow tempo fluctuations. As Studenka (2008) noted, pacing of circle drawing with a series of discrete auditory events by no means brings about a radical change from emergent timing to event-based timing. However, participants' ability to maintain synchrony with the metronome does indicate that the timing of circle drawing cannot be totally emergent; there must be some additional event-based mechanism for sensorimotor coupling to the discrete events presented by the metronome. The apparently greater success of the present participants in synchronizing circle drawing with a metronome, compared to Studenka's participants, could be due to several factors, including musical training, use of a raised drawing template, and, perhaps most importantly, longer target cycle durations and smaller circle size. Slower movement velocities enable participants to achieve better temporal resolution in their visual and kinesthetic perception of target point crossings, which thus become more sharply defined as reference events in the movement cycle and can be coupled more effectively with the metronome tones. The coupling mechanism and the resulting phase error correction thus must be event-based, even though the timing of circle drawing also remains emergent (i.e., regulated by continuous control of a nontemporal parameter). Torre et al. (in press) considered continuous coupling of oscillatory movement with a metronome, but it is not clear to us how a movement can be coupled continuously with a series of discrete events. One theoretical possibility is that these events entrain a continuous internal process (i.e., an internal oscillator; cf. Large & Jones, 1999) to which the movement is then coupled. The obvious alternative is that synchronized circle drawing, similar to synchronized tapping, is governed in part by a cognitive timer that measures interval durations between metronome tones and times kinematic events relative to those tones. Only the kinematic events in circle drawing are more poorly delineated than those in tapping, and event-based timing is more difficult to implement because of the continuous motion.

Simultaneous Tapping and Circle Drawing

We now turn to the novel part of our study, the dual task, and begin with discussion of the synchronization phase. During synchronization with the metronome, it was not necessary to coordinate tapping and circle drawing directly because they were automatically coordinated as long as both activities were synchronized with the metronome, as they were. Nevertheless, some interactions between the two activities were observed. Perhaps the least surprising of these is increased variability in both activities, which probably just reflects an increase in overall task difficulty. On one hand, circle drawing was less familiar and more difficult than tapping, which made it vulnerable to the addition of a second activity; on the other hand, participants clearly focused their gaze and attention on circle drawing, and this made tapping more vulnerable to interference. Indeed, the increase in variability was greater for tapping than for circle drawing.

The large change in the mean asynchrony of circle drawing is a much more interesting finding. Simultaneous tapping greatly reduced the anticipation tendency in circle drawing, thereby bringing tapping and circle drawing into closer synchrony (on average). This could imply intentional coordination between the two activities, in addition to their coordination with the metronome, but it could also be because of an unintended effect of tapping on the velocity profile of circle drawing. However, because intentional coordination also might result in some modification of circle drawing dynamics, these two alternatives are difficult to distinguish. Our analysis of quarter-cycle durations yielded evidence of a more gradual and more pronounced deceleration following a target point crossing when circle drawing was accompanied by tapping than when it was not, especially at the slower tempo. Also, the reduced variability of asynchronies at the circle target point, indicative of an anchor point, was more pronounced in the presence of tapping, as was the lower variability of the W–W cycle compared to other cardinal point cycles at the slower tempo. Studies that investigate interactions between bimanual rhythmic (oscillatory) and single discrete movements have found a momentary acceleration in the oscillation at the time that the discrete movement occurred (Wei, Wertman, & Sternad, 2003). This seems consistent with the greater deceleration prior to target points found here, enabling greater acceleration around the target point. It should be noted that tapping had no effect on the autocorrelation functions of circle drawing, which means that the basic emergent timing characteristics of circle drawing remained intact.

Another striking finding was the unidirectional effect of circle drawing on tapping cycle variability during the synchronization phase. It seems to suggest unilateral coordination of tapping with circle drawing, which is plausible because circle drawing was carried out with the dominant hand and was at the focus of visual attention. Indeed, the results of the CC analysis were consistent with this interpretation, although the correlations were very small. However, coordination of taps with circle drawing would also seem to imply an increased presence of emergent timing characteristics in tapping because the taps would be tracking the time series of circle target point crossings. Remarkably, however, circle drawing had no effect whatsoever on the autocorrelation functions of either asynchronies or cycle durations in tapping, and it is in those functions that a tracking of the tempo instabilities of circle drawing should be reflected. Therefore, the increase in tapping variability appears to have been merely random, caused by reduced attention to the left hand in the dual task situation, and there may not have been any specific coordination between tapping and circle drawing during synchronization with the metronome.

