Force and Timing Variability in Rhythmic Unimanual Tapping

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ABSTRACT. In 3 experiments the interdependencies between timing and force production in unimanual paced and self-paced rhythmic tapping tasks were examined as participants ($N = 6$ in each experiment) tapped (a) to 1 of 3 target periods (333 ms, 500 ms, and 1,000 ms), while they simultaneously produced a constant peak force ($PF$) over a 50-s trial; (b) to produce 1 of 3 target forces (5, 10, and 15 N) at their preferred frequency, while keeping their rhythm as invariant as possible; and (c) to all combinations of target force and period. The results showed that (a) magnitudes of force and period were largely independent; (b) variability in timing increased proportionally with tapping period, and the variability in force increased with peak force; (c) force variability decreased at faster tapping rates; and (d) timing variability decreased with increasing force levels. (e) Analysis of tap-to-tap variability revealed adjustments over sequences of taps and an acceleration in the tapping rate in unpaced conditions. The interdependencies of force and time are discussed with respect to the challenges they provide for an oscillator-based account.

Key words: force control, oscillator modeling, rhythmic timing, variability

For more than a century, the study of the perception and production of rhythm has revolved around the observation that even in simple periodic sequences successive intervals are neither perceived nor produced in exactly the same way. As early as 1886, Stevens found that in a rhythmic tapping task the response intervals vary and very often alternate in their relative duration, such that longer than average intervals are followed by shorter than average intervals and vice versa. That first quantitative description of the variability of rhythmic timing opened the way for a large number of experimental investigations into the variability of tapping movement sequences. Those investigations generally have followed through the prevailing theoretical orientations of the psychology of human performance over the last century, ranging from psychophysics (Weber, 1834) and Gestalt psychology (Fraisse, 1954) to information-processing and cognitive approaches (Keele, Pokorny, Corcos, & Ivry, 1985; Michon, 1967; Semjen, Garcia-Colera, & Requin, 1984; Shaffer, 1982; Wing, 1980). More recently, connectionist accounts (Church & Broadbent, 1991; Collyer & Church, 1998) and interpretations founded on an oscillator perspective (Billon, Semjen, Cole, & Gauthier, 1996; Large & Kolar, 1994) have been brought to bear on that issue.

An influential theoretical proposition originating in the psychophysics of the last century, one that has motivated many studies on the perception and production of temporal intervals, is Weber's law (Weber, 1834). According to Weber's law, the ability to discriminate between two stimulus magnitudes—of any sensory modality—is directly proportional to the absolute magnitude of the stimulus, and the fraction is constant across different stimulus magnitudes. In early work within the psychophysical domain, the applicability of Weber’s law for perceiving temporal intervals was tested, with time being the sensory dimension of interest (Allan, 1979; Allan & Kristofferson, 1974). In parallel, Weber's law has also been introduced into the research on movement coordination and the issue of accuracy or variability in performance (e.g., Fullerton & Cattell, 1892; Schmidt, Zelaznik, Frank, Hawkins, & Quinn, 1979; Woodworth, 1899). Specifically, for producing a sequence of finger taps of equal interresponse intervals, Weber's law translates into the prediction that the variability ($Var$) of maintaining an invariant time interval is a function of the absolute magnitude of that interresponse interval ($IRI$):
\[ \text{Var}(\text{IRI}) = k_w \times \text{IRI} \]

where \( k_w \), the so-called Weber fraction, is considered to be constant across different stimulus magnitudes. Although that relation has been shown to hold for intermediate sensory ranges, when larger ranges were studied the relation was found to follow a negatively accelerating rate with increments in the duration of the interval (Michon, 1967). Those controversial results gave rise to a number of alternative models in which a distinction has been proposed between duration-dependent and duration-independent components in the associated variability (Creelman, 1962; Getty, 1975; Ivry & Hazeltine, 1995; Killeen & Weiss, 1987).

