The distinction between tapping and circle drawing with and without tactile feedback: An examination of the sources of timing variance

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An internal clock-like process has been implicated in the control of rhythmic movements performed for short (250–2,000 ms) time scales. However, in the past decade, it has been claimed that a clock-like central timing mechanism is not required for smooth cyclical movements. The distinguishing characteristic delineating clock-like (event) from non-clock-like (emergent) timing is thought to be the kinematic differences between tapping (discrete-like) and circle drawing (smooth). In the archetypal event-timed task (tapping), presence of perceptual events is confounded with the discrete kinematics of movement (table contact). Recently, it has been suggested that discrete perceptual events help participants synchronize with a metronome. However, whether discrete tactile events directly elicit event timing has yet to be determined. In the present study, we examined whether a tactile event inserted into the circle drawing timing task could elicit event timing in a self-paced (continuation) timing task. For a majority of participants, inserting an event into the circle drawing task elicited timing behaviour consistent with the idea that an internal timekeeper was employed (a correlation of circle drawing with tapping). Additionally, some participants exhibited characteristics of event timing in the typically emergently timed circle drawing task. We conclude that the use of event timing can be influenced by the insertion of perceptual events, and it also exhibits persistence over time and over tasks within certain individuals.

Keywords: Interval timing; Event timing; Emergent timing; Sensory feedback.

A large body of evidence supports the notion that timing in tapping and circle drawing occurs via different timing strategies, or processes. Ivry, Spencer, and Zelaznik (Huys, Studenka, Zelaznik, & Jirsa, 2010; Ivry, Spencer, Zelaznik, & Diedrichsen, 2002; Spencer, Zelaznik, Diedrichsen, & Ivry, 2003; Zelaznik et al., 2005) have demonstrated differences between tapping and circle drawing and have proposed that timing in tapping relies upon event, sometimes called clock-like, timing, whereas timing in circle drawing does not utilize an event, clock-like process. In circle drawing, timing is thought to be an emergent property of trajectory control. The

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most obvious difference between tapping and circle drawing is that the tapping task is discrete-like with pauses in movement trajectory when the finger tip contacts the tabletop, whereas the circle drawing task is smoothly produced without discernable pauses. The natural association thus, is that discrete movement timing uses an internal clock, whereas smooth movement timing emerges from trajectory control (Ivry et al., 2002; Robertson et al., 1999; Spencer et al., 2003; Zelaznik, Spencer, & Ivry, 2002). In addition, Hogan and Sternad (2007) have claimed that discrete movements form a different class from continuous movements.

Two recent studies (Studenka & Zelaznik, 2011b; Zelaznik & Rosenbaum, 2010) provide evidence that differences in timing between tapping and circle drawing may not be solely due to kinematic differences. In Zelaznik and Rosenbaum (2010), participants performed a tapping and a circle drawing task with guidance from a metronome (synchronization) and then continued to produce timed intervals after the metronome turned off (continuation). In half of the conditions, during the continuation phase of timing, a participant received auditory feedback (auditory click) at the moment when he/she reached the timing goal. The authors argued that if tapping and circle drawing were given a common perceptual goal, timing performance in these two tasks would be related, due to the sharing of a common timing process. Significant individual difference correlations, not previously shown, were seen between some conditions of the tapping and circle drawing tasks that were performed with discrete auditory feedback. Purportedly, a common auditory goal was shared between the two tasks, supporting the notion that kinematic differences between tapping and circle drawing are not always sufficient to show that these tasks do not share a common timing process.

In another study, participants performed synchronization tapping and circle drawing with or without an inserted tactile feedback event (Studenka & Zelaznik, 2011b). Tactile feedback was added to the timing target of the circle drawing task via a 1×2-cm piece of Velcro. The typical circle drawing task, with only a printed target, was termed the no-tactile feedback circle drawing task. Tactile feedback was removed from the tapping task by having participants tap without contacting the supporting surface of the table (no-tactile feedback tapping). Tactile feedback tapping required a participant to touch the table coincident with each metronome tone. Tactile feedback circle drawing required a participant to pass his/her finger over the Velcro coincident with each metronome tone. No-tactile feedback tapping required a participant to touch an "imaginary table top", at the level of the actual table, coincident with each metronome tone. No-tactile feedback circle drawing required a participant to pass his/her finger over a printed timing target coincident with each metronome tone. The rate and completeness of correction to a perturbation of one interval was calculated as the number of intervals required for returning to a synchronization mode with the metronome and by the proximity of the participant's postperturbation asynchronies to their preperturbation asynchronies. Complete correction was seen for tasks with tactile feedback events, whereas incomplete and more prolonged correction was seen for the no-tactile feedback circle drawing task. Thus, events in movement need not be kinematic; events can also be perceptual in nature. However, whether or not the tactile feedback given on the circle drawing task elicited event timing (an internal clock) warranted further exploration and was the basis for the present study.