Turning now to the continuation phase, we note first that, with the exception of only a few trials, participants maintained synchrony between tapping and circle drawing, without having been specifically instructed to do so. Of course, it could be argued that synchronization was implied by the instruction to continue both activities at the same tempo. In any case, it seemed a natural thing for participants to do, despite the presumed different timing control regimes of tapping and circle drawing. It might then be asked again whether participants now used the circles as the reference with which to synchronize the taps, or vice versa. Even though the circle target point crossings constitute a rather uncertain temporal reference for tapping and in turn could be synchronized only poorly with taps, one nevertheless would expect changes in the timing characteristics of either tapping or circle drawing. However, these characteristics remained largely unchanged from the synchronization phase. Only one index changed: The lag-1 autocorrelation of tapping cycle durations was less negative in dual-task continuation than in dual-task synchronization, but more negative than in single-task continuation. By contrast, the lag-1 autocorrelation of cycle durations in dual-task circle drawing did not differ from that of single-task continuation. So, dual-task continuation specifically affected tapping.

We interpreted the large negative lag-1 autocorrelation of tapping cycles in the synchronization phase as being due to phase correction. Therefore, one possible interpretation of the moderately negative lag-1 autocorrelation of tapping in the dual-task continuation phase is that it represents (weaker) phase correction when synchronizing tapping with circle drawing, which served as the temporal reference. The CC analysis also was consistent with that interpretation. Another possible interpretation is that the moderately negative lag-1 autocorrelation of tapping in the dual-task continuation phase represents increased motor variance, due to lack of attention to the left hand. It is unclear, however, why this should have occurred only during continuation and not also during synchronization. The slightly lower autocorrelations of asynchronies between tapping and circle drawing during continuation than during synchronization also suggest that tapping and circle drawing may have been coordinated directly during continuation, although they do not indicate whether the coordination was unilateral or bilateral. The absence of significant lag-0 CCs between the cycle durations of tapping and circle drawing in the dual-task continuation phase argues against the hypothesis that both activities were paced by a single cognitive timer or by two coupled timers (Ivry & Richardson, 2002). The data, as far as they go, suggest that tapping was unilaterally coupled to emergently timed circle drawing in the dual-task continuation phase, with the relative weakness of coupling being a reflection of the poor delineation of the target events (now constituting pacing events) in the circle trajectory.

EXPERIMENT 2

The purpose of Experiment 2 was to assess the extent of immediate phase correction in tapping and circle drawing when performed separately or simultaneously in synchrony with a metronome. Experiment 2 differed from Experiment 1 in only two respects: There was no continuation phase, and the auditory pacing sequences contained local timing perturbations (phase shifts) that were expected to elicit phase correction responses (PCRs). Our analyses focused on these PCRs. We expected them to be smaller in circle drawing than in tapping but nevertheless systematically related to the magnitude of the phase shifts in the pacing sequence, perhaps more so than in Studenka's (2008) research. We also wondered at what point in the circle drawing cycle phase correction following a phase shift would first become evident. In tapping, the PCR can only be assessed at the time of the next tap, but in circle drawing the gradual evolution of phase correction can be observed in the continuous movement.

Method

Participants

The participants were the same as in Experiment 1, minus one graduate student (a violinist) who was no longer available. Several months had elapsed since Experiment 1, during which the participants had performed in a variety of other experiments that often involved right-hand tapping but never left-hand tapping or circle drawing.

Materials and Equipment

Materials and equipment were the same as in Experiment 1, except for the following differences. Each trial consisted of a tone sequence of variable length, with baseline IOIs of either 600 or 800 ms. Each sequence contained 10 phase shifts (i.e., single shortened or lengthened IOIs) whose magnitudes ranged from -15% to 15% of the baseline IOI in steps of 3%, not including zero. The order in which the 10 phase shift magnitudes occurred was determined randomly for each sequence. The number of unchanged IOIs between phase shifts ranged from 5 to 7 and was likewise a random variable; hence the variable sequence length. The first phase shift occurred at the end of the 9th, 10th, or 11th IOI.

