Journal of Experimental Psychology:
Human Perception and Performance
2002, Vol. 28, No. 3, 575–588

0096-1523/02/$5.00 DOI: 10.1037//0096-1523.28.3.575

Dissociation of Explicit and Implicit Timing in Repetitive Tapping and Drawing Movements

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Four experiments explored the hypothesis that temporal processes may be represented and controlled explicitly or implicitly. Tasks hypothesized to require explicit timing were duration discrimination, tapping, and intermittent circle drawing. In contrast, it was hypothesized that timing control during continuous circle drawing does not rely on an explicit temporal representation; rather, temporal control is an emergent property of other control processes (i.e., timing is controlled implicitly). Temporal consistency on the tapping and intermittent drawing tasks was related, and performance on both of these tasks was correlated with temporal acuity on an auditory duration discrimination task. However, timing variability of these 3 tasks was not correlated with timing variability of continuous circle drawing. These results support the hypothesized distinction between explicit and implicit temporal representations.

Many tasks have clear temporal goals or require precise temporal information for their successful achievement. The distance runner establishes target times for each lap before the start of a race. The sprinter must anticipate the firing of the starter's gun to get a jump on the competition. How does an individual translate such temporal goals into an action? In this article, we present evidence to indicate that performers, depending on the nature of the task, can do so through two processes. One process depends on an explicit representation of the passage of time, what we call explicit timing. For the other process, the temporal properties of the action may be emergent (Turvey, 1977), in the sense that an explicit representation of time does not directly guide performance (Ornstein, 1969; Zeiler, 1998). We call this timing implicit as a contrast to the explicit timing process. In the examples from track and field, we expect that the sprinter relies on explicit timing to anticipate the start of the race; the distance runner adopts a pace that will produce the target lap times in an emergent manner. Four experiments are presented that lead us to conclude that the timing of movement initiation is an explicit process, whereas the timing of movement duration is an implicit one. First, we turn our attention to notions of explicit timing.

One approach to the study of timing involves describing how different neural structures and architectures can represent time. For example, Braitenberg and colleagues have proposed a model in which waves of activity across the parallel fibers of the cerebellar cortex provide a range of temporal delays that support coordinated interactions between different limb segments (see Braitenberg, Heck, & Sultan, 1997). Similarly, Rosenbaum's (1998) broadcast theory of timing is based on the idea that the distance traversed across neuronlike units forms a range of temporally tuned elements.

On a more psychological level, models of internal timing have considered both oscillatory (Treisman, Faulkner, & Naish, 1992) and interval (Ivry & Hazeltine, 1995) forms of representation. These models are behavioral, seeking to describe and explain a wide range of temporal phenomena that can be observed in many different tasks. One such task is repetitive tapping. Wing and Kristofferson (1973) proposed a two-process model to account for the variability of intertap intervals. A central timing process is presumed to regulate movement initiation, and a motor implementation process is presumed to determine when the actual response occurs. These two processes are hypothesized to contribute independently to overall timing variability, an assumption supported by a large number of studies (see Wing, 1980, 2002). Within the framework of this two-process model, the central mechanism is believed to provide an explicit representation of the target interval.

Ivry, Keele, and Diener (1988) provided neurophysiological evidence that central timing and implementation timing processes are independent. Patients with a lesion only in the medial region of a cerebellar hemisphere exhibited increases in implementation timing variance for the ipsilesional hand relative to the contralesional hand, whereas patients with localized lateral damage to a cerebellar hemisphere exhibited increases in central clocklike variability for the ipsilesional hand relative to the contralesional hand. Patients with cerebellar lesions also were impaired on a variety of

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Howard N. Zelaznik and Rebecca M. C. Spencer were supported by National Institutes of Health (NIH) Grant DC 02527, and Richard B. Ivry was supported by NIH Grants NS 30256 and 1778 and National Science Foundation Grant ECS-9873474.

We thank Tricia Martinic for help in data collection in Experiment 1, and Sarah Crain, Jennifer Marty, and Rethy Subramanian for help in data collection in Experiment 2. Special thanks to Kristi Hall, Beth Carroll, Dawn Chambers, Marie Phillips, and Mary Kaye Rueth for their assistance in data collection for Experiment 4.

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perceptual temporal processing tasks, suggesting that this structure operates as an internal timing system that is exploited for both motor and nonmotor tasks that require the precise representation of temporal information (for a review, see Ivry, 1997).

A different approach for exploring whether a common system underlies motor and perceptual timing involves examining the function relating timing variance to the interval to be timed. Across a range of tasks, temporal variability exhibits a scalar property (Gibbon, 1977; Gibbon, Malapani, Dale, & Gallistel, 1997). Variability is proportional to the interval being timed (i.e., a form of Weber's law in the temporal domain). The Weber fraction—that is, the slope of the variability function—is hypothesized to represent the noise properties of the duration-dependent, central component of timing. Ivry and Hazeltine (1995) observed that the variance of auditory duration discrimination and the variance of timing during finger tapping exhibit the same slope. Similarly, Green, Ivry, and Woodruff-Pak (1999) reported that variance in the onset of the conditioned eyeblink response is related linearly to the duration of the interval between the conditioned and unconditioned stimuli and that the Weber fraction for this function is statistically equivalent to that found for finger tapping. Ivry and colleagues concluded that equivalent Weber relations are the result of the operation of a common representational timing process, what we call explicit timing.

Individual-difference studies provide a third approach for exploring the viability of a general internal clock construct. If two tasks share a common timing process, variability in timing on one of those tasks will be predictive of variability in timing on the other task. In other words, there should be a significant positive correlation for timing variability across the two tasks. Individual differences in timing variability are correlated across movements involving different effectors such as finger and arm (Keele & Hawkins, 1982) or arm and jaw (Franz, Zelaznik, & Smith, 1992). Moreover, variability in timing in finger tapping is correlated with duration-discrimination performance (Keele, Pokorny, Corcos, & Ivry, 1985).

The studies just described provide support for the hypothesis that many tasks share a common timing process. However, the motor demands on these tasks appear to be relatively minor. For example, finger tapping, arm tapping, jaw movements, and the eyeblink response all involve movement along a single axis of rotation. Furthermore, individuals can satisfy task demands by controlling the timing of movement initiation. During eyeblink conditioning, the participant must associate the conditioned stimulus and unconditioned stimulus and learn when to initiate the eyeblink. Similarly, in repetitive tapping tasks, the participant could adopt a strategy of producing a fixed duration movement and vary the interval of time between initiations to meet the demands of the task.

It seems reasonable that, in such tasks, an explicit representation of time would be important. However, certain tasks might not require an explicit representation of time to control periodic behavior (Ivry & Hazeltine, 1992; Semjen, 1992). To examine this issue, we tested participants on two tasks, a finger tapping task and a continuous circle drawing task (Robertson et al., 1999). The period of motion of the tapping task was the same as the period of motion for circle drawing. Two important results were obtained. First, individual differences in timing variability in the tapping task were not significantly correlated with individual differences in timing variability in drawing. Second, when the cycle period was varied, the slopes of the variability function for tapping and circle drawing were not the same. Tapping had a much steeper slope than circle drawing. In a follow-up study, Zelaznik, Spencer, and Doffin (2000) showed that the differences in temporal variability across the two tasks were not due to differences in preferred rate of motion. Even when participants were allowed to adopt their preferred rate for each task, timing variability in tapping and circle drawing remained uncorrelated. Thus, we have argued (Robertson et al., 1999; Zelaznik et al., 2000) that not all timing tasks share the same explicit timing process.

In the present set of experiments, we explored the idea that the timing of movement initiation processes involves an explicit representation of time, whereas movements that are continuous may not require an explicit temporal representation. We hypothesize that, once initiated, these latter movements no longer involve explicit temporal control. Rather, temporal regularities are emergent, reflecting the operation of a different control process. We refer to this latter type of timing as implicit. The issue at hand is whether the use of explicit timing depends on movements that are relatively discrete, or at least not smooth and continuous.