The Wing and Kristofferson (1973) model of timing is one of the most employed models for the study of event timing. According to Wing and Kristofferson, interval duration is composed of the interval produced by an internal clock plus the duration of a subsequent motor delay minus the duration for the preceding motor delay. The variance of a series of intervals can be decomposed into respective clock and motor variance components. Assuming independence between and within clock and motor delay intervals, the lag one autocovariance of the interval time series approximates the motor implementation variance in timing. The clock variance can then be derived by subtracting the calculated motor variance from

the total variance. The correlation of a time series of interval durations with the same time series lagged by one interval should fall between –.5 and 0. This prediction of the Wing and Kristofferson model has been supported for tapping data (Greene & Williams, 1993; Semjen, Schulze, & Vorberg, 2000; Williams, Woollacott, & Ivry, 1992; Wing & Kristofferson, 1973). Tasks believed to be timed emergently do not exhibit lag one autocorrelation between –.5 and 0 (Delignières, Torre, & Lemoine, 2008; Studenka & Zelaznik, 2008). Therefore, one generally accepted indicator that a task uses event timing is the presence of lag one autocorrelation between –.5 and 0 (seen in table tapping) and likewise a correlation of timing variability with timing variability of the event-timed table tapping task (Robertson et al., 1999; Zelaznik, Spencer, & Doffin, 2000). Significant negative lag one covariance values were previously reported for tapping and some circle drawing tasks with auditory feedback goals indicating that perceptual goals are sometimes sufficient for eliciting behaviour characteristic of event timing (Zelaznik & Rosenbaum, 2010). However, whether or not a nonauditory feedback event would also elicit behaviour characteristic of event timing has yet to be shown.

Lag one covariance analysis could not be performed in the study involving tactile feedback because participants performed timing only in synchronization, and the Wing and Kristofferson (1973) model assumes a negligible role of feedback and error correction clearly present during synchronization (Studenka & Zelaznik, 2011b). Thus, it remains unclear whether tactile feedback at the timing target in the tactile feedback circle drawing task elicited event timing (Studenka & Zelaznik, 2011b). Furthermore, each participant performed the four tasks in a different order, making the use of individual difference correlations problematic. The main aim of the current study was to further the findings of Zelaznik and Rosenbaum (2010) with respect to tactile feedback and timing. In the study conducted by Zelaznik and Rosenbaum, participants received additional auditory feedback upon completion of a cycle of timing. It was unclear whether the correlation

seen between some conditions of tapping and circle drawing was driven by the addition of an auditory event related to each cycle completion, or to the more general addition of a specific event in each movement cycle. Additionally, the correlation between tapping and circle drawing was only seen in the slower (800 ms per cycle) conditions. The current study was performed in order to assess the role of tactile feedback in eliciting event timing during a continuation task, using the same feedback manipulations as those used in Studenka and Zelaznik (2011b). If tactile feedback elicits event timing in the circle drawing condition, characteristics of event timing, including the classic lag one autocorrelation between –.5 and 0, and an individual difference correlation (using coefficient of variation) with tactile feedback tapping should be observed. A lack of event-timing characteristics in the no-tactile feedback tapping and circle drawing tasks will lend additional support for the hypothesis that timing events can be perceptual as well as kinematic. In addition, we expected to observe significant correlations for motor variance (calculated using the Wing and Kristofferson model) within the tapping tasks and within the circle drawing tasks. In theory, clock variance cannot be computed for trials that do not fit the Wing and Kristofferson model. Because trials that fit the model are thought to exhibit event timing, and only these trials are used to calculate clock variance, it is reasonable to expect that clock variance will be correlated for all tasks, even though some tasks had fewer trials that fitted the Wing and Kristofferson model. We hypothesize, however, that clock-like timing for tasks that do not typically exhibit event timing will be less systematic and more variable, leading to lower overall correlation with clock-timed tasks. Therefore, we expected high correlations for clock variance within the no-tactile feedback and within the tactile feedback tasks.

Method

Participants

Forty university students and faculty (14 male, 26 female) with a mean age of 25.2 ($SD = 4.3$) years participated. Four of these participants were

excluded from further analysis due to coefficient of variation values larger than three times the sample standard deviation. Participants used for analysis (13 male, 23 female) had a mean age of 25.4 ($SD = 4.2$) years. Thirty-three participants were right-handed, and three were left-handed. Participants had an average of 6.3 ($SD = 7.7$) years of musical experience. Informed consent procedures were in accordance with local ethical guidelines and conformed to the Declaration of Helsinki.