Procedure

Participants completed six blocks of six trials each. As in Experiment 1, participants saw an instruction on the screen that told them which task (tapping, circle drawing, or both) to perform in each trial. They were informed that the sequence contained small deviations from regularity and were asked to adjust to them, so as to maintain synchrony throughout.

Analysis

The (immediate) PCR was defined as the shift of the first tap or circle target point crossing following a phase shift in the pacing sequence, relative to an estimate of when the response event might have occurred in the absence of a phase shift. Thus, we calculated the PCR as the difference between the asynchrony associated with the tone following a phase shift and the asynchrony associated with the phase-shifted tone; this is equivalent to subtracting the baseline IOI from the movement cycle duration following the phase shift. PCRs for the same phase shift magnitude in the same experimental condition were averaged across the 6 repetitions (blocks) before linearly regressing these 10 average PCRs onto phase shift magnitude. The slope of the regression line expressed the mean PCR as a proportion of phase shift magnitude. Although the individual PCR data were often quite noisy, tapping and circle drawing data were generally fit well by straight lines; mean R^2 values ranged from .85 to .95 across conditions. The mean PCR functions were highly linear in all conditions, with R^2 values ranging from .966 to .996. In order to examine the evolution of phase correction during the first circle drawing cycle following a phase shift, we conducted PCR analyses not only at the W target point but also at the three other cardinal points following a phase shift (but preceding W), in each case subtracting the W asynchrony at the phase shift from the much larger asynchrony at the cardinal point to obtain a PCR that was then regressed onto phase shift magnitude.[5]

Results

Figure 7 shows the mean PCRs (i.e., the mean slopes of the PCR functions) for all eight conditions. It is clear that circle drawing showed a healthy PCR, although it was smaller than for tapping, as predicted, $F(1, 8) = 49.75, p < .001$. Also as expected (see Repp, 2008), PCRs were larger at the slower than at the faster tempo, $F(1, 8) = 58.20, p < .001$, especially in circle drawing, as reflected in a significant interaction, $F(1, 8) = 8.54, p = .019$. The main effect of task fell short of significance, $F(1, 8) = 4.62, p = .064$, but the Activity × Task interaction was significant, $F(1, 8) = 7.75, p = .024$, because tapping showed a somewhat smaller PCR when it was accompanied by circle drawing, whereas circle drawing showed no effect of simultaneous tapping. A

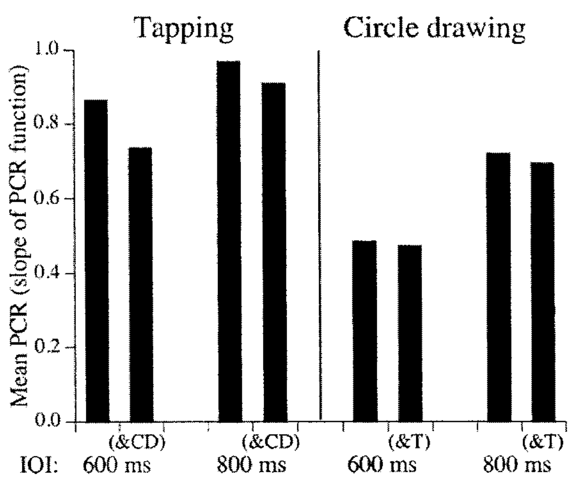

FIGURE 7. Mean phase correction responses (PCRs) in all conditions. CD = circle drawing; T = tapping.

separate analysis of the tapping data confirmed a significant task effect, $F(1, 8) = 11.54$, $p = .009$, but there was no significant interaction with tempo.[6]

Figure 8 shows the mean PCRs at the four cardinal points during the first postperturbation cycle of circle drawing. It is evident that phase correction evolved gradually during the cycle following a phase shift, with hardly any PCR at S, a clear incipient PCR at E, and about half the full PCR at N. Even at the S point, the mean PCR was significantly greater than zero in three of the four conditions, $t(8) > 3.16, p < .05$; only in the circle drawing (600) condition was there no evidence of phase correction at this early point. All participants