In a seminal article, Wing and Kristofferson (1973) addressed the issue of timing variability by proposing a timekeeper model for rhythmic movement that accounted for the “long and short” phenomenon of Stevens (1886) with two independent processes residing at a central and at a peripheral level. An internal clock produces signals in an entirely open-loop fashion that are subject to stochastic variability; the implementation of those periodic signals within the peripheral motor system imposes delays that are likewise accompanied by stochastic variability. Response intervals are therefore “contaminated” by the summed effect of the two independent sources of variability of the pacemaker and the peripheral motor system. One needs no further assumptions, nor is feedback needed, to account for the negative correlation between successive intervals. An attractive feature of the model is that it affords the decomposition of the timing variability in empirical data into a “clock” and a “motor” component. Theorists have applied that tool to a number of different tasks and subject populations in an attempt to attribute variability in the timing to either central or mechanical components (for example, see Ivry & Keele, 1989; Ivry, Keele, & Diener, 1988; Keele & Ivry, 1991; Keele, Manchester, & Rafał, 1985; Turvey, Schmidt, & Rosenblum, 1989; Wing, 1977).

In all of the aforementioned studies of rhythmic timing, a facet of movement control that is undeniable important in any such tapping action has been ignored or bracketed out: the control of force. In fact, as either an implicit assumption or an explicit hypothesis, the researchers goal in those studies was to investigate whether timing per se can be conceptualized as an isolable component of the central nervous system that operates independently of other aspects in motor control, such as force or speed control. Most notably, Keele, Ivry, and their colleagues have pursued in a series of studies the question of whether the general construct of motor coordination can be broken down into separate modules, which are then fundamental operations to many different tasks (Keele & Ivry, 1987). Using a correlational approach across different individuals as well as neuropsychological experiments on patient groups with cortical and cerebellar lesions, Ivry and Keele (1989; Keele, Ivry, & Pokorny, 1987; Keele, Pokorny, Corcos, & Ivry, 1985) have obtained some evidence for such computational modules for timing and force control, as well as for speed and sequencing. Additionally, those authors showed that accuracy in perception and production tasks correlate, and that finding therefore speaks to a shared mechanism that underlies both the production and perception of time. That computational approach is in agreement with earlier theoretical propositions from the generalization motor program approach, that timing and force are independent parameters scaling the realization of a general motor program (Schmidt & Lee, 1998). Yet, the data were also somewhat ambiguous, because there were signs that the variability in force and timing correlated within subjects and therefore did not fit their modular hypothesis (Keele, Ivry, & Pokorny, 1987). In the present study, we revisited that question, and we hypothesized that force and time control are tightly intertwined.

A line of research that supports the hypothesis that force production cannot be extricated from timing can be found in the literature on discrete isometric force production. In studying the variability of isometric force, Newell and Carlton (1985) showed a systematic dependence of the variability in peak force on temporal aspects of the impulse. For instance, the time taken to rise to a target level of peak force was highly correlated with the variability of the produced peak force. Those results were paralleled by studies on motor unit recruitment and cortical activity in which the same isometric force production task was used (Smith, Hepp-Reymond, & Wyss 1975; Tanji & Kato, 1973). In more recent work, it has been shown that the variability of force production can be described by a simple scaling relation of the force and time properties of the impulse (Carlton & Newell, 1993; Newell & Carlton, 1988). The scaling relation of the force–time properties of the impulse is necessarily embedded in any measure of the temporal durations of sequential tapping. Moreover, that finding makes it difficult to separate central and peripheral contributions to timing variability alone, in spite of investigators’ efforts to isolate the role of a central timekeeper through minimizing the contribution of the peripheral musculature to the response. Indeed, even the premotor latency of a key press is determined by the dynamics of the to-be-produced response (Carlton, Carlson, & Newell, 1987).

Attempts to explicitly explore the relation between movement timing and force control in rhythmic performance have been relatively few. The paucity of such attempts is particularly surprising because, in tasks like piano playing, stress and accentuation are central components of performance. Notable exceptions are the studies by Billon, Semjen, and their colleagues (Billon, Semjen, Cole, & Gauthier, 1996; Billon, Semjen, & Stelmach, 1996; Semjen & Garcia-Colera, 1986), who focused on a task that required the accentuation of one tap in short sequences of usually five finger taps. The recurrent finding in those studies was that the duration of the interresponse interval preceding the accentuated tap was shortened and the interval following the accentuated taps was lengthened as compared with the interresponse intervals surrounding a sequence of unaccentuated taps. In their most recent articles, the authors...
suggested that an internal clock should be conceived of as a self-sustained oscillation that, in turn, phase entrains the movement system, which is itself assumed to be a self-assembled oscillation. That framework is more advantageous than feedback-based error correction models in accounting for compensatory actions and observed transients resulting from the intentional accentuations (Hary & Moore, 1985, 1987; Mates, 1994a, 1994b). However, they made no attempts to explicitly match an oscillator model to the identified time–force relations. If one adopts that perspective, then the hypothesis of force–time interdependence is a direct consequence. If an oscillator prepares for a specified impact force, that is, acceleration, the cycle time will be affected.