Apparatus and tasks

Participants were seated at an 80-cm-high table. Four tasks were performed: tactile feedback tapping, tactile feedback circle drawing, no-tactile feedback tapping, and no-tactile feedback circle drawing. Tactile feedback tapping required a participant to touch the tabletop with his or her index finger, coincident with each metronome beat and in regular intervals after the beats terminated. For no-tactile feedback tapping, a platform with a 6 × 6-cm cut-out was placed on the table, allowing for tapping without table contact (see Figure 1a). A participant situated the platform so that tapping was comfortable and so that the finger did not hit the edges of the cut-out during the tapping movement. No-tactile feedback tapping required a participant to reach the level of the tabletop coincident with the metronome beat. For the circle drawing tasks, a printed template with a circle 7 cm in diameter was taped to the table. At the top of this circle (most distal from the participant; 12 o'clock), a 1 × 2-cm printed mark served as the timing target. For tactile feedback circle drawing, a Velcro strip 1 × 2 cm was taped over the black mark on the circle template (see Figure 1b). A transparency sheet was taped over the top of the template, and for tactile feedback circle drawing, a 1 × 2-cm hole was cut out, allowing for the Velcro to show through. A participant was instructed to pass his or her finger over the mark coincident with the metronome beat and to continue to produce circles at the same rate once the metronome had turned off. The finger stayed in contact with the transparency sheet on the tabletop during the entire trial. Accuracy and
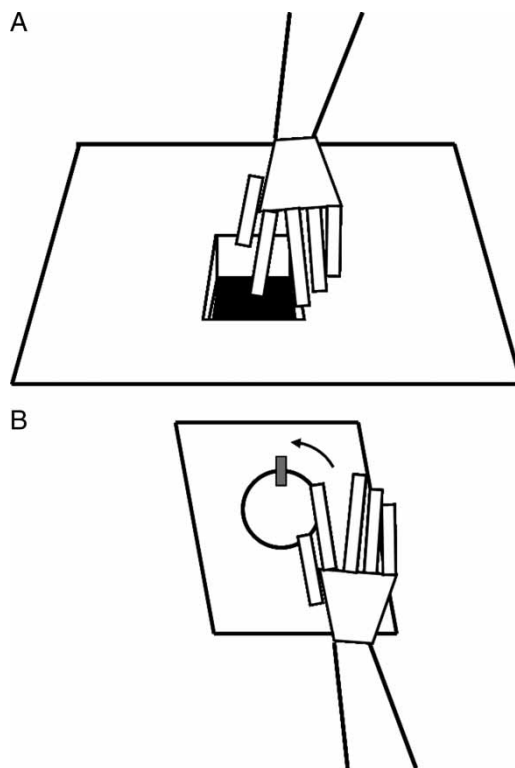

Figure 1. *Picture of (a) the no-tactile feedback tapping task, and (b) the tactile feedback circle drawing task (Velcro depicted by the grey rectangle at the top of the circle).*

consistency of timing rather than the spatial aspect of drawing were emphasized.

Procedure

Upon entering the lab, tasks were explained to participants, and informed consent was obtained. Prior to performing each condition, participants performed one practice trial. A trial began when the experimenter asked whether a participant was "ready", after which the metronome engaged, and the participant moved in synchrony with it. The metronome tone (15 ms, 800 Hz) sounded 17 times at 500-ms intervals, after which the metronome turned off, and participants attempted to move at the prescribed pace. Enough time was given to allow for an additional 35 intervals of movement at the prescribed pace. A trial ended with an 800-ms, higher pitched, tone (1,000 Hz).

Participants were given 20 s of rest between trials. Each session included 12 trials for each of four tasks. A session lasted about one hour.

Design

The design was a 2 (feedback condition: no-tactile vs. tactile) × 2 (task: tapping vs. circle drawing) design. Tactile feedback indicated when participants had reached one position (the timing target) in each movement cycle. The no-tactile feedback condition indicated that participants did not contact discrete tactile feedback anywhere in the movement cycle. To allow for individual difference correlations, each participant performed all tasks in the same order (tactile feedback tapping, tactile feedback circle drawing, no-tactile feedback tapping, no-tactile feedback circle drawing).

Data collection and reduction

Kinematic data were collected using a Vicon Nexus (Vicon Motion Systems, Oxford, UK) motion capture system. A reflective Vicon marker (14 mm in diameter) was placed on a participant's index finger. Data were sampled at 200 Hz. The kinematic data were filtered using a low-pass, 5th-order Butterworth filter. The end of each cycle was scored based on a graphical routine in Matlab (Mathworks, Natick, MA). The time series of inferior–superior movement for tapping and anterior–posterior movement for circle drawing was plotted, and cycle end points were marked at points when the trajectory crossed a location criterion. For tapping, this criterion was the z-position (inferior–superior dimension) of a marker placed on the table. For circle drawing, this criterion was the x-position (medial–lateral dimension) of a marker centred over the (printed or Velcro) mark on the sheet of paper. Additionally, cycle end points were marked at points when the velocity reached 3% of maximal velocity toward the timing target. Biberstine, Zelaznik, Kennedy, and Whetter (2005) showed that scoring cycles via the location versus the velocity criterion slightly increased the variability of circle drawing; however, the location and velocity criterion were not directly compared for table tapping. Timing for no-feedback tapping, in

particular, may benefit from perceptual information received at the point of maximal flexion, suggesting that variance in timing might be lower scored from the minimal velocity criterion than from the location of the tabletop.

Cycle duration was calculated for the continuation portion of each trial (30 intervals) as the duration from the end of one cycle of movement to the end of the next cycle of movement. This series of cycle durations was linearly detrended, removing any within-trial drift. Averages for cycle duration and variability were calculated per trial and were then averaged over the best 10 trials per condition for each participant. The coefficient of variation was calculated as the standard deviation divided by the mean of the movement cycles, converted to a percentage. Lag one covariance was computed for each trial as the covariance between the cycle duration time series, and this same time series shifted by one position. The values for clock and motor variance were calculated based on the Wing and Kristofferson (1973) derivations and a modification outlined by Vorberg and Wing (1996) to account for statistical biases due to small sample size and sequence length. In addition, autocorrelations in a time series (autocovariance/variance) indicated the fit of the series to the Wing and Kristofferson model. Lag one autocorrelation between −.5 and 0 indicated that intervals were negatively correlated and fell under the assumptions of the Wing and Kristofferson model. In order to assess whether the tactile feedback manipulation unintentionally changed the task kinematics, normalized mean squared jerk was calculated for each trial of movement. The value of jerk was normalized by multiplying jerk by the interval duration raised to the fifth power, divided by distance in centimetres squared (see Teulings, Contreras-Vidal, Stelmach, & Adler, 1997).