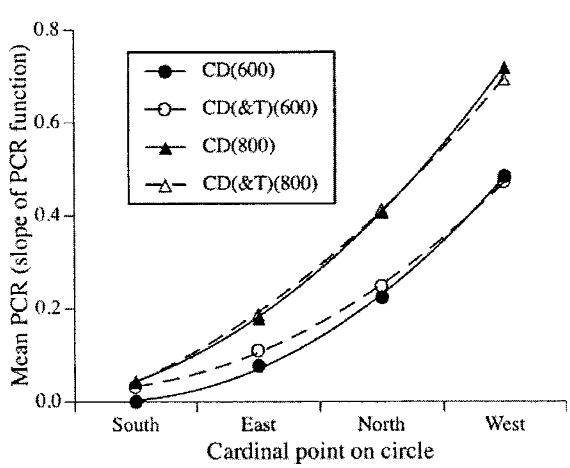

FIGURE 8. Mean phase correction responses (PCRs) at the four cardinal points in circle drawing (CD). T = tapping.

in all four circle drawing conditions showed similar patterns of PCR evolution during the first cycle following a phase shift. The mean data are fit almost perfectly by quadratic functions, as shown ($R^2 > .999$ in each case).[7]

Discussion

The mean PCRs in single-task tapping were larger than in a recent study that included very similar conditions and employed some of the same participants (Repp, 2008). This difference may be due to the use of the nondominant hand for tapping in the present study. Repp's (2008) proposed explanation of why phase correction is rarely instantaneous is that complete phase resetting is inhibited by an autonomous tendency to maintain the tapping period, and that this tendency decreases with tempo, so that the PCR increases as the tempo decreases, as was also observed in the present study. Other recent findings (Repp, in press) suggest that the maintenance tendency increases (because the PCR decreases) with practice. Thus, the maintenance tendency may have been weaker in the nondominant hand than in the dominant hand because participants had little practice tapping with that hand.

Participants also had little practice with circle drawing but nevertheless exhibited smaller PCRs than in tapping. This is easy to explain with the same concepts. It is plausible that there would be a greater maintenance tendency in circle drawing than in tapping, due to the continuous movement and the inertia connected with it. Indeed, the hypothesized maintenance tendency is equivalent to emergent timing: It is a self-referential mode of timing whose goal is continuity and stationarity; it is decoupled from the external pacing sequence and therefore inhibits phase correction. Phase correction, in our view (Repp, 2005), occurs via the coupling of discrete events (unless both the pacing signal and the movement are continuous), with the external events serving as reference points for phase resetting of the produced events. The difference between tapping and circle drawing with regard to the PCR was only one of degree. Clearly, the strong emergent timing component in circle drawing did not prevent systematic and sometimes quite rapid phase correction within the first cycle following a phase shift in the pacing sequence. In that respect the present data differ from those of Studenka (2008), who found only weak and slow phase correction in circle drawing. Her participants moved with a higher tangential movement velocity, which can be assumed to increase the maintenance tendency as well as temporal uncertainty about the target event in the trajectory. In agreement with Studenka, who considered that emergent timing may be a matter of degree, we suggest that event-based and emergent timing can coexist not only in two simultaneous tasks but also within each single task; they represent cognitive and dynamic levels of timing control that jointly determine the observable behavior.

Simultaneous tapping had no influence whatsoever on phase correction in circle drawing. The larger PCR of the discrete movement did not boost the PCR of the continuous movement. However, circle drawing inhibited the PCR of tapping somewhat, especially at the faster tempo. We tentatively attribute this to an increase in the maintenance tendency of tapping, due to either withdrawal of attention or some degree of direct coordination with circle drawing. Because previous research has suggested that phase correction in tapping does not require attention (Repp & Keller, 2004), the second possibility seems more plausible.