To test this hypothesis, we developed a hybrid circle drawing task: intermittent circle drawing. The participant was required to insert a pause between each drawing cycle. A metronome prescribed the duration of the circle and the duration of the pause. The participant was trained to produce the two equal epochs. We assumed that the pause would require explicit timing because of the need to set the timing for movement initiation with each cycle. On the basis of our assumption that a common timing system is invoked for tasks involving an explicit temporal representation, we expected to observe a significant correlation between measures of temporal precision obtained during the repetitive tapping and intermittent circle drawing tasks. Alternatively, if the difference between tapping and drawing is due to the complexity of trajectory control, then we would expect to find tapping and intermittent circle drawing to be uncorrelated, similar to what has been observed with tapping and continuous circle drawing (Robertson et al., 1999).

Experiment 1

In Experiment 1, participants performed the repetitive tapping task, attempting to match a target interval of 1,000 ms. Participants also performed the intermittent circle drawing task, in which the goal was to draw a circle with a 500-ms movement time followed by a 500-ms pause. Both tasks were performed with the continuation procedure routinely used for studying timing.

Method

Participants. Twenty-five (7 male and 18 female) students 18–22 years of age volunteered for the experiment in exchange for payment. All participants except one were right-handed. All had normal or corrected-to-normal vision and no known neurological impairments. The Purdue University Committee on the Usage of Human Research Subjects approved recruitment of participants and informed-consent procedures.

Tasks. Two tasks were used in this study. In both, a computer-controlled metronome produced an alternating high-pitch tone (800 Hz) and a low-pitch tone (400 Hz) of 20 ms in duration. The interstimulus interval between successive tones was 500 ms. For the repetitive tapping task, the participants were instructed to tap the index finger of their dominant hand on the table coincident with the high-pitch tone (i.e., a cycle duration of 1,000 ms). We chose this duration and the metronome characteristics on the basis of pilot testing and the capabilities of our instrumentation interface. After a synchronization phase, the metronome was disengaged. During this continuation phase of each trial, participants were instructed to continue tapping at the prescribed frequency.

For intermittent circle drawing, participants were required to complete one circle during the interval between the low-pitch tone and high-pitch tone (i.e., movement time of 500 ms) and then to pause during the subsequent 500-ms interval between the two tones. Thus, they alternated every half second between circle drawing and pausing, using the tones to partition the 1,000-ms interval during the synchronization phase. They were instructed to continue in this fashion during the continuation phase.

The target diameter of the circle was 8 cm. Participants were not required to trace a circle but were guided with four 1.5-cm-diameter circles positioned at 0°, 90°, 180°, and 270° along the imagined circumference of the 8-cm target circle. In Figure 1 we present a schematic representation of the circle template. The task required participants to pass through these guides during the circle drawing task. The guide at 90° was shaded and served as the location of the on-time marker. This is where the participant's pencil needed to be when the appropriate tone was presented. Because of the relatively large size of the tracing guides relative to the circle diameter, the spatial demands of the task were low, allowing participants to give priority to the temporal aspects of the task. Instructions emphasized that the main goal was to be on time, and the template was to provide a guide for the approximate size of the circle and the location of the temporal synchrony point.

Apparatus. The response apparatus consisted of a 79-cm-high table on which a target sheet was secured. A Mars-Staedtler 2-mm pencil holder was used for the circle drawing task. The bottom portion of the pencil was wrapped tightly with adhesive tape, resulting in a 1-cm-diameter barrel. Attached below the taped portion of the pencil was an infrared light emitting diode (IRED) from a Watsmart kinematic recording system (Northern Digital, Waterloo, Ontario, Canada). For the tapping task, a Band-Aid was wrapped around the nail of the index finger of the dominant hand. The IRED was secured to the Band-Aid with Velcro.

An MS-DOS-based computer was used to generate the metronome signal. The computer was programmed to produce an alternating sequence of high (800 Hz) and low (400 Hz) tones, 20 ms in duration, with a 500-ms interstimulus interval.

Procedure. After informed consent was obtained and participants were provided with general instructions, testing began. A trial began with participants placing their finger (for tapping) or pencil (drawing) on the target circle on the tabletop. The experimenter said "Ready, begin," and the metronome was engaged. Participants entrained their movements to the metronome. When the metronome was disengaged, participants attempted to maintain the same rate during the continuation portion of the trial. After a period of time sufficiently long to produce 35 continuation movements, the trial ended with a series of five tones with a 50-ms interval between adjacent tones. In the drawing tasks, the paper containing the circle template was replaced after each trial. There was a 25-s intertrial interval.

We used the standard protocol for correlational studies examining individual differences (e.g., Keele et al., 1985; Robertson et al., 1999). Tasks were performed in a fixed order. Tapping was performed first, followed by intermittent circle drawing. Preliminary testing had revealed that producing equal pause and movement segment durations during continuation was difficult. Thus, we included a training procedure for both tasks consisting of 10 trials of 54 cycles each. On the 1st training trial, all of the movements were performed with the metronome. On each of the subsequent 9 training trials, the number of synchronization cycles decreased by 4, and the number of continuation cycles increased by 4. Thus, at the end of the 10th training trial, there were 18 synchronization and 36 continuation cycles. Participants then continued with the test phase. This phase consisted of 10 trials, each composed of 18 synchronization cycles and 36 continuation cycles.

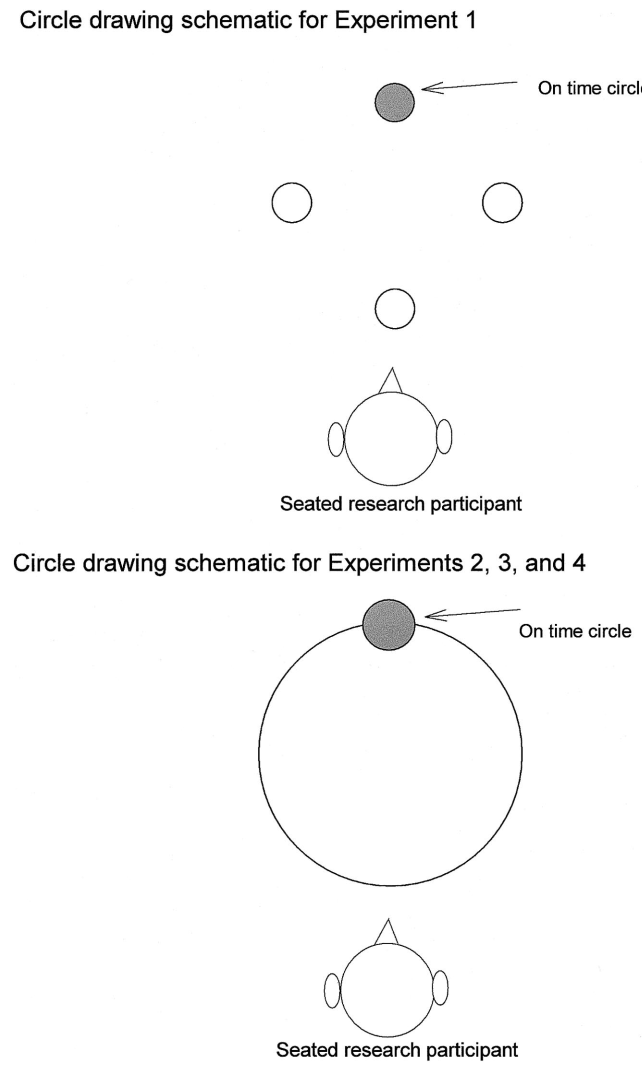

Figure 1. Schematic representation of a top view of the circle drawing tasks for the four experiments. Drawings are not to scale but are presented to give an understanding of the nature of the circle task and, in particular, to show the temporal synchronization location.

Data acquisition. A two-camera Watsmart kinematic recording system sampled the location of the IRED at 256 Hz. The three-dimensional data series were reconstructed off-line.