Data from the exploration of such interdependencies in rhythmic tapping were published by Inui, Ichihara, Minami, and Matsui (1998). In their investigations of short sequences of finger taps performed at different self-selected rates and force levels, the authors found significant positive correlations between tapping force and interval duration—however, only for high tapping frequencies. At low tapping rates, no such dependence was found. The fact that the accuracy was considerably higher in contact forces than in intertap intervals was interpreted as another sign of the independence of force and time control. Those somewhat ambiguous results may have resulted from the fact that the task required participants to select only high, medium, and low peak forces, and the self-chosen relative force levels and tapping rates differed widely across participants.

Given the spectrum of conflicting results in the literature, and motivated by an oscillator-based perspective, in the present study we revisited the issue of force and timing with a series of experiments in which peak forces and tapping rates were tightly controlled. We report here on three experiments that we set up to examine the possible interdependencies between timing and force production in unimanual rhythmic tapping actions. The movement tasks varied in their constraints on force and time and also contained conditions in which tapping force or rhythm was self-selected by the participants; we used those constraints and conditions to assess the intrinsic preferences of the tapping movements (Kugler & Turvey, 1987). There are several questions on force and time variability at the center of the present study. What are the effects of (a) explicit timing requirements on the production of an impact force and (b) specific force requirements on timing performance? (c) What factors influence those effects, either selectively or together? We examined those questions in regard to the force and timing variability of tapping performance and the sequential structure of the repetitive taps. The results are interpreted as a data base for an oscillator account for rhythmic tapping.

**EXPERIMENT 1**

We designed Experiment 1 to examine the effect of force constraints upon the timing of rhythmic unimanual tapping. Our primary goal in this experiment was to determine whether the requirement of producing an invariant impact force in a rhythmic tapping task alters the temporal intervals of the tapping movement. In addition, by contrasting performance at a set frequency with self-selected tapping, we conducted a broader examination of the effect of sequential timing upon the production of force and its variability.

**Method**

**Participants**

Six participants (4 men, 2 women; age range, from 23 to 30 years) volunteered for this experiment. All were graduate students of The Pennsylvania State University. All were right-handed and had no history of injury to either hand or wrist. Prior to the data collection, participants gave their informed consent in accordance with the University Regulatory Compliance Office.

**Apparatus and Task**

Participants were seated on a chair, with their forearms placed on 10-cm-wide horizontal armrests that were padded with foam. Positioned in front of each hand was a horizontal 10-cm × 10-cm steel plate, which was mounted on a tripod of adjustable height. The surfaces of the steel plates were covered with a thin hard rubber mat and were level with the horizontal armrests. Each plate was attached to a steel brace, which in turn was mounted on the tripod. Two vertical steel supports were connected by two horizontal

![Experimental apparatus with strain gauges measuring impact forces. The construction was designed so that variations in the location of the finger contact did not yield different deformations and, consequently, different measures of force. The padding dampened the mechanical vibrations following each impact and reset the force plate to a steady zero value within 30 ms.](image-url)
aluminum plates, arranged as described in Figure 1. Four strain gauges were attached underneath the upper aluminum plate, one at each corner, in a Wheatstone bridge configuration (foil gauges SG-6/120 LY 43 [Omega, Stamford, CT]; gauge factor approximately 2.0). The supporting steel braces were designed so that the deformations of the strain gauges were indifferent to the location of force application on the contact plate itself. We put soft padding underneath the free vertical brace to dampen vibrations that occurred after finger impact. The analog output of the strain gauges was recorded by a 486 PC computer with a 12-bit A/D converter (DT 2801 board; Data Translation, Marlboro, MA) and was digitized at a 1000-Hz sampling frequency.