The continuous movement of circle drawing made it possible to trace the implementation of phase correction within a movement cycle. In agreement with the recent results of Torre and Balasubramaniam (in press), the present findings demonstrate that phase correction in circle drawing begins very soon after occurrence of the phase-shifted tone and increases gradually and nonlinearly throughout the cycle leading up to the next target point crossing. This implies a gradual change of velocity, which is consistent with emergent timing and the inertial properties of continuous motion. In the discontinuous movement of tapping, by contrast, phase correction is naturally implemented during periods of low or zero velocity (hold or dwell times, depending on tapping style), in which there is little or no resistance to change. Consistent with this hypothesis, Balasubramaniam, Wing, and Daffertshofer (2004) suggested that asymmetric movement trajectories in synchronization facilitate error correction. Recently, Elliott, Welchman, and Wing (2009) compared phase correction in tapping and finger oscillation, and found more gradual phase correction in the latter task, which they attributed to greater uncertainty about the asynchronies between movements and pacing tones. However, Repp (2005, 2008) has argued that phase correction is not based on perception of asynchronies as long as they are small; therefore, our preferred interpretation is that continuous movement results in an increased maintenance tendency (emergent timing) that inhibits phase correction.

It could be hypothesized that circle drawing relies on period correction rather than phase correction in response to perturbations. Here the strong linearity of the PCR functions is a useful diagnostic. Because earlier studies have shown that period correction is enabled or at least facilitated by conscious detection of a tempo change in the pacing sequence (Repp, 2001; Repp & Keller, 2004), the PCR function would be expected to have a shallower slope in the vicinity of zero, indicating reduced error correction near and below the detection threshold, if period correction were involved. However, there was no trace of any such nonlinearity in the present PCR functions and, therefore, we conclude that phase correction in tapping and circle drawing represents the same underlying process. The relatively large PCRs in circle drawing also confirm that perception of asynchronies, which are poorly defined in circle drawing, did not play an important role. Rather, as in tapping, phase correction in circle drawing can be conceptualized as phase resetting in response to the preceding pacing tone, which the two tasks have in common. While the principle of phase resetting thus is likely to be the same in the two tasks (contrary to what Torre & Balasubramaniam [in press] seem to have argued), its implementation differs because different movements differ in their resistance to change and in the precision with which they define discrete events for cognitive timing.

CONCLUSIONS

In the present study, we explored a new paradigm in which tapping and circle drawing, two tasks paradigmatic of event-based and emergent timing respectively, were carried out simultaneously. Comparisons with appropriate single-task control conditions indicated that the typical characteristics of each activity were largely preserved in the dual-task condition, even though the activities were coordinated rhythmically with each other or with a metronome. This shows that event-based and emergent timing can coexist in two separate tasks, carried out with different hands. We have also shown that circle drawing exhibits clear phase correction in response to timing perturbations in a pacing sequence, although the process is less effective than in tapping. We attribute this to the dynamics of continuous movement in circle drawing, which makes the trajectory more resistant to change than in the case of discrete tapping movements, and to the poor definition of temporal reference events in circle drawing. The continuous dynamics are also responsible for the emergent timing qualities of circle drawing, but we suggest emergent timing is a matter of degree and can (and usually does) coexist with event-based timing even in a single task. Event-based timing requires discrete events to be timed, and the clarity with which such events are delineated in a particular experimental situation will determine the relative strength of the event-based timing component. The continuity of the movement is largely what determines the relative strength of emergent timing. Synchronization with a metronome requires event-based timing. By viewing each task as a particular combination of emergent and event-based timing processes, we hope to contribute to a unification of dynamic and cognitive approaches to movement timing (Pressing, 1999; Wing & Beek, 2002).

NOTES

1. We prefer *event-based timing* over *event timing* because *event-based* and *emergent* are both adjectives.
2. The direction of movement is often not specified in published studies but was generally counterclockwise (Zelaznik, personal communication, May 2009). Given this direction, a West or South target point seemed more natural to us than North or East.
3. We assumed the electronic processing delay for the tablet input to be similar to that of the MIDI input, but we did not measure it directly. Also, the 8-ms temporal resolution of the tablet added a few milliseconds to asynchronies and their variability. Therefore, the values shown in Figures 1B, 1C, 2B, and 2C contain some constant error, believed to be small. Note that comparisons between single- and dual-task conditions, comparisons between the synchronization and continuation phases, and correlational measures of circle drawing were not affected by this error.
4. Circle drawing trials occasionally showed problems that necessitated omission of data or repairs. Out of a total of 10