Results and Discussion

Data analysis and reduction. We used an interactive graphical routine to determine the cycle duration for tapping and to parse the intermittent circle drawing record into the movement and pause components. This procedure has been shown to be extremely accurate (plus or minus one sample) and reliable (interrater reliability: $r > .98$) in identifying specific target points within a movement cycle (see Robertson et al., 1999). The raw displacement record and the filtered displacement record (25 Hz, low pass, forward and backward) were displayed on a monitor. A mouse-

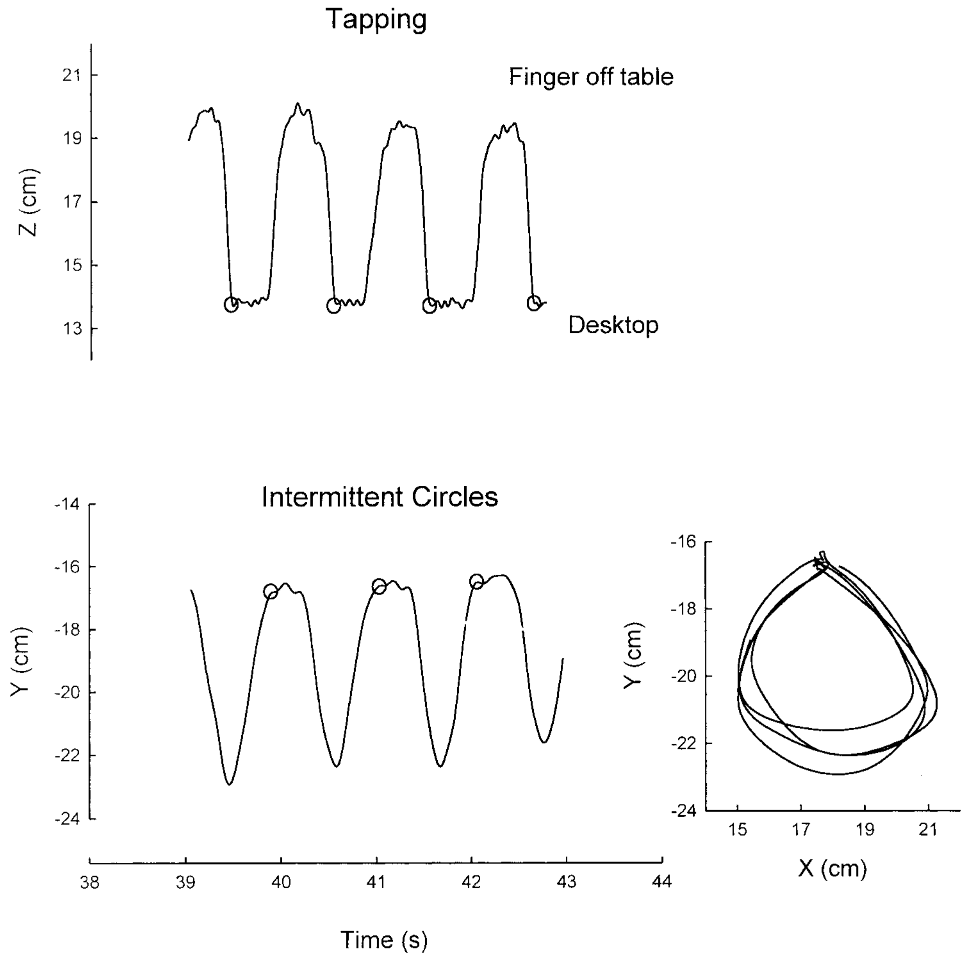

Figure 2. Representative 4-s slice of behavior in the tapping (top left) and intermittent drawing (bottom left) tasks during the continuation portion of the trial in Experiment 1. These data are not heavily filtered, and as such, the high-frequency noise apparent in the tapping and intermittent drawing trajectory during the pause portion of the movement is evident. The small circles superimposed on the trajectories represent the points in time that are the beginning of cycle *n* and the end of cycle $n - 1$. Right: In the *y* dimension, the spatial path for the intermittent drawing task for this 4-s period.

controlled crosshair was moved to mark the end of the downward movement of the index finger for tapping or the pause and movement components for intermittent drawing. On the basis of this procedure, we determined the duration of each cycle and retained the middle 31 cycles of the continuation phase for further analysis. A linear regression analysis was performed on these cycles, and the measure of timing variability was based on the residuals from the regression line. This procedure eliminates temporal variability arising from global changes in performance rate (i.e., tendency to speed up or slow down) and has been used in many studies of repetitive tapping (see Keele et al., 1985; Vorberg & Wing, 1996).[1] Because we were interested in variability in timing under the best of conditions, only the six trials with the lowest variability were included in the analyses reported subsequently (see Peters, 1989, for further logic on this issue).

Descriptive findings. In Figure 2, a typical trajectory for 4 s of continuation performance is presented for both tapping and intermittent drawing. A distinct pause can be seen during tapping as well as intermittent drawing. The descriptive data are presented in Table 1. The main dependent variable in terms of temporal variability was the coefficient of variation, computed as the standard deviation in timing divided by the mean interval. On average, the participants performed the tasks successfully, with the mean cycle duration close to the target interval of 1,000 ms. The observed coefficient of variation values were in accord with those of previous reports (e.g., Allan, 1979; Ivry & Hazeltine, 1995). The cycle for circle drawing was partitioned into movement duration and pause duration components. Participants had some difficulty in parsing the intermittent circle into equal pause and movement durations. Thus, although the participants were very successful in sustaining the overall duration, they did not maintain a 1:1 ratio of movement and pause time. The variability of these components

[1] The drift was minor in almost all cases, yielding a detrended variance that was just slightly lower than that obtained from the raw data.

Table 1
Descriptive Data for Experiment 1

	Temporal					Spatial				
Task	MT (ms)	*SE*	CV (%)	*SE*	Reliability	Displacement (cm)	*SE*	CV (%)	*SE*	Reliability
Tapping	1,019.6	11.7	6.2	0.3	.89	3.3	0.5	7.1	1.2	.85
I circle										
Total	1,030.3	11.9	5.5	1.0	.86					
Movement	653.9	14.2	7.1	0.5	.83	3.9	0.5	12.3	1.0	.88
Pause	376.4	15.7	13.2	0.5	.83					

Note. MT = average time; CV = coefficient of variation; I circle = intermittent circle drawing.

was larger (in terms of percentages) than the variability of the total cycle duration. Thus, there was greater inconsistency in maintaining the movement and pause subintervals in comparison with the total interval. Billon, Semjen, and Stelmach (1996) have argued that this type of result is indicative of a hierarchical representation of the action, with the primary temporal goal associated with maintaining the overall period.

Descriptive spatial variables also are included in Table 1. For the finger tapping task, we determined the maximum height of the IRED with respect to the tabletop. In the case of intermittent circle drawing, the center of the circle was computed on a cycle-by-cycle basis as mean x and y coordinates. Then the radius for each sample with respect to that center was calculated. For each cycle, the average radius was calculated and averaged over cycles within a trial. Within a cycle, the standard deviation of the radius was computed. This is a measure of the integrity of the circle shape, and a smaller standard deviation indicates that the trajectory is more circular. The standard deviation was converted to a coefficient of variation and then averaged across cycles. As can be seen in Table 1, the average radius of the circle was 3.9 cm, and the coefficient of variation was about 12%. The average tapping displacement was slightly greater than 3 cm with a coefficient of variation of about 7%.

Correlational analysis. Separate Subject × Trial analyses of variance (ANOVAs) were conducted for the best six trials on each task to compute reliability values for each task. Reliability, which varies between zero and one, was computed from the ANOVA by calculating the ratio of variance due to participants relative to the variance due to the trial and Participant × Trial interaction terms (see Thomas & Nelson, 1996). As can be seen in Table 1, reliability values were equal to or greater than .83. These values were similar to those observed in our previous individual-differences work (Franz et al., 1992; Robertson et al., 1999; Zelaznik et al., 2000).

The primary analyses centered on the correlation matrix between the variability scores on the two tasks. These values are presented in Table 2. With 25 participants, an r value of .37 is significant at the .05 level. There was a significant correlation between tapping and intermittent circle drawing ($r = .55$). When tapping variability was compared with the components of intermittent drawing, we found that tapping variability was significantly correlated with the variability of the pause subinterval ($r = .55$) but not the variability of the movement subinterval ($r = .21$). However, the two phases of the intermittent task were correlated ($r = .65$).