A monitor was placed at eye height in front of the participant at approximately .75-m viewing distance. The 640-× 480-pixel monitor (13 in.) displayed the force of the impacts on the vertical axis against time on the horizontal axis. The display of the impulses began at the bottom left side of the screen, with succeeding spikes shown along the horizontal line until the end of the trial. All spikes remained visible throughout the whole trial. Because the screen displayed 50,000 samples for the 50-s trials, the shape of the impact forces was not visible, and the produced forces were recognized only as the maxima of vertical spikes from a baseline. The vertical axis of the screen was set to a maximum of 2.5 N, rendering a resolution for the magnitude of force of .052 N per pixel on the display. That resolution was kept constant for all manipulations and experiments. The impact spikes, which typically spanned one-third to one-half of the height of the screen, gave concurrent visual feedback about the actual peak forces produced by the participant. The complete series of spikes from the beginning to the end of a trial, which contained approximately 50 to 150 taps, remained visible on the screen. With a trial length of 50,000 data points to be displayed on the monitor, the force values for 78 ms were written into one pixel column. Because the pixels were not overwritten, the largest data points remained visible on the screen and gave the participant online feedback about the maximum force they produced in each tap.

Participants wore headphones through which they heard a metronome signal throughout the entire trial. The PC computer that collected the data also generated a series of beeps that were separated by invariant intervals of 333 ms, 500 ms, and 1,000 ms. The duration of the beep was 125 ms for all target periods.

Procedure

Each participant was seated in front of the monitor, and we adjusted the chair position to a standardized marked position on the floor in order to ensure the same viewing distance for all participants. Prior to data collection, the two “drum pads” were positioned so that at rest the participant’s forearms, hand, and fingers were aligned and the participant’s fingertips rested on the center of each drum pad. To allow maximal mobility, we positioned the partic-

pant’s wrist so that it slightly protruded from the front end of the armrest.

Participants were instructed to produce a sequence of unimanual tapping movements initiated from one wrist joint, either with their left or right hand; the movement involved a rhythmic alternation between extension and flexion of the wrist. The single-joint wrist action was preferred to the more commonly used finger taps, that is, single-joint actions performed around the metacarpophalangeal joint, because unused fingers tend to touch the force plate in the finger tapping task, giving inaccurate force feedback. Participants were instructed to tap rhythmically on the pad so that the impacts would be in synchrony with the metronome. The experimenter also emphasized that they should hit the pad with their fingertips, without resting on the pad for any extended length of time, that is, as if they were touching a hot plate. No external devices were used to immobilize the joints of the fingers and hands, but participants were instructed that those joints should remain relatively stiff, leaving the wrist as the major active joint. Additionally, they were required to produce a consistent impact force level that reflected their most comfortable level. The visual display showed the produced tap forces on-line and thereby gave feedback about the variability of the tapping force. Feedback about the temporal accuracy could not be obtained because the spacing of the spikes was too dense to enable the participants to differentiate between different intertap intervals. No summary feedback about the performed accuracy was given after the trial. The unimanual conditions were performed with the right and left hands alternating so that fatigue effects in the hands and fingers could be avoided. Before commencing the data collection, four practice trials were administered to the participants, in which hand (left or right) was alternated and target period was randomly selected from the four frequency conditions. Each trial lasted 50 s. The duration of the data-collection session lasted approximately 30 min.

Experimental Conditions and Design

Three target periods of 333 ms, 500 ms, and 1,000 ms (3 Hz, 2 Hz, and 1 Hz, respectively) were prescribed via the headphones. Additionally, there was a self-paced condition in which participants were given no auditory metronome signal and were instructed to tap rhythmically at their preferred frequency. The target periods were determined following pilot trials in which participants performed tapping movements at a range of their self-selected comfortable frequencies as well as their most comfortable frequency. In the experiment proper, participants performed the rhythmic task with each hand. The trials were performed in two blocks of eight trials each; in each of the two blocks, participants experienced each pairing of hand and period condition once. Target period conditions were pseudo-randomized, constrained by the condition that participants should alternate right and left hands to avoid fatigue. At the end of the first block of trials, we exchanged the drum pads to off-
set any potential differences in mechanical or electronic sensitivity between the two force gauges.