It may be that, even though normalized mean squared jerk was low for circle drawing, addition of tactile feedback reduced variability at the timing target (also known as anchoring). A reduction of variability at the timing target for tactile feedback circle drawing would indicate that feedback changed circle drawing kinematics,

which was not our intent. Therefore, an analysis was performed on the phase plane of each task in order to assess kinematic changes (spatial anchoring effects) driven by the feedback manipulation (see Fink, Foo, Jirsa, & Kelso, 2000). The time series of continuation intervals was normalized so that movement displacement would fall between −1 and 1. The inferior–superior dimension of movement was used for tapping, and the anterior–posterior dimension of movement was used for circle drawing, which meant that, for circle drawing, at movement reversal (close to the timing target), a participant had zero velocity in the relevant dimension. Velocity of the trajectory was calculated and normalized based on the maximal absolute velocity. Velocity was plotted against displacement for each interval (a phase plane). Cycles were determined as the movement trajectory between two scored points when a participant reached the timing target and the next time the target was reached. Cycles were normalized to 100% (100 data points). Using (0,0) as the midpoint in a Cartesian plane, the angle in degrees was measured to each point on the trajectory (100 points) cycle by cycle. For points that had negative displacement values, the calculated angle was subtracted from 180 degrees. Circle drawing movement reached the timing target at a zero-degree phase angle. A 180-degree phase angle represented the place where movement reached the point opposite the timing target. For each trial, the radius values (distance from the middle of the circle to the drawing trajectory) of 30 intervals were recorded at both 0 and 180

degrees. A smaller standard deviation of phase plane radius near the timing target, when compared to other places on the circle, indicated a larger anchoring effect.

Results

Location versus velocity scoring criterion

The coefficient of variation for each condition and scoring criterion was calculated (see Table 1). A 2 (scoring criterion) $\times$ 2 (feedback condition) $\times$ 2 (task) analysis of variance (ANOVA) was run to test for a significant influence of scoring criterion. The coefficient of variation scored from the location criterion (4.1%) was significantly greater than the coefficient of variation scored from the velocity criterion (3.9%), $F(1, 35) = 33.76$, $p < .0001$. Additionally, there was a significant Task $\times$ Scoring Condition interaction, $F(1, 35) = 35.30$, $p < .0001$, reflecting a significant difference between scoring criterion within the circle drawing (3.1, 2.7% for location and velocity, respectively), $F(1, 35) = 73.47$, $p < .0001$, but not within the tapping task (5.0, 5.0%; $F < 1$). There were no other significant interactions involving scoring method. A contrast between the location (5.6%) and velocity (5.6%) scoring criterion for no-feedback tapping was not significant, $F < 1$, indicating that where cycles were scored did not influence the variance of no-feedback tapping. A contrast between the location (4.5%) and velocity (4.4%) scoring criterion for feedback tapping was also not significant, $F < 1$. Based on the task goal of reaching a specified location at the onset

Table 1. *Descriptive statistics*

Task	CD (ms)	CV (%)	CV (%)[a]	Trials (No.)	Part. (No.)	NMSJ	VarM (ms²)	VarN (ms²)
Tactile feedback tapping	496	4.5	4.4	8.5	28	3,203	547	494
Tactile feedback circle drawing	503	3.1	3.1	2.7	15	911	271	250
No-tactile feedback tapping	488	5.6	5.6	6.9	16	1,314	835	888
No-tactile feedback circle drawing	500	3.1	2.7	5.5	8	801	264	241

Note: CD = cycle duration; CV = coefficient of variation; Trials = number of trials with autocorrelation between −.5 and 0; Part. = number of participants with significant autocorrelation between −.5 and 0; NMSJ = normalized mean squared jerk; VarM = variance of trials that fitted the Wing and Kristofferson (1973) model; VarN = variance of trials that did not fit the Wing and Kristofferson model.
[a]CV based on the velocity criterion.

of each metronome tone, and no significant difference between scoring criterion for no-feedback tapping with respect to coefficient of variation, cycle durations scored using the location criterion were used for all analyses.

Descriptive statistics

The 10 best trials (based on the smallest coefficient of variation values) of each condition were used for all descriptive statistics. The coefficient of variation was significantly larger for tapping (5.0%) than for circle drawing (3.1%) tasks, $F(1, 35) = 190.58$, $p < .0001$ (see Table 1), and these values fall within a normal range based on previous studies. As expected, the coefficient of variation was significantly larger for no-tactile (4.3%) than for tactile (3.8%) feedback conditions, $F(1, 35) = 51.14$, $p < .0001$. A significant Task × Feedback Condition interaction, $F(1, 35) = 55.56$, $p < .0001$, indicated that no-tactile feedback tapping had a significantly larger coefficient of variation than tactile feedback tapping, $F(1, 35) = 104.85$, $p < .0001$, whereas the coefficient of variation for tactile feedback circle drawing did not differ from that for no-tactile feedback circle drawing, $F < 1$, indicating that removing tactile feedback increased variability of tapping timing, but increasing the tactile feedback did not significantly reduce the variability of circle drawing timing.