It is interesting to note that, for intermittent circles, the variability in the spatial aspect of the circle was correlated with the temporal variability of the movement portion of the circle but not with the pause. Finger tapping timing variability was not related to finger tapping spatial variability. Finally, spatial variability in tapping was not correlated with spatial variability in circle drawing.

A significant correlation between temporal variability on the tapping and intermittent circle drawing tasks was obtained. This finding contrasts with the earlier report of Robertson et al. (1999) in which temporal variability in continuous drawing and tapping was not correlated. We believe that the discrepancy reflects a fundamental difference in how people achieve a temporal goal when drawing circles in a continuous or intermittent manner. As outlined earlier, we hypothesize that a series of periodic, discrete movements requires an explicit temporal representation. We propose that when a pause is inserted in the circle task, participants must use an internal timing process to directly control the required interval between movement cycles and to orchestrate movement initiation. This process is assumed to be similar to that invoked in the repetitive tapping task. The pause, by transforming the cycles of the circle task from continuous to discrete, makes the task more similar to tapping in terms of control processes. We hypothesize that this explicit control of timing is used under such discrete conditions, providing the requisite representation for specific events (e.g., the time of contact in tapping or the duration of the pause or interonset times in the circle drawing task).

Table 2
Correlation Values for Experiment 1 Based on Temporal and Spatial Coefficients of Variation

	Temporal: I circle			Spatial	
Measure	Total	Movement	Pause	Tapping	I circle: movement
Temporal					
Tapping	**.55**	.21	**.55**	.30	.23
I circle					
Total		**.78**	**.67**	.11	.22
Movement			**.65**	.09	**.38**
Pause				.21	−.09
Spatial					
Tapping					.08

Note. Significant correlations ($p < .05$) are shown in boldface. I circle = intermittent circle drawing.

Experiment 2

To allow for direct comparisons between discrete and continuous tasks, we included a continuous circle drawing condition in Experiment 2 along with the tapping and intermittent circle tasks. Examining the patterns of correlations among the three tasks would allow us to better assess the proposed distinction between explicit and implicit timing. On the basis of Experiment 1 and our previous work (Robertson et al., 1999; Zelaznik et al., 2000), we expected to obtain a positive correlation between the measures of temporal variability on the tapping and intermittent circle drawing tasks. Conversely, we expected a low correlation between tapping and continuous circle drawing.

Of central interest is the relationship between temporal variability on the two circle drawing tasks. One possibility is that these tasks will be positively correlated given shared processes associated with trajectory formation or processes involved in the visual control of circle drawing. However, on the basis of our assumption that the intermittent circle task entails explicit temporal control as a result of the timing requirements of movement initiation, we predicted that the correlation between the two circle drawing tasks would be low despite their superficial similarity.

A second change in Experiment 2 involved the cycle duration. The rate of movement in Experiment 1 (1 Hz) was slower than that typically used in repetitive tapping studies and slower than the rates used in the experiments of Robertson et al. (1999). It is possible that the observed correlation between discrete circle drawing and tapping in Experiment 1 was due to the use of this slow rate rather than the intermittency of the circle drawing task. For example, perhaps feedback processes become more relevant as the cycle duration increases, and the correlational results reflect individual differences in the use of feedback. Thus, we adopted a cycle duration of 800 ms in Experiment 2, one of the rates used in the studies of Robertson et al. (1999).

Method

Participants. Twenty-five right-handed, college-aged adults (14 men and 11 women) volunteered for the experiment in exchange for payment. Informed consent was obtained from all participants according to procedures approved by the Purdue University Committee on the Usage of Human Research Subjects.

Apparatus, tasks, and procedure. To ensure that the participants could complete the circle in the targeted time, we reduced the circle template on the target sheet to 5 cm in diameter. Only one tracing guide (a small circle 1 cm in diameter) was shown on the circumference of the 5-cm-diameter circle, positioned at 90° (see Figure 1, bottom). The tapping and intermittent circle drawing tasks were the same as in Experiment 1, except for the change in target frequency. The interstimulus interval for the high- and low-pitch tones was set to 400 ms. Tapping and intermittent circle drawing were performed in a manner identical to that of Experiment 1. For the continuous circle task, the participants were to complete one circle every two beats (800-ms movement time), moving continuously between cycles.

Participants first completed a training phase structured in a manner similar to that of Experiment 1. During the test phase, there were 10 trials, each consisting of 18 paced cycles and 36 unpaced cycles. A fixed order was used, with the tapping condition performed first, followed by intermittent circle drawing and, finally, continuous circle drawing.

Data collection. Kinematic three-dimensional displacement data were collected with an Ascension Technology miniBIRD (Burlington, VT) magnetic system that sampled the location of the markers at 140 Hz.

Results and Discussion

Data reduction and analysis. As in Experiment 1, a graphical analysis routine was used to score the tapping and intermittent circle drawing data. Because the continuous circle drawing task was performed very smoothly without pauses, the kinematic data were low-pass filtered (8 Hz cutoff, forward and backward). The displacement records along the y-axis were differentiated, and a numerical algorithm was used to determine when the velocity in the y-dimension changed sign (a movement reversal). The interval between reversal n and reversal $n + 2$ was recorded as the duration of one complete cycle. Regression analyses were used as in Experiment 1 to remove global changes in movement rate that might have occurred across cycles. After detrending, the standard deviations of the residuals of the time series were computed. The six trials with the lowest detrended standard deviations were included in the analyses.

Descriptive data. In Figure 3, we present representative kinematic traces for each of the three tasks. Both the tapping and the intermittent circle tasks showed discernible pauses. The pauses during tapping were uninstructed, reflecting the natural mode that participants adopt when tapping at the 800-ms rate; for the intermittent drawing task, the instructions specified that a pause be inserted between each movement cycle. In contrast, the continuous circle drawing trajectory was very smooth, without any discernible pauses.

The descriptive data are presented in Table 3. Participants were able to meet the demands of each task. In contrast to Experiment 1, the participants were able to parse the full cycle into pause and movement phases that were of approximately equal duration in the intermittent circle drawing task. For all three tasks, reliability values were high, and the coefficient of variation on the temporal measure was less than 6%. For the spatial domain, the circles were drawn at about the appropriate size for both drawing tasks. However, the measure of spatial variability was much lower for the continuous circles than for the intermittent circles.

Correlational analysis. In Table 4, we present the correlation values based on the coefficient of variation measures (critical r value: .37, $p < .05$). Replicating Experiment 1, temporal variability in the tapping and intermittent circle drawing tasks was significantly correlated ($r = .50$). However, although positive correlations were obtained between continuous circle drawing and the tapping and intermittent circle tasks, neither value was significant. Thus, individual differences in temporal control were significantly related between the two tasks hypothesized to require explicit temporal control. In contrast, correlations were reduced between these tasks and the continuous drawing task.