Data Analysis

A custom-written program that used Matlab routines extracted the peak value of each tapping impact together with the time at which it occurred in the continuous force-time series. Subsequently, we computed trial means from the series of peak force values, PF, and the intervals between the corresponding impact times, the interresponse intervals, IRI. To capture the variability in performance for a given trial, we computed standard deviations and coefficients of variation. We eliminated the first five peaks at the beginning of each trial from all statistical analyses to avoid contamination from transient behavior during which participant gauged their tapping to the visual display and metronome frequency. Additionally, averages were computed across the two repetitions per condition as well as across the participants.

We performed auto- and cross-correlations by using the series of PFs and IRIs at various lags (the subscript n denotes the individual spikes and periods). We determined the effects of PFn on the duration of the surrounding IRIs by calculating a cross-correlation that related the duration of the IRI to the magnitude of the PFn. Lag 0 (r0) correlated the PFn of the tap that terminated the respective IRI (Figure 2). The term r refers to the correlation coefficient. A lag 1 (r1) related PFn to the following IRI+n1, whereas r1 related PFn to the IRI−1 that ended at the preceding tap.

Results and Discussion

Interresponse Intervals and Their Variability

To assess whether participants completed the assigned task, we calculated and submitted mean IRIs of each trial to a 4 (target period) × 2 (hand) × 2 (repetition) repeated-measures analysis of variance (ANOVA). A highly significant main effect for target period confirmed that participants successfully produced three different tapping periods when following the metronome (p < .0001). Averaged across participants, all mean IRI values were within ±2 ms of the pacing intervals at 333 ms, 500 ms, and 1,000 ms; and the largest deviation from the prescribed target IRI in an individual trial was less than 5 ms. The mean IRI in the self-paced condition for all participants was 436 ms, but their individual trial means in all four repetitions performed by either the right or the left hand showed a wide range between 219 ms and 872 ms. The mean preferred periods of all 6 participants are listed in Table 1. All other effects between conditions on IRI failed to reach significance.

To investigate the timing variability associated with the different target periods, we performed the same 4 × 2 × 2 ANOVA on the standard deviations around the mean IRI, SD(IRI). SD(IRI) significantly increased with target period, F(3, 15) = 22.16, p < .001, as illustrated in Figure 3. The dark column shows the self-selected condition, which is rank-ordered with the three metronome conditions according to the mean periods that each of the participants selected.

That effect was further corroborated when SD(IRI) values of individual trials were regressed against the respective mean IRIs on a participant-by-participant basis. The same significant dependence of SD(IRI) on IRI was found for each participant: r values ranged from .62 to .94. The intercepts of 3 participants were significantly different from zero, and the slopes of the linear regressions ranged between .02 to .07. It is noteworthy that the SD(IRI) values associated with the self-chosen IRIs ordered systematically with IRI (compare with Table 2) because, from an oscillator-based perspective, the self-paced trials are viewed as representing the intrinsically preferred mode of rhythmic oscillation. One would expect such trials to be accompanied by the lowest level of fluctuations because they are regarded as the most stable mode of performance (e.g., Schmidt, Shaw, & Turvey, 1993; Sterman, Amazeen, & Turvey, 1996). Instead, the fluctuations were rank-ordered with the metronome-paced trials, suggesting that the actual duration of the tapped interval is more formative for the temporal accuracy than the preferred timing.

There was also a significant interaction between hand

FIGURE 2. The definition of lags used in the cross-correlations between peak force and interresponse intervals. PFn-2 to PFn+1 = peak force at specific taps n - 2, n - 1, n, n + 1. Similarly, IRI = interresponse interval between taps n - 2, n - 1, ..., n + 1.

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and repetition, $F(1, 5) = 11.59, p < .05$, which resulted from a decrease in $SD(IRI)$ in the nondominant hand from the first to the second repetition. The $SD(IRI)$ for the dominant hand remained the same across the two repetitions.