(participants) × 8 (blocks) × 4 (conditions) = 320 circle drawing trials, 4 complete trials, the synchronization phases of 2 trials, and the continuation phases of 8 other trials were omitted because of clear failures to synchronize (phase wrapping) or missing data. These trials came from several participants, not just a single one. An additional 16 trials exhibited local problems such as hesitations or backtracking that affected only a few cycles at most. We repaired those by deleting the erratic data points (if they were at the end of the continuation phase) or replacing them with parallel data points from another trial in the same condition.

5. There were fewer irregularities in the raw data than in Experiment 1; it seemed that participants still benefited from the circle drawing practice in Experiment 1. Only one circle drawing trial was rejected because of phase wrapping, and an additional 13 out of 9 (participants) × 6 (blocks) × 6 (trials) × 10 (phase shifts) = 3,240 individual PCR data points were lost for various reasons. One participants' tapping data from the last three blocks had not been saved because of a technical error, so her tapping data were based on the first three blocks only.

6. Some individual differences are worth mentioning. The first author showed much smaller mean PCRs than did all other participants, in tapping (0.53) and circle drawing (0.37). Thus the mean PCRs for the other participants are even somewhat larger than shown in Figure 7. An ANOVA with the first author's data excluded yielded results similar to those just reported. Although the first author's small PCRs might be due to his advanced age, they might also (or instead) reflect his long experience with synchronization tasks because a recent study has suggested that the PCR decreases with experience (Repp, in press). One participant (curiously, the one who had the largest variability of asynchronies and occasionally had shown phase wrapping in Experiment 1) showed perfect phase correction (mean PCR $\approx$ 1) in circle drawing at the slower tempo, and two other participants had mean PCRs approaching 1 in circle drawing. Thus, phase correction in response to perturbations can be quite rapid in circle drawing, even when synchronization is poor. Another participant was unique in showing consistently smaller PCRs to negative phase shifts (advances) than to positive phase shifts (delays), in tapping and circle drawing.

7. We did not pursue phase correction beyond the first cycle because, given the way the present data were tabulated and analyzed, this would have been quite laborious. Because phase correction from cycle to cycle typically follows an exponential function (see Repp, 2005), we assume that phase correction was completed within several cycles, perhaps about three at IOI = 800 ms and five at IOI = 600 ms, on average.

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REFERENCES

Aschersleben, G. (2002). Temporal control of movements in sensorimotor synchronization. *Brain and Cognition, 48*, 66–79.

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

Beek, P. J., Turvey, M. T., & Schmidt, R. C. (1992). Autonomous and nonautonomous dynamics of coordinated movements. *Ecological Psychology, 4*, 65–95.

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.

Franz, E. A., Zelaznik, H. N., & Smith, A. (1992). Evidence of common timing processes in the control of manual, orofacial, and speech movements. *Journal of Motor Behavior, 24*, 281–287.

Helmuth, L., & Ivry, R. B. (1996). When two hands are better than one: Reduced timing variability during bimanual movements. *Journal of Experimental Psychology: Human Perception and Performance, 22*, 278–293.

Hogan, N., & Sternad, D. (2007). On rhythmic and discrete movements: reflections, definitions and implications for motor control. *Experimental Brain Research, 181*, 13–30.

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., & 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*, 3–18.

Ivry, R. B., & Richardson, T. C. (2002). Temporal control and coordination: The multiple timer model. *Brain and Cognition, 48*, 117–132.

Ivry, R. B., Spencer, R. M., Zelaznik, H. N., & Diedrichsen, J. (2002). The cerebellum and event timing. In S. M. Highstein & W. T. Thach (Eds.), *The cerebellum: Recent developments in cerebellar research* (Vol. 978, pp. 302–317). New York: New York Academy of Sciences.

Keele, S. W., & Hawkins, H. L. (1982). Explorations of individual differences relevant to high level skill. *Journal of Motor Behavior, 14*, 3–23.

Keele, S. W., & Ivry, R. B. (1987). Modular analysis of timing in motor skill. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 21, pp. 183–228). San Diego, CA: Academic Press.