In Table 4 the correlation matrix based on temporal variability associated with the movement and pause phases of the intermittent drawing task are also presented. Total variability on this task was more highly correlated with the pause phase than with the movement phase. This result is consistent with the hypothesis that explicit temporal control is related to timing the onset of each cycle, and it is the pause phase in which such control is most required. Further support comes from the fact that the pause phase during intermittent circle drawing was correlated with tapping variability, whereas the movement phase was not. However, contrary to our expectations, the pause phase was also correlated with variability on the continuous drawing task, although to a lesser degree than with tapping ($r = .39$ vs. .53). The overall pattern of

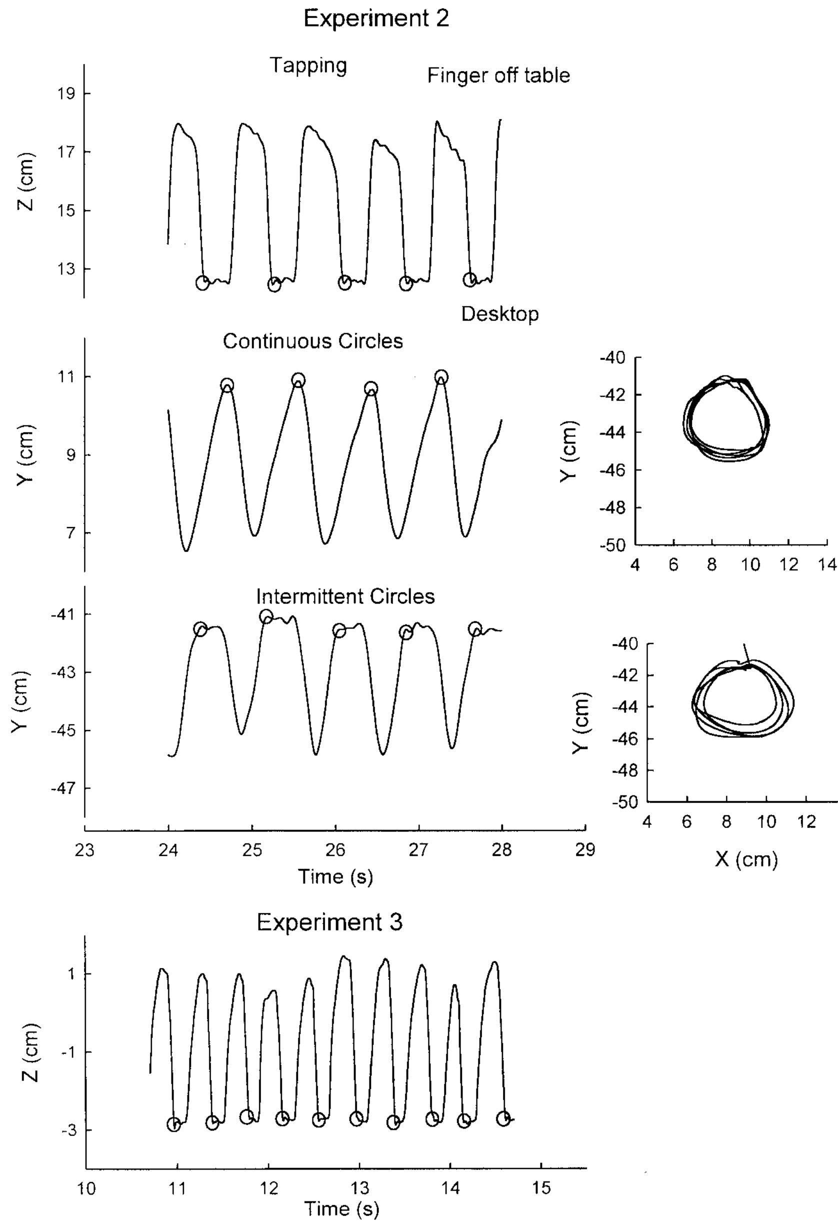

Figure 3. Representative 4-s slice of behavior in the tapping (top left), continuous drawing (left, second from top), and intermittent drawing (left, third from top) tasks during the continuation portion of a trial in Experiment 2. The small circles superimposed on the trajectories represent the points in time that are the beginning of cycle n and the end of cycle $n - 1$. Top and bottom right: Spatial path of each type of circle drawing movement. Bottom left: Four-s slice of tapping performance during the continuation portion of a typical trial in Experiment 3. As can be seen from this panel, even a 400-ms tapping task has a discernible pause in its movement.

positive correlations observed in this experiment suggests that there is a shared timing factor associated with all three tasks (and used to a lesser extent in continuous circle drawing) or that part of the individual-differences variation is related to general factors.

The correlation values for the spatial and temporal measures revealed some interesting patterns. In general, these correlations were positive but low, indicating that factors contributing to temporal and spatial variability are to some extent dissociable. However, it is interesting to note that the few values that approached significance involved correlations between measures of spatial and temporal variability on the same circle drawing tasks. In addition, a significant correlation was found between the measures of spatial variability on the two circle drawing tasks.

In regard to temporal variability, the low correlation, between the two circle drawing tasks is noteworthy for three reasons. First, at a superficial level, the continuous and intermittent circle drawing tasks appear to be the most similar of the three tasks. Both require multijoint movements, and the task goal entails the production of not only periodic movements but movements that conform to a specified trajectory. In contrast, tapping involves a

Table 3
Descriptive Data for Experiment 2

Task	Temporal					Spatial				
	MT (ms)	*SE*	CV (%)	*SE*	Reliability	Displacement (cm)	*SE*	CV (%)	*SE*	Reliability
Tapping	803.5	5.45	5.9	0.27	.92	3.34	0.66	10.1	1.04	.89
C circle	784.9	8.98	5.9	0.14	.90	2.54	0.20	6.3	0.36	.91
I circle										
Total	823.4	8.12	5.7	0.21	.91					
Movement	420.4	5.55	8.6	0.23	.86	2.62	0.24	17.9	1.58	.88
Pause	403.1	7.45	10.7	0.39	.83					

Note. MT = average deviation; CV = coefficient of variation; C circle = continuous circle drawing; I circle = intermittent circle drawing.

single joint movement, and there is little reference to a target trajectory. Nonetheless, temporal variability was more closely related between the tapping and intermittent drawing tasks.

Second, the hypothesis that the low correlations between tapping and continuous drawing tasks, both in the current experiments and in those of Robertson et al. (1999), arise because variability on the drawing tasks reflects noise in processes associated with trajectory planning and execution was not supported. One might suppose that such factors are relevant for the circle drawing tasks. The circle requires more degrees of freedom (a greater number of involved joints) than tapping, and the use of on-line visual guidance is likely to be higher. If these factors were relevant, we would expect the continuous circle drawing task to be more highly correlated with intermittent circle drawing than tapping. This was not the case. Continuous circle drawing was modestly correlated with both of the other two tasks, but this nonsignificant correlation was no higher for intermittent drawing than for tapping.

Third, the lack of correlation between the continuous drawing task and the intermittent drawing task (and the tapping task) suggests that the individual differences underlying the correlation matrix are not associated with a general factor that applies across all tasks. In summary, the major results of Experiment 2 were in accord with the predictions derived from the explicit–implicit timing distinction. The two tasks that we hypothesized required explicit timing, those involving noncontinuous responses, exhibited significant correlations on the measure of temporal variability. In contrast, the correlations were reduced and failed to reach significance between these two tasks and the continuous circle drawing task. Taken together, Experiments 1 and 2 demonstrate the importance of movement continuity in accounting for individual differences in temporal variability on repetitive movement tasks. We believe that this factor is critical for the distinction between explicit and implicit temporal control in the current set of tasks. We hypothesize that the timing of successive cycle onsets forms the basis for an explicit temporal representation when the task involves a series of relatively discrete responses. In contrast, timing may become secondary to other control parameters used to ensure that the movements remain continuous and smooth.

Experiment 3

The hypothesis that tapping and discrete circle drawing share a common explicit timing process was supported in the first two experiments. We have proposed that in such movements, the temporal goal is explicitly represented, providing a signal for when each relatively discrete movement should be initiated. In Experiment 3, we turned to the relationship of these tasks with a nonmotor task in which explicit timing is required.

Keele et al. (1985) found that performance on an auditory duration discrimination task was correlated with timing precision

Table 4
Correlation Values for Experiment 2 Based on Temporal and Spatial Coefficients of Variation

Measure	Temporal				Spatial		
		I circle					I circle
	C circle	Total	Movement	Pause	Tapping	C circle	Movement
Temporal							
Tapping	.28	**.50**	.18	**.53**	.10	.18	.00
C circle		.27	.32	**.39**	−.01	.33	.29
I circle							
Total			**.47**	**.81**	.09	.22	.06
Movement				.27	.20	.36	.29
Pause					−.03	.13	.33
Spatial							
Tapping						−.18	.09
C circle							**.39**

Note. Significant correlations ($p < .05$) are shown in boldface. C circle = continuous circle drawing; I circle = intermittent circle drawing.

in tapping ($r = .50$). Keele et al. inferred that these two tasks share a common timing mechanism. We replicated and extended this work in Experiment 3, examining the correlation matrix between these two tasks as well as our continuous and intermittent circle drawing tasks. We predicted that tapping, intermittent circle drawing, and duration discrimination would all be positively correlated, reflecting the fact that each shares an internal timing system required for providing explicit temporal representations. In contrast, we predicted that the correlations would be lower or even absent between variability in continuous circle drawing and the other three tasks. This prediction provided a strong test of the hypothesized distinction between tasks involving explicit and implicit timing given the substantial differences among the tapping, intermittent drawing, and duration discrimination tasks. As such, Experiment 3 provided an important generalization of the extent of explicit timing in motor and nonmotor tasks.