Tapping tasks had significantly larger values of normalized mean squared jerk (2,265) than circle drawing tasks (857), $F(1, 35) = 825.21$, $p < .0001$ (see Table 1). The tactile feedback conditions had significantly larger normalized mean squared jerk (2,057) than the no-tactile feedback conditions (1,061), $F(1, 35) = 664.21$, $p < .0001$. A significant Feedback × Task interaction, $F(1, 35) = 636.27$, $p < .0001$, indicated a larger difference between the normalized mean squared jerk of tactile and no-tactile feedback tapping (1,889 ms), $F(1, 35) = 1,435.15$, $p < .0001$, than between tactile and no-tactile feedback circle drawing (110 ms), $F(1, 35) = 4.89$, $p = .03$ (see Table 1). Tactile feedback did have slightly higher jerk than no-tactile feedback circle drawing, indicating that tactile feedback may have

caused circle drawing to become more discrete; however, the normalized mean squared jerk of both tapping tasks was greater.

Wing and Kristofferson analysis

In order to assess the values of clock and motor variance, it is important to examine trials in which the predictions of the Wing and Kristofferson (1973) model are not violated. Violations of these predictions on certain trials could be due to nonindependent clock- or motor-related processes. In other words, trials that meet the assumptions of the Wing and Kristofferson model are thought to infer event timing. Therefore, we conducted the calculations of clock and motor variance on a subset of trials (out of the best 10) for each condition in which the lag one autocorrelation fell between −.5 and 0. Additionally, a chi-squared test was run to assess whether more participants exhibited lag one autocorrelation that fitted the Wing and Kristofferson model for the tactile feedback than for the no-tactile feedback conditions. Whether or not a participant exhibited significant lag one autocorrelation between −.5 and 0 was determined by examining the autocorrelation confidence interval of 10 trials per participant. If the confidence interval range was less than 0 and greater than −.5, the participant was deemed to be using event timing for a certain task. In Table 1, the number of participants who significantly fitted the model for all task and feedback conditions is presented. More participants fitted the model for tapping (43) than for circle drawing (23); $\chi^2(1) = 11.2$, $p = .0008$. Additionally, more participants fitted the model for tactile feedback (43) than for no-tactile feedback (23); $\chi^2(1) = 11.2$, $p = .0008$. Within tapping, more participants fitted the model for tactile feedback (28) than for no-tactile feedback (15); $\chi^2(1) = 9.8$, $p = .002$. Within circle drawing, more participants fitted the model for tactile feedback (15) than for no-tactile feedback (8); $\chi^2(1) = 3.1$, $p = .08$.

Reliability

In order to validate the correlation analysis, test–retest reliabilities for coefficient of variation and clock and motor variance of each task were

Table 2. *Reliabilities for coefficient of variation and clock and motor variance of each task*

Task	CV	CV[a]	Clock variance[a]	Motor variance[a]
Tactile feedback tapping	.99	.99	.78	.84
Tactile feedback circle drawing	.99	.99	.77	.84
No-tactile feedback tapping	.97	.99	.83	.76
No-tactile feedback circle drawing	.99	.99	.65	.85

Note: $N = 36$. CV = coefficient of variation.
[a]Values calculated with only trials that exhibited lag one autocorrelation between −.5 and 0.

Table 3. *Individual differences in coefficient of variation correlations*

	Tactile feedback circle drawing	No-tactile feedback tapping	No-tactile feedback circle drawing
Tactile feedback tapping	.37[a]	.62[a]	.47[a]
Tactile feedback circle drawing		.23	.84[a]
No-tactile feedback tapping			.25

Note: $N = 36$.
[a]Indicates significance at $\alpha = .05$.

calculated using standardized Cronbach's coefficient alpha. All tasks showed high reliability (see Table 2).

Individual differences

Individual difference correlations were calculated using the coefficient of variation of the best 10-trial data set (see Table 3). The main prediction of a significant correlation between tactile feedback tapping and tactile feedback circle drawing (.37) was supported. Additionally, a significant correlation was found between tactile feedback tapping and no-tactile feedback tapping (.62). The correlation between tactile feedback tapping and no-tactile feedback circle drawing (.47) was surprising because these two tasks have not been previously correlated. There was also a correlation between tactile feedback circle drawing and no-tactile feedback circle drawing (.84).

Individual difference correlations were also calculated using the coefficient of variation of the data set containing only trials that fitted the Wing and Kristofferson (1973) timing model (see Table 4). For this data set, the correlation between tactile feedback tapping and tactile feedback circle drawing was significant (.37). Correlations were

Table 4. *Individual differences in coefficient of variation correlations for only trials with lag one autocorrelation between −.5 and 0*

	Tactile feedback circle drawing	No-tactile feedback tapping	No-tactile feedback circle drawing
Tactile feedback tapping	.37[a]	.69[a]	.46[a]
Tactile feedback circle drawing		.28	.76[a]
No-tactile feedback tapping			.30

Note: $N = 36$.
[a]Indicates significance at $\alpha = .05$.

also observed between tactile feedback tapping and no-tactile feedback tapping (.69), tactile feedback tapping and no-tactile feedback circle drawing (.46), and tactile feedback circle drawing and no-tactile feedback circle drawing (.76).