We calculated a $4 \times 2 \times 2$ ANOVA with the coefficient of variation of $IRI$, or Weber fraction, $CV(IRI)$, as dependent measure. Similar to $SD(IRI)$, $CV(IRI)$ varied systematically with target period, as evidenced by a significant main effect, $F(3, 15) = 3.99, p < .05$. Contrary to $SD(IRI)$, and contrary to our expectation on the basis of Weber’s law, that normalized measure of variability decreased with increasing target period. From performing linear regressions on $CV(IRI)$ on individual participants’ data separately, we observed a significant decrease with increasing movement period in 3 of the 6 participants ($r^2$s between .49 and .63). The regression included the self-paced condition, whose $CV(IRI)$ again ordered with the other prescribed frequencies (see Table 2 for all individual participants’ data).

The increase in timing variability with increasing period of movement found in the present study is consistent with numerous previous studies of rhythmic timing tasks that did not include the control of force level (Ivry & Hazeltine, 1995; Killeen & Weiss, 1987; Wing, 1980). Given the robustness of the result, the exact shape of the functional dependence of temporal acuity on target period, both for perceptual and production tasks, has been the subject of extensive debate. The observed increase in $SD(IRI)$ in conjunction with a drop of $CV(IRI)$ at short periods has been observed by Getty (1975) for perceptual discrimination tasks and has led to the formulation of a generalized Weber’s law: $\sigma^2(IRI) = k_1 + k_2 \cdot IRI^2$, where $\sigma^2(IRI)$ refers to the variance of the interresponse intervals. That equation has also been interpreted as distinguishing between duration-independent ($k_1$) and duration-dependent ($k_2$) variability and has been supported in a number of studies (Ivry & Hazeltine, 1995; Warden & McShane, 1988). To compare our results with those, we additionally performed regression analyses relating trial variances of $IRI$ against $IRI^2$. Unlike the findings in Ivry and Hazeltine (1995), however, the slopes in the original regression did not differ significantly from those derived by using the generalized Weber’s law; the $r^2$ values did not noticeably improve and were between .97 and .99. Yet, that result is not entirely surprising,

<table>
<thead>
<tr>
<th>Participant</th>
<th>1</th>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tr>
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<td>434</td>
<td>442</td>
<td>501</td>
<td>696</td>
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</table>

FIGURE 3. Mean values of the standard deviation of interresponse intervals, $SD(IRI)$, of all 6 participants for the three paced conditions at 333 ms, 500 ms, and 1,000 ms of Experiment 1. The trial means of $SD(IRI)$ for the unpaced trials have been inserted according to their mean $IRI$. 254
because there were only four data points, and the 1,000-ms condition exerted higher leverage than the other three conditions did. Therefore, the data were not sufficient to enable us to make any further statement as to the functional form of the dependence.

In comparing our findings with other results in the literature, it should also be mentioned that the method used in most of those studies was the so-called continuation paradigm, in which the metronome pacing was switched off after an initial sequence of beeps, although participants continued tapping the prescribed rhythm. To evaluate whether the concomitant pacing of tapping movements, which effectively acts as feedback available for every interval, changed participants’ performance, we regressed the data of the unpaced and paced conditions separately. Using the average of the four repetitions of each condition for each of the 6 participants, we regressed the values for $SD(\text{IRI})$ against $\text{IRI}$, both in the paced and the unpaced conditions. When a 95% confidence interval was used as the criterion, the coefficients of the linear regression were not significantly different from each other. From that comparison, we concluded that the presence of the metronome played only a subordinate role for the variability estimates. In sum, despite the slightly different protocol used in the present experiment, the results conformed with those from the literature in all aspects. With respect to our primary goal in the experiment, the present result suggests that the imposition of force constraints and the simultaneous visual feedback of participants’ force production did not change the fundamental nature of the timing variability. No timing differences could be discerned from results in previous experiments in which explicit force constraints were not imposed.