Method

Participants. Thirty-five students (21 women and 14 men) 18–24 years of age volunteered for the experiment in exchange for payment. Informed consent was obtained from all participants according to procedures approved by the Purdue University Committee on the Usage of Human Research Subjects.

Apparatus. The auditory duration discrimination task was run on an MS-DOS-based computer. An amplifier and speaker controlled by the computer were positioned behind the participant. The apparatus for the temporal production tasks was the same as in Experiment 2.

Tasks and procedure. All of the temporal production tasks were administered as in Experiment 2. The duration discrimination task was identical to that used by Keele et al. (1985). In brief, each trial contained four tones grouped into two pairs of two tones, with the pairs separated by 1 s. The first pair formed the standard interval and was always separated by 400 ms. The interval between the second pair varied, constituting the comparison interval. Participants judged whether the comparison interval was shorter or longer than the standard interval by pressing the *S* key (if the comparison interval was perceived as shorter) or the *L* key (if the comparison interval was perceived as longer) on the computer keyboard.

The comparison interval was set to a value that was either shorter or longer than the standard interval on the basis of an adaptive parameter estimation by sequential testing (PEST) procedure (Ivry & Hazeltine, 1995). The PEST procedure sets the comparison value to the current estimate of a participant's difference threshold. In the current experiment, the estimated threshold corresponded to one standard deviation on the assumed psychophysical function, or a point at which participants would be correct on approximately 72% of the trials. Separate estimates were made for the threshold in which the comparison interval was shorter than the standard and the threshold in which the comparison was longer than the standard, although the trials used to estimate these thresholds were intermixed within the test block. The psychophysical function was recalculated after each response, providing a new estimate of the difference threshold and thus generating the test value for the next trial. The threshold estimates after 60 trials (30 per threshold) provided a measure of temporal acuity. The difference between the two estimates corresponded to a range of two standard deviations on the psychophysical function, and we used half of this value (one standard deviation) as our measure for the analyses. The test trials were preceded by 11 practice trials. The first 10 of these trials involved a set of fixed durations, selected to be easily discriminable. The comparison interval for the final practice trial was equal to the standard interval (400 ms) to minimize between-trials bias.

Task order was fixed. The order was duration discrimination for one trial block followed by tapping, continuous circle drawing, intermittent circle drawing, and, finally, a second block of duration discrimination. The entire experiment lasted approximately 85 min.

Data collection. A miniBIRD kinematic data collection system sampled the three-dimensional location of the magnetic markers at 140 Hz. Only kinematic data from the continuation portion of the testing trial were collected.

Results and Discussion

Descriptive data. One participant with scores clearly outside the range of the other participants was not included in the analysis. This participant's average cycle duration was 557 ms for the movement portion of intermittent circles, 100 ms greater than that of any other participant. Analyses of the data from the remaining 34 participants were based on the best six testing trials in each movement task, as determined by the detrended variance. The bottom portion of Figure 3 shows a sample of representative tapping data (at a 400-ms rate) for this experiment. Even at this more rapid rate of tapping, there were discernible pauses in the tapping movements.[2]

In Table 5, the movement times and coefficients of variation for all of the temporal production tasks are displayed. Participants produced appropriate average durations with the exception of intermittent circles, which varied slightly from the goal of 400-ms circle intervals followed by 400-ms pause intervals. The mean coefficients of variation were in the 5%–6% range, consistent with previous studies and Experiments 1 and 2. Moreover, the coefficient of variation values for the pause and movement of the intermittent circle task were greater than the coefficient of variation for total cycle time. The radius for intermittent circles was about the same as that for continuous circles; however, as in Experiment 2, the intermittent circles had about 50% more spatial variability than the continuous circles. All reliabilities for the temporal production tasks were greater than .83.

The mean standard deviation of the duration task across the two trial blocks was 36 ms. The point of subjective equality, the value at which participants were equally likely to judge a comparison interval as shorter or longer than the standard, was 415 ms, indicating a bias to report the comparison interval as shorter than the standard. Our focus in the correlational analyses described subsequently was restricted to the standard deviation scores, because these scores provided an estimate of temporal variability. As with the production tasks, reliability was quite high on the discrimination task (.79).

Correlational analysis. In Table 6 the correlation matrix for the various measures from the four tasks is presented. With 34 participants, correlation scores greater than .34 are significant at the .05 level.

Consider first the correlations among the temporal measures. As can be seen in the top row of Table 6, timing variability on the tapping task was significantly correlated with timing variability on both the intermittent circle drawing task and the duration discrimination task. Performance during tapping was also positively correlated with performance during continuous circle drawing, but the value was lower and not statistically significant. In contrast, the correlations between the continuous circle drawing task (second

[2] That the 400-ms tapping movements showed a pause even without participants having to tap on every other beat, as in the 800- and 1,000-ms tasks, leads us to believe that the pause was a natural component of the tapping movement and not an artifact of the metronome characteristics of the first two experiments.

Table 5
Descriptive Data for Experiment 3

	Temporal					Spatial				
Task	MT (ms)	*SE*	CV (%)	*SE*	Reliability	Displacement (cm)	*SE*	CV (%)	*SE*	Reliability
Tapping	404.7	2.83	6.6	0.30	.94	2.9	0.26	13.3	0.99	.90
C circle	402.9	6.77	5.1	0.27	.87	2.6	0.18	11.1	0.96	.97
I circle										
Total	862.3	11.32	5.3	0.28	.90					
Movement	419.1	8.87	6.4	0.35	.90	2.4	0.30	15.6	2.13	.85
Pause	441.4	9.82	9.5	0.50	.83					

Note. MT = average duration; CV = coefficient of variation; C circle = continuous circle drawing; I circle = intermittent circle drawing.

row) and the various measures of variability on the intermittent drawing task were all nonsignificant. Most interesting, whereas no correlation was found between the continuous drawing task and the discrimination task ($r = -.15$), the correlation for total variability on the intermittent drawing task and the discrimination task was high ($r = .56$). Finally, the correlation between the duration discrimination and temporal variability of the pause phase was .55.

The correlations between the spatial and temporal variability measures were very similar to those observed in the previous experiments. Spatial variability and temporal variability were related for continuous circles. In the case of the intermittent drawing task, these measures were correlated only for the movement phase ($r = .42$). Spatial variability in continuous circles was positively related ($r = .33$) to temporal variability of the movement segment of intermittent circles, although this value was only marginally significant. Spatial variability of intermittent circles was related to spatial variability of continuous circles ($r = .61$). The corresponding value in Experiment 2 was .39, suggesting a shared process associated with trajectory control. Surprisingly, spatial variability on the tapping and continuous circle drawing tasks was significantly correlated in this experiment ($r = .36$); in Experiment 2, this correlation was $-.18$. Given the lack of consistency across experiments, we assume that this result is spurious.

In summary, the correlation matrix indicates that individual differences in temporal variability on the continuous circle drawing task are not related to factors associated with the other three tasks. Performance on the continuous drawing task failed to correlate with measures of temporal variability on tapping, intermittent circle drawing, or duration discrimination. In contrast, the latter three tasks were all significantly correlated with each other.

This pattern of results provides support for two hypotheses. First, control of cycle duration in continuous drawing is different from that of intermittent drawing. Second, tapping, intermittent drawing, and duration discrimination tasks draw on a common timing process, and this process is distinct from that used to control timing in the continuous circle drawing task. We believe that the commonality among tapping, intermittent drawing, and duration discrimination reflects the fact that all three tasks require an explicit representation of temporal information. The observed correlations result from individual differences in the noise associated with this internal timing system.