Keele, S. W., Ivry, R. B., & Pokorny, R A. (1987). Force control and its relation to timing. *Journal of Motor Behavior, 19*, 96–114.

Keele, S. W., Pokorny, R. A., Corcos, D. M., & Ivry, R. B. (1985). Do perception and motor production share common timing mechanisms: A correlational analysis. *Acta Psychologica, 60*, 173–191.

Kennerley, S. W., Diedrichsen, J., Hazeltine, E., Semjen, A., & Ivry, R. B. (2002). Callosotomy patients exhibit temporal uncoupling during continuous bimanual movements. *Nature Neuroscience, 5*, 376–381.

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

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.

Pressing, J. (1999). The referential dynamics of cognition and action. *Psychological Review, 106,* 714–747.

Repp, B. H. (2001). Processes underlying adaptation to tempo changes in sensorimotor synchronization. *Human Movement Science, 20,* 277–312.

Repp, B. H. (2003). Rate limits in sensorimotor synchronization with auditory and visual sequences: The synchronization threshold and the benefits and costs of interval subdivision. *Journal of Motor Behavior, 35,* 355–370.

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. (in press). Sensorimotor synchronization skills in relation to music training and task experience. *Human Movement Science.*

Repp, B. H., & Keller, P. E. (2004). Adaptation to tempo changes in sensorimotor synchronization: Effects of intention, attention, and awareness. *Quarterly Journal of Experimental Psychology, 57A,* 499–521.

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.

Roerdink, M. (2008). *Anchoring: Moving from theory to therapy.* Amsterdam: Vrije Universiteit.

Roerdink, M., Ophoff, E. D., Peper, C. E., & Beek, P. J. (2008). Visual and musculoskeletal underpinnings of anchoring in rhythmic visuo-motor tracking. *Experimental Brain Research, 184,* 143–156.

Schöner, G. (2002). Timing, clocks, and dynamical systems. *Brain and Cognition, 48,* 31–51.

Semjen, A. (1996). Emergent versus programmed temporal properties of movement sequences. In H. Helfrich (Ed.), *Time and mind* (pp. 23–43). Seattle: Hogrefe & Huber.

Spencer, R. M. C., & Ivry, R. B. (2007). The temporal representation of in-phase and anti-phase movements. *Human Movement Science, 26,* 226–234.

Spencer, R. M. C., & Zelaznik, H. N. (2003). Weber (slope) analyses of timing variability in tapping and drawing tasks. *Journal of Motor Behavior, 35,* 371–381.

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 doctoral dissertation, Purdue University, West Lafayette, Indiana.

Studenka, B. E., & Zelaznik, H. N. (2008). The influence of dominant versus non-dominant hand on event and emergent motor timing. *Human Movement Science, 27,* 29–52.

Summers, J. J., Maeder, S., Hiraga, C. Y., & Alexander, J. R. M. (2008). Coordination dynamics and attentional costs of continuous and discontinuous bimanual circle drawing movements. *Human Movement Science, 27,* 823–837.

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

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

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.

Treisman, M., Faulkner, A., & Naish, P. (1992). On the relation between time perception and the timing of motor action: Evidence for a temporal oscillator controlling the timing of movement. *Quarterly Journal of Experimental Psychology, 45A,* 235–263.

Turvey, M. T. (1977). Preliminaries to a theory of action with reference to vision. In R. E. Shaw & J. Bransford (Eds.), *Perceiving, acting, and knowing* (pp. 211–265). Hillsdale, NJ: Erlbaum.

Wei, K., Wertman, G., & Sternad, D. (2003). Interactions between rhythmic and discrete components in a bimanual task. *Motor Control, 7,* 134–154.

Wing, A. M. (1980). The long and short of timing in response sequences. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 469–486). Amsterdam: North-Holland.

Wing, A. M., & Beek, P. J. (2002). Movement timing: A tutorial. In W. Prinz & B. Hommel (Eds.), *Common mechanisms in perception and action—Attention and performance XIX* (pp. 202–226). Oxford: Oxford University Press.

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. (submitted). Timing processes are shared when tasks have the same goal.

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., 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.

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