**Peak Force**

In addition to the task of tapping at the rhythm of the metronome, participants were requested to produce the taps at a preferred force level and to maintain that level as constant as possible. A key question was whether the metronome period influenced the selection of mean preferred peak force values, $PF$. A $4 \times 2 \times 2$ ANOVA applied to the mean peak force values per trial did not render any systematic relation of $PF$ on the metronome periods or on the self-selected periods. Participants produced $PF$ magnitudes that varied widely across trials, ranging from 1.7 N (Participant 4, 1,000 ms, nondominant hand) to 26.9 N (Participant 3, 1,000 ms, nondominant hand). In Table 3 are listed the $PF$ means across two repetitions and hands determined for all conditions. In the ANOVA, only one significant interaction between hand and repetition was detected; that interaction signified that the nondominant hand decreased its force in the second repetition, $F(1, 5) = 6.94, p < .05$. Clearly, the wide range of mean peak forces

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**TABLE 2**

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<tr>
<th>Period</th>
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<th>Participant 3</th>
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<th></th>
<th>Participant 4</th>
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<tr>
<td></td>
<td>$SD(\text{IRI})$</td>
<td>$CV(\text{IRI})$</td>
<td>$SD(\text{IRI})$</td>
<td>$CV(\text{IRI})$</td>
<td>$SD(\text{IRI})$</td>
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<td>13</td>
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</table>

*Note. Each value is the average across four trials, two performed with the left hand and two performed with the right hand, respectively. $SD(\text{IRI})$ = standard deviation of interresponse interval, $CV(\text{IRI})$ = coefficient of variation of interresponse interval.*

**TABLE 3**

<table>
<thead>
<tr>
<th>Period</th>
<th>Participant 1</th>
<th></th>
<th></th>
<th>Participant 2</th>
<th></th>
<th></th>
<th>Participant 3</th>
<th></th>
<th></th>
<th>Participant 4</th>
<th></th>
<th></th>
<th>Participant 5</th>
<th></th>
<th></th>
<th>Participant 6</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$PF$</td>
<td>$CV(\text{PF})$</td>
<td></td>
<td>$PF$</td>
<td>$CV(\text{PF})$</td>
<td></td>
<td>$PF$</td>
<td>$CV(\text{PF})$</td>
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<td>$PF$</td>
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<td>$PF$</td>
<td>$CV(\text{PF})$</td>
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<td>----------</td>
<td>----------</td>
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<td>----------</td>
</tr>
<tr>
<td>1,000 ms</td>
<td>9.82</td>
<td>0.35</td>
<td></td>
<td>15.57</td>
<td>0.23</td>
<td></td>
<td>24.73</td>
<td>0.09</td>
<td></td>
<td>3.37</td>
<td>0.36</td>
<td></td>
<td>11.23</td>
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<td>13.55</td>
<td>0.19</td>
</tr>
<tr>
<td>500 ms</td>
<td>12.65</td>
<td>0.29</td>
<td></td>
<td>14.33</td>
<td>0.22</td>
<td></td>
<td>22.73</td>
<td>0.09</td>
<td></td>
<td>3.43</td>
<td>0.32</td>
<td></td>
<td>11.61</td>
<td>0.19</td>
<td></td>
<td>10.65</td>
<td>0.18</td>
</tr>
<tr>
<td>333 ms</td>
<td>11.92</td>
<td>0.26</td>
<td></td>
<td>16.34</td>
<td>0.17</td>
<td></td>
<td>22.09</td>
<td>0.09</td>
<td></td>
<td>4.82</td>
<td>0.29</td>
<td></td>
<td>11.04</td>
<td>0.19</td>
<td></td>
<td>11.69</td>
<td>0.17</td>
</tr>
<tr>
<td>Self-paced</td>
<td>8.95</td>
<td>0.28</td>
<td></td>
<td>14.04</td>
<td>0.19</td>
<td></td>
<td>22.67</td>
<td>0.09</td>
<td></td>
<td>4.66</td>
<td>0.25</td>
<td></td>
<td>9.43</td>
<td>0.19</td>
<td></td>
<td>14.33</td>
<td>0.16</td>
</tr>
</tbody>
</table>

*Note. The values are averages across four trials, two performed with the left hand and two performed with the right hand, respectively.*
and their nonsystematic relationship with mean target period speaks to the independence of force and time. The nonsystematic relationship found here contrasts with the one reported by Inui et al. (1998), who found positive correlations between IRI and PF at higher rates, but is in accordance with the results of Keele et al. (1987) on isometric tapping. One reason for the incompatibility of results could be that tapping movements with contact times of up to 20% of the IRI were performed in the other studies. In the present study, in contrast, the participants were instructed to hit the force plate as fast as possible; that led to impulse durations of approximately 20 ms. Therefore, additional parameters, such as rise time to peak force, could be regarded as insignificant (see also Vaughan, Mattson, & Rosenbaum, 1998; Vaughan, Rosenbaum, Diedrich, & Moore, 1996).