Experiment 4

The significant correlations between temporal variability in tapping and intermittent circle drawing in Experiments 1–3 were observed over a range of target intervals. Tapping was tested at 1,000 ms, 800 ms, and 400 ms. The cycle duration of the intermittent task was either 1,000 ms or 800 ms, with a corresponding target movement phase of either 500 ms or 400 ms. The consistent

Table 6
Correlation Values for Experiment 3 Based on Temporal and Spatial Coefficients of Variation

	Temporal				Spatial			
		I circle						I circle
Measure	C circle	Total	Movement	Pause	Perceptual	Tapping	C circle	Movement
Temporal								
Tapping	.26	**.40**	**.52**	**.39**	**.39**	.22	−.09	.14
C circle		.18	.30	.16	−.15	.11	**.40**	.21
I circle								
Total			**.84**	**.63**	**.56**	.18	.11	−.01
Movement				**.35**	.29	.12	.33	**.42**
Pause					**.55**	.24	.06	−.09
Spatial								
Discrimination						.13	.13	.08
Tapping							**.36**	.12
C circle								**.61**

Note. Significant correlations ($p < .05$) are shown in boldface. C circle = continuous circle drawing; I circle = intermittent circle drawing. Perceptual = perceptual timing.

pattern of results indicates that the correlations are not dependent on specific intervals, at least within the range explored here. Moreover, the continuous circle drawing task was performed with target intervals ranging from 400 to 800 ms, and at all rates failed to produce reliable correlations with the other two production tasks.

In our final experiment, we explored whether there is any specificity in individual differences in the duration discrimination task relative to the intermittent circle drawing task and tapping. Participants were tested on two versions of the duration discrimination task, one in which the standard interval was 400 ms and a second in which the standard interval was 800 ms. In addition, participants performed the tapping task with an 800-ms target interval and an intermittent drawing task with an overall duration of 800 ms, partitioned into a 400-ms pause and a 400-ms movement phase. This design allowed us to examine whether the correlation pattern varied as a function of the intervals being used for the three tasks. Specifically, would the correlations between duration discrimination and intermittent circle drawing be highest when the intervals for the two tasks matched (a) in terms of overall duration or (b) duration of the intermittent movement's components? The inclusion of a second duration discrimination task also allowed us to replicate the findings of Experiment 3 with a second duration. To limit the number of tasks, we did not include tapping at 400 ms or the continuous circle drawing task.

Method

Participants. Thirty graduate and undergraduate students (24 women and 6 men) volunteered for the experiment in exchange for payment. Informed consent was obtained from all participants according to procedures approved by the Purdue University Committee on the Usage of Human Research Subjects.

Tasks and procedure. The procedures were the same as in Experiment 3. The duration discrimination task was performed with standard intervals of 400 ms and 800 ms. For both temporal production tasks, the metronome period was set to 400 ms. Participants were instructed to tap coincident with every other beat in the tapping task and to complete the movement phase between two successive tones in the intermittent drawing task. For each task, there were 15 trials, 5 training trials and 10 test trials. In the first trial, the metronome was engaged for all cycles. Trials 2–5 were paced for 45, 36, 27, and 18 movement cycles, respectively (90, 72, 54, and 36 metronome beats), and were followed by a sufficient period of time to allow 9, 18, 27, and 36 movement cycles, respectively. On test trials, the metronome was engaged for the first 18 cycles (36 beats), followed by an unpaced phase of 28.8 s (equal to 72 beats). Participants produced approximately 36 additional movement cycles during this phase.

Tasks were performed in a fixed order: an 800-ms discrimination trial, followed by a 400-ms discrimination trial, finger tapping, intermittent circle drawing, a second 800-ms discrimination trial, and, finally, a second 400-ms discrimination trial. Participants were given a 25-s intertrial rest interval and a 5-min rest interval between tasks. During the period between tasks, detailed instructions for the following task were given. The experiment lasted approximately 70 min.

Results and Discussion

Descriptive data. Descriptive variables and reliability coefficients are presented in Table 7. The mean tapping rate was close to the goal of 800 ms. The mean cycle time for the intermittent circle drawing task was considerably longer than the target time, with participants extending the movement phase of the cycle. Performance on the 400-ms discrimination task was similar to that of Experiment 3. The standard deviation for this condition was 38 ms. For the 800-ms condition, the standard deviation rose to 61 ms. Reliability values were .78 and .72 for the 400-ms and 800-ms tasks, respectively.

Correlational analysis. The coefficient of variation for the production tasks and the average standard deviation for the perception tasks were used to calculate the correlation matrix. The value for significance was .36 ($n = 30$, $p < .05$). The correlation values are presented in Table 8.

As in the preceding experiments, temporal precision in finger tapping and intermittent circle drawing was highly correlated ($r = .65$). The pause portion of the intermittent circle task, but not the movement portion, was correlated with tapping in this experiment, similar to what was found in Experiments 1 and 2. Variability measures of tapping and overall cycle duration on the intermittent circle tasks were significantly correlated with the two versions of the perception task. Furthermore, performance on the two perception tasks was correlated. Thus, the results provide additional support for the hypothesis that the three tasks share a common process, one that we have proposed is involved in the explicit representation of temporal information.

Experiment 4 allowed us to further assess whether the correlations varied as a function of the represented interval. Interestingly, two results suggest that the correlations were highest for common intervals across the perception and production tasks. First, 800-ms tapping was more strongly correlated with the 800-ms version of the perception task than the 400-ms version. Second, the reverse pattern was found for the correlations between duration discrimination and the pause phase of the intermittent circle drawing task. Here, the higher correlation was found with the 400-ms version of the perception task. Although the results are limited by the fact that we did not include a 400-ms tapping condition or an intermittent circle drawing task with an 800-ms pause, temporal specificity

Table 7
Descriptive Data for Experiment 4

	Temporal					Spatial				
Task	MT (ms)	*SE*	CV (%)	*SE*	Reliability	Displacement (cm)	*SE*	CV (%)	*SE*	Reliability
Tapping	826.5	8.00	7.1	0.30	.96	1.9	0.25	9.8	0.74	.78
I circle										
Total	864.3	8.93	6.1	0.28	.90					
Movement	501.0	8.37	11.0	0.50	.84	2.4	0.03	18.4	1.78	.90
Pause	363.4	7.92	7.4	0.35	.88					

Note. MT = average duration; CV = coefficient of variation; I circle = intermittent circle drawing.

Table 8
Correlation Values for Experiment 4 Based on Temporal and Spatial Coefficients of Variation

	Temporal					Spatial	
	I circle			Discrimination			I circle
Measure	Total	Movement	Pause	800	400	Tapping	Movement
Temporal							
Tapping	**.65**	.05	**.50**	.57	**.36**	.32	.01
I circle							
Total		**.41**	**.76**	**.47**	**.56**	.24	.29
Movement			**.39**	.17	.25	.26	**.41**
Pause				.32	**.66**	.12	.07
Discrimination							
800					**.54**	.25	.06
400						.09	.02
Spatial							
Tapping							.18

Note. Significant correlations ($p < .05$) are shown in boldface. I circle = intermittent circle drawing.

may be an additional factor with explicit timing in understanding these significant correlations.

The only significant correlation between temporal and spatial variability was within the movement phase of the intermittent circle drawing task. Similar correlations were observed in the first three experiments, indicating that some shared process is involved in regulating the spatial and temporal properties of a trajectory. As expected, the spatial measures were not related to duration discrimination performance.

General Discussion

On the basis of the results of the present four experiments, the hypothesis that there is an important distinction between the control processes associated with timing tasks involving discrete and continuous events has been supported. Temporal consistency on the tapping and intermittent circle drawing tasks was significantly correlated in all of the experiments, and performance on these tasks also was correlated with acuity on a duration discrimination task. In contrast, the correlations were either weaker or absent between these tasks and the continuous circle drawing task. All of the tasks could be considered *timing* tasks; in a broad sense, however, there are considerable differences between them: motor versus perceptual focus, one-dimensional versus two-dimensional trajectories, single-joint versus multijoint movements, and use of distal versus proximal muscles. Despite these differences, the pattern of correlations is in accord with the hypothesized distinction between tasks in which the temporal representation is explicit and those in which timing is implicit.