A significant correlation for the coefficient of variation could be due to shared clock and/or

Table 5. *Individual differences in clock variance correlations*

	Tactile feedback circle drawing	*No-tactile feedback tapping*	*No-tactile feedback circle drawing*
Tactile feedback tapping	.27	.53[a]	.24
Tactile feedback circle drawing		.44[a]	.33
No-tactile feedback tapping			.43[a]

Note: $N = 36$.
[a]Indicates significance at $\alpha = .05$.

motor variability. Therefore, in an attempt to support that the coefficient of variation correlation between tactile feedback tapping and tactile feedback circle drawing was due to a shared clock and to explore why tactile feedback tapping and no-tactile feedback circle drawing were correlated, we also examined individual difference correlations in clock and motor variability between tasks using trials that obeyed the Wing and Kristofferson (1973) model (see Tables 5 and 6).

There was a significant correlation in the clock variability between tactile feedback tapping and no-tactile feedback tapping (.53), between tactile feedback circle drawing and no-tactile feedback tapping (.44), and between no-tactile feedback tapping and no-tactile feedback circle drawing (.43). These results do not lend support to the prediction that the correlation between tactile feedback tapping and tactile feedback circle drawing was due to a shared clock process. It is important to note

that these correlations were based on a significantly smaller number of trials for the no-tactile feedback circle drawing condition than for the other conditions. The only significant correlation for motor variance was between tactile feedback and no-tactile feedback circle drawing (.63). Because neither clock nor motor variance showed significant correlation between tactile feedback tapping and tactile feedback circle drawing or between tactile feedback tapping and no-tactile feedback circle drawing, we sought additional explanation as to what drove the original covariance correlation between these two tasks.

Additional analyses

The correlation for the coefficient of variation between tactile feedback tapping and no-tactile feedback circle drawing was surprising. This correlation is not consistent with previous research and may have been caused by the unique conditions and order of tasks in the present experiment. In the present experiment, the tactile feedback tapping task was performed first and the no-tactile feedback circle drawing task fourth in a series of tasks that all exhibited some degree of event-like timing. If the correlation in coefficient of variation was driven by a persisting clock variance, we should have seen that the clock component of tactile feedback tapping and no-tactile feedback circle drawing was correlated; conversely, if the correlation in coefficient of variation was driven by a persisting motor component, we would expect to see a correlation in the motor variance of these two tasks. For the full group of participants (36), no significant correlation in clock or motor variance was seen. We postulated that there might be a subset of participants uniquely

Table 6. *Individual differences in motor variance correlations*

	Tactile feedback circle drawing	*No-tactile feedback tapping*	*No-tactile feedback circle drawing*
Tactile feedback tapping	.25	.30	.19
Tactile feedback circle drawing		.22	.63[a]
No-tactile feedback tapping			.08

Note: $N = 36$.
[a]Indicates significance at $\alpha = .05$.

influenced by the order of tasks. The most obvious subset would be participants who exhibited atypical (event-like) timing in the no-tactile circle drawing task. Based on an average of all trials performed (12), 8 participants exhibited significant lag one autocorrelation between −.5 and 0 in the no-tactile feedback circle drawing task. All trials were used instead of the aforementioned 10 best trials in order to determine which participants were using a more event-timing strategy overall, not only on the trials with the lowest coefficient of variation. Therefore, correlations were computed on the coefficient of variation, clock variance, and motor variance of the subset of 28 participants who did not exhibit clock-like behaviour in the

no-tactile feedback circle drawing task (see reliabilities in Table 7 and Tables 8, 9, and 10). The correlation in coefficient of variation between tactile feedback tapping and no-tactile feedback circle drawing persisted (.68); however, a significant correlation in the motor variance (.45), but not clock variance (.30) of these two tasks was now seen. This correlation suggests that the driving force behind the correlation between tactile feedback tapping and no-tactile feedback circle drawing was related to the motor variance. Furthermore, there was a significant correlation between the clock variance of tactile feedback tapping and tactile feedback circle drawing for this subset of participants (.41) supporting our

Table 7. *Reliabilities for a subset of participants*

Task	CV	CV[a]	Clock variance[a]	Motor variance[a]
Tactile feedback tapping	.99	.99	.75	.85
Tactile feedback circle drawing	.99	.98	.71	.64
No-tactile feedback tapping	.98	.99	.83	.68
No-tactile feedback circle drawing	.99	.99	.90	.55

Note: $N = 28$. CV = coefficient of variation.
[a]Values calculated with only trials that exhibited lag one autocorrelation between −.5 and 0.

Table 8. *Individual differences in coefficient of variation correlations for trials with lag one autocorrelation between −.5 and 0, for a subset of participants*

	Tactile feedback circle drawing	No-tactile feedback tapping	No-tactile feedback circle drawing
Tactile feedback tapping	.55[a]	.68[a]	.68[a]
Tactile feedback circle drawing		.22	.70[a]
No-tactile feedback tapping			.30

Note: $N = 28$.
[a]Indicates significance at $\alpha = .05$.