Admittedly, the distinction between explicit and implicit timing is not clear. Unlike the vast literature on memory, we do not mean to imply anything about a difference between conscious knowledge and unconscious knowledge. Rather, we adopt these terms to refer to the manner in which temporal information is represented. For tasks involving explicit timing, we propose that an explicit representation of the temporal goal is required and is used to produce appropriately timed intervals. In tapping and intermittent circle drawing, the goal is in terms of *when* some salient point is achieved within the movement cycle. This might be the point of movement initiation; alternatively, at least in tapping, it could correspond to the point of contact with the table surface (Billon et al., 1996). For either case, we assume that an explicit temporal representation is used to guide performance during each cycle.

In contrast, we propose that implicit timing during a task such as continuous circle drawing involves what we call the *how* of timing. We assume that the timing characteristics of these movements are the result of the motor system controlling another kinematic and/or kinetic variable. This idea is derived from the notion that timing is an emergent process (Turvey, 1977). Temporal regularities may emerge as individuals attempt to minimize kinematic (Hogan, 1984) or neural (Kawato, 1996) variables. For example, consider the case of a baseball batter attempting to hit a home run. The batter attempts to generate more kinetic energy by swinging faster. The fact that the movement time of the bat is decreased does not imply that the movement time of the bat is directly controlled. Rather, it is just as likely that the speed of the bat results in a particular movement time. Turvey (1977; see also Zeiler, 1998) has argued that one need not postulate the explicit control of time for events that unfold in a precise temporal manner. We believe that temporal regularities may emerge as a function of the higher level conceptualization of the task. When one is drawing ellipses, for example, the control parameter may center on the relationship between curvature and velocity (Viviani & Terzuolo, 1980, 1982). Circles, having constant curvature, can be produced by keeping the magnitude of tangential velocity constant. Movement rate in such tasks may be controlled by varying the stiffness of orthogonal oscillators in a continuous manner. Temporal regularities would thus be an emergent property in that cycle duration is not directly represented.

The terms *explicit timing* and *implicit timing* refer to the underlying processes involved in controlling time, not the requirements of the tasks. The temporal goals of intermittent drawing, continuous drawing, and tapping are identical: to complete a cycle of movement at the prescribed duration and to be as accurate and consistent as possible in producing the temporal requirements. We believe that participants meet this goal for continuous drawing in a manner in which an explicit representation of an individual temporal interval is not required.

However, an explicit temporal representation is probably part of the overall goal in our continuous circle drawing task. The target interval is externally specified, and participants are quite adept in adjusting their performance to match this target. However, we believe that people transform this explicit temporal goal into a different control variable once the task is initiated. For example, achieving a circling period of 800 ms rather than 1,000 ms may require control and modulation of the stiffness of the limb. There no longer exists a need to maintain an explicit temporal representation once the motor execution processes are put into play. On the other hand, the temporal goal may still persist, perhaps providing a means for monitoring performance over several cycles to determine whether the cycle durations drift from the desired target duration. This hypothesis may account for the fact that we observed positive, albeit nonsignificant, correlations between continuous circle drawing and the two explicit movement tasks in Experiments 2 and 3.

Introduction of the intermittent circle drawing task provided an important extension of the findings of Robertson et al. (1999). In that study, temporal precision in tapping and continuous circle drawing was not related, even though the period of motion was equivalent for the two tasks. This null result led to the proposal that these tasks involve different timing processes. The intermittent circle drawing task was designed to test whether this difference reflected the differential reliance on explicit timing. Intermittent circle drawing is a hybrid of tapping and continuous circle drawing. As with continuous circle drawing, the intermittent task requires participants to produce a specified trajectory in addition to a constant rhythm. Moreover, if such trajectories involve visual guidance, the demands here would be similar for the continuous and intermittent versions (see Zelaznik & Lantero, 1996, concerning the role of vision in timing circle drawing movements). However, similar to the natural strategy adopted during tapping, the intermittent task entails a pause between successive cycles.

The correlation between tapping and intermittent circle drawing also indicates that the critical factor is not related to the complexity of the movements. For example, one might hypothesize that movements along one axis of motion may be different from those that require coordination along multiple axes of motion. This idea is not consistent with results showing a modest correlation between line drawing and circle drawing (Robertson et al., 1999). Furthermore, temporal variability in line drawing and temporal variability in tapping were unrelated (Robertson et al., 1999), even though both movements are one-dimensional. We obtained significant correlations between tapping and intermittent circle drawing even though circle drawing involves two-dimensional movements and tapping involves only one-dimensional movements. Thus, spatial complexity does not appear to be a relevant factor.

The current results have important implications for the use of tapping as the preparation in studies of timing. We believe that tapping is an excellent task to examine explicit timing processes (see Wing, 2002) but that it cannot serve as a general model for timing in motor control, even when there is a specific temporal goal. The implicit timing processes that we believe are emergent must be accounted for in continuous drawing tasks. The temporal properties of continuous drawing tasks probably emerge from the interaction between centrally driven components and the local bone–muscle machinery (see Kugler, Kelso, & Turvey, 1982). Under such conditions, a central explicit component of timing might be hidden from direct examination as a result of nonlinearities in the peripheral processes (Heuer, Schmidt, & Ghodsian, 1995).

The results involving the perceptual tasks used in Experiments 3 and 4 offer converging evidence for the hypothesized explicit–implicit distinction. Significant correlations were observed among the perception tasks, tapping, and intermittent circle drawing. In contrast, no significant correlations were found between the perception tasks and continuous circle drawing. These results are important for two reasons. First, the dissociation provided a strong test of predictions derived from the explicit–implicit hypothesis. Second, when conducting individual-differences research, it is important to verify that positive correlations are not obtained across all tasks so as to be certain that one has not captured a general factor such as motivation across these tasks.

In Experiment 4, the strongest relationship among the tasks involving explicit timing was found between temporal measures based on similar intervals. The 800-ms tapping task exhibited specificity with respect to duration discrimination. The correlation was stronger between tapping and 800-ms discrimination than between tapping and 400-ms discrimination. Furthermore, we observed a stronger correlation between 400-ms discrimination and the pause phase of intermittent drawing (400 ms). One possibility is that explicit timing in the intermittent circle drawing task is restricted to the pause phase, with this interval being summed with that produced by the implicitly timed movement phase. Alternatively, the intermittent task may entail a hierarchical temporal representation with a top level representing the time between successive movement onsets and a subordinate timer used to impose the pause interval. The latter hypothesis is supported by the fact that the coefficient of variation was substantially lower when measured for the total interval than for the pause phase.

An important question for future research concerns the neurological basis for the distinction between explicit and implicit timing. Ivry (1996, 1997; Ivry & Keele, 1989) has argued that the cerebellum is essential for tasks requiring a precise temporal representation, such as repetitive tapping, duration discrimination, and eyeblink conditioning. As such, the cerebellum would be an essential structure involved in explicit timing. It is, however, possible that the cerebellum is also involved in the control of tasks for which timing may be implicit. For example, patients with cerebellar ataxia are impaired on tasks involving complex trajectories such as throwing (Martin, Keating, Goodkin, Bastian, & Thach, 1996; Timmann, Watts, & Hore, 1999). Detailed analysis of kinematic and electromyogram records during these movements indicate that their impairment appears to involve fine temporal coordination between the gestures of different limb segments.

What may change on tasks involving implicit timing is the contribution of other processes to overall temporal variability. For example, temporal consistency during continuous circle drawing may reflect processes associated with trajectory formation and control, and these processes may be associated with noncerebellar structures. Indeed, the neurological literature suggests that spatial planning arises at a cortical level (e.g., Desmurget et al., 1999; Franz, Eliassen, Ivry, & Gazzaniga, 1996). Perhaps variability in this aspect of coordination dominates performance during continuous circle drawing.

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Received January 6, 2000
Revision received August 28, 2001
Accepted September 4, 2001 ■