Table 9. *Individual differences in clock variance correlations for a subset of participants*

	Tactile feedback circle drawing	No-tactile feedback tapping	No-tactile feedback circle drawing
Tactile feedback tapping	.41[a]	.56[a]	.30
Tactile feedback circle drawing		.36	.30
No-tactile feedback tapping			.46[a]

Note: $N = 28$.
[a]Indicates significance at $\alpha = .05$.

Table 10. *Individual differences in motor variance correlations for a subset of participants*

	Tactile feedback circle drawing	No-tactile feedback tapping	No-tactile feedback circle drawing
Tactile feedback tapping	.37	.31	.45[a]
Tactile feedback circle drawing		.04	.34
No-tactile feedback tapping			−.05

Note: $N = 28$.
[a]Indicates significance at $\alpha = .05$.

main expectation that tactile feedback elicits event timing in circle drawing. It is of note that the reliabilities of the clock and motor variance for this subset were not as good as those for the group of 36 participants.

In a more homogeneous set of participants (those that did not exhibit clock-like timing for the no-tactile circle drawing task), motor variance appeared to be driving the correlation between tactile feedback tapping and no-tactile feedback circle drawing. This seeming persistence of motor variance from the first task(s) performed into the next task has not been previously documented and might be considered in the design of future timing experiments. Additionally, it is unclear what aspect of motor variance could have carried over into the circle drawing task as this movement appeared cyclical without discernable pauses. An additional spatial anchoring analysis was performed in order to assess whether or not variability at the location of the timing goal was influenced by tactile feedback. Correlations could not be computed on only 8 participants; therefore, it remains uncertain which correlations might exist for those participants who did exhibit event-like timing in the no-tactile circle drawing task.

Spatial anchoring analysis

The standard deviation of the phase plane radius values at 0 and 180 degrees was calculated for each trial. These values were averaged over trials and participants, and a 2 (task) × 2 (feedback condition) × 2 (phase plane angle; 0 vs. 180 degrees) ANOVA was run. A significant Task × Feedback Condition interaction, $F(1, 35) = 168.05$, $p < .0001$, was driven by the small standard deviation of the radius in the tactile feedback tapping condition (.07) versus the no-tactile feedback tapping condition (.12; see Figure 2). Spatial variability did not differ for the 0-degree location between tactile and no-tactile feedback circle drawing, $F < 1$, indicating that participants were
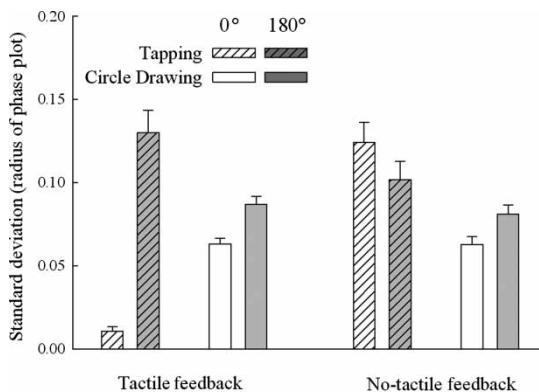

Figure 2. *Standard deviation of the radius of phase plane angles for tapping and circle drawing in tactile and no-tactile feedback conditions. Error bars represent standard error.*

not changing their anchoring strategy based on the presence or absence of tactile feedback events. However, the presence of anchoring in the no-tactile feedback circle drawing task, despite other research indicating no anchoring for circle drawing (Studenka & Zelaznik, 2011a), does suggest that having performed other tasks with events may have elicited more anchoring in no-tactile feedback circle drawing, increasing the motor variance.

Discussion

We found that adding a discrete, perceivable event influenced the structure of timing variability for circle drawing. Adding an event to circle drawing increased the number of trials as well as participants exhibiting lag one correlation between −.5 and 0. Furthermore, the effect of event information was independent of the task kinematics. Mean squared jerk and spatial anchoring at the timing target for tactile feedback and no-tactile feedback circle drawing was not different. This finding supports the hypothesis that strictly perceptual events can influence timing variability. The new results we report add an important line of evidence that the nature of perceptual feedback has strong effects on the nature of timing control.

The question of whether or not tactile feedback at the timing goal necessarily elicited event timing is more ambiguous. In the present study, it was hypothesized that, if participants used an internal clock to pace circle drawing and tapping with tactile feedback, the time series of intervals would exhibit lag one autocorrelation between −.5 and 0, and the variability in producing self-paced tactile feedback circle drawing cycles would correlate with variability in producing self-paced tactile feedback tapping. This hypothesis was supported, but only for a subset of the total 36 participants. This subset (28) was the majority and exhibited significant correlation between tactile feedback tapping and tactile feedback circle drawing for both coefficient of variation and clock variance. So, it did appear that, for most participants, tactile feedback did elicit event timing.

A minority of participants, surprisingly, exhibited characteristics of event timing in the no-tactile feedback circle drawing task. It may have been that these participants were more susceptible to the influence of the task order; the no-tactile feedback circle drawing was performed last. Jantzen, Steinberg, and Kelso (2002, 2004) provided support for the idea that practising one timing task can produce timing strategies that persist even though a different task is being performed. Jantzen et al. (2002, 2004) examined participants' brain activation during two different entrainment conditions: synchronization and syncopation. Greater brain activation was seen during performance of the syncopation task, which was attributed to greater attentional and sensory demands of tapping off the beat. With extended practice at this task, the level of brain activation was reduced. When these same participants were tested with respect to the "easier" synchronization task, brain activation increased above that normally seen for synchronization, indicating that practising the syncopation task increased the brain activation needed for synchronization. In a follow-up study, Jantzen et al. (2004) examined the same tasks in paced and unpaced conditions. As in the Jantzen et al. (2002) study, greater and more distributed brain activation was seen when participants performed syncopation (tapping synchronous with the off-beat) than when they performed synchronization. Additionally, this increased level of brain activation carried over into the continuation task, even when no metronome was present. The authors concluded that the manner in which timing was instantiated persisted even when multiple timing strategies would achieve the same task goal, and they argued for the flexibility of timing strategies. Thus, the history of timing strategy, at least regarding brain activation, had a direct influence on the control of a subsequent timing task. Although timing strategy in both synchronized and syncopated tapping is presumed to be event-like, a similar mechanism may be at play when participants performed three tasks with a larger event-timing component than the fourth and final no-tactile feedback circle drawing task. In other words, having performed a task/tasks

with more event information may bias a participant to maintain event timing into the typically emergently timed circle drawing task.

The recent study by Zelaznik and Rosenbaum (2010) also provides insight into the persistence of timing processes. In this experiment, participants performed tapping and circle drawing, which corresponded to our tactile feedback tapping and no-tactile feedback circle drawing task. Although the main question in the Zelaznik and Rosenbaum study was whether the control of an auditory event would induce event timing in an otherwise nonevent timed task, because tapping and circle drawing were performed alternately, persistence in timing strategy from one task to the other can be examined. The first two blocks (tapping then circle drawing at 500 ms) that participants performed without auditory feedback exhibited no significant correlation, as expected. The next block was tapping at 800 ms followed by circle drawing at 800 ms. If the same timing process was used for tapping at both 500 and 800 ms, and likewise for circle drawing at both 500 and 800 ms, no correlation between tapping and circle drawing at 800 ms would be expected; however, the correlation between 800-ms tapping and circle drawing was significant (.61). The correlation between 800-ms circle drawing and 500-ms tapping was also significant (.42), indicating that the timing process used for 800-ms circle drawing might be more similar to that used for the two tapping tasks. These correlations were run on the coefficient of variation, a measure of total variance, which could be influenced by sources other than variance in the timing process; however, these results along with those of Jantzen et al. (2002, 2004) provide a preliminary framework to suggest that timing is more flexible that previously thought and that participants may have adopted timing strategies in the first three tasks of the present study that carried over to the fourth (no-tactile feedback circle drawing). The order effects seen by Zelaznik and Rosenbaum (2010), as well as the persistence effects observed by Jantzen et al. (2002, 2004) highlight the idea that the event–emergent distinction is not an all-or-none process. Our hypothesized order effects are consistent with this idea.

If emergent timing and event timing are completely separable, so that timing is solely one process or the other, practising one type of timing should not bias the other type of timing. Therefore, based on the finding that the number of trials that fitted the Wing and Kristofferson (1973) model varied both within a task and within a participant, we might contend, as Repp (2008) has, that all timing performance is influenced by both an emergent and an event component. According to Repp, something akin to momentum of movement creates an emergent inertia of the moving limb, which competes with a short-term phase correction process that is based on an internal clock. Repp showed perfect phase correction in tapping that was performed very slowly (0.83 Hz) in support of the idea that, when inertia of movement is low enough, it does not interfere with phase correction, which allowed perfect correction to be achieved. If we take this view, we can consider the emergently timed circle drawing task to have a large inertia in that, once the limb is moving, it is very difficult to adjust this movement pattern. If we pair a large inertia with a low detectability of events when the target is presented visually (i.e., no tactile or auditory information), there is little competition from phase correction, and the timing is controlled mostly via the emergent control of the moving limb dynamics. When the detectability of the timing event increases (tactile feedback is added), phase correction ability is improved and thus competes more readily with the continuous dynamics of the moving limb. This allows more clock-dependent phase correction (see Studenka & Zelaznik, 2011b), but behaviour does not approximate that of table tapping because the event and emergent properties between circle drawing with feedback and table tapping still differ. In fact, it would be difficult to experimentally equate the event and emergent properties of either task, as these properties have not been modelled. Instead, we have used a model that, strictly speaking, considers that movement variability is due to a central (clock) and a peripheral component (motor). This peripheral component is estimated via the relation of one interval to the next interval throughout the time

series, and the central component is assumed to be the "left-over" variance. In this sense, much could be contributing to the value of the clock/central variance, including nonclock, central processes that may not be shared, even between tasks that use the same or similar internal clock(s). The main point here is that the Wing and Kristofferson model can only take us so far. When we begin to compare tasks that are both kinematically and strategically different, and if we consider that event and emergent timing may not be strictly dichotomous, it is evident that much more influences timing variance than an open loop clock and implementation delays. We do not refute the notion that events improve clock-dependent timing, nor do we refute the notion of timing having event-like and/or emergent properties. Here, we have demonstrated that event-timing strategy may be represented more centrally and may be more flexible than in earlier conceptions.

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