In sum, the absence of significant dependencies between mean levels of PF and IRI demonstrates that, in general, humans are capable of combining arbitrary levels of force with any timing.

Variability of Peak Force

In a second set of tests, we focused on the variability of the chosen peak forces and their relationship to the specified periods. Contrary to previous conclusions of independence, the ANOVA revealed that SD(PF) significantly increased with longer target periods, F(3, 15) = 3.29, p < .05. The participants' means for the four frequency conditions were 2.51 N for the 1,000-ms period, 2.32 N for the 500-ms period, 2.23 N for the 333-ms period, and 2.01 N in the self-paced condition. We obtained a statistically significant difference, by using post hoc Tukey tests, only between the self-paced and the 1,000-ms conditions; in the latter condition, significantly higher values of SD(PF) were displayed. It is worth pointing out that the variability of SD(PF) was not correlated with the actual PF. The lack of dependence runs counter to the frequent finding in the literature on force production that variability of produced peak force increases with magnitude of force (Inui et al., 1998; Newell & Carlton; 1988 Schmidt et al., 1979).

Examining CV(PF), we obtained a significant main effect for target period, F(3, 15) = 5.14, p < .01, which expressed an increasing trend in CV(PF) with increasing target period. Pairwise post hoc Tukey tests repeated the significant differences that were already found for SD(PF), but, in addition, they marked the CV(PF) for the 1,000-ms target period as different from that of the 333-ms target interval. Those results were shown in 5 of the 6 participants listed in Table 3. Note, that in the self-paced condition the variability was lowest. That finding was valid for both variability measures and was seen in the overall means as well as in the individual participants.

Contrary to the results on the timing variables, the performance of the two hands showed significant differences. The dominant hand performed with less variability, judging from lower SD(PF), than the nondominant hand, F(1, 5) = 7.17, p < .05. An interaction between frequency and repetition was also significant (p < .05), showing that in the 1,000-ms condition the SD(PF) decreased significantly in the second trial, whereas in other target period conditions it remained constant across repetitions.

It is worth pointing out that the variability of the periodic impact forces was relatively high, with SD(PF) at approximately 2 N for mean impact forces around the overall mean of 12.74 N. That value represents an approximately 20% band of errors around the mean force. Compared with timing accuracy, precision in force control was considerably less.

In sum, the most important result is that in both SD(PF) and CV(PF), a first indication for an interrelationship between force and tapping period was seen. That effect is noteworthy because the systematic relationship was not paralleled between the mean PF and the mean IRI values. That result was already hinted at in a study by Keele et al. (1987) in which participants performed a rhythmic sequence of isometric taps. Although Keele and his colleagues emphasized other results supporting the hypothesis of an independent timing module, they nevertheless reported similar relationships in the variability estimates.

Analysis of Sequential Effects Between Peak Force and Interresponse Interval

To scrutinize the tap-to-tap variability within each trial, we performed autocorrelations and cross-correlations on the sequence of PFs and IRIs. First, the sequence of each trial's PF values was autocorrelated for a lag of up to order 5. Across all participants, 22 trials (out of 96) showed significant positive correlations for lag 1. Given that the number of taps varied across trials in the different conditions (between 50 and 150), the significance cut-off for r value (at the 5% probability level) was approximated by the formula 1.98/n10, where n equals the number of samples. We chose a conservative value of .30 for all conditions to determine significant correlations. In approximately 50% of the significant cases, also lag 2, and sometimes even lag 3, were significantly positive. The positive correlations identified adjustments that stretched across two to four taps in the PF values. Using the same analysis, we also examined the trial sequences of IRI values. Although there were no consistent effects in the paced trials, significant positive correlations for lag 1 were found in the unpaced trials for 5 out of a total of 24 trials, indicating a frequency drift across the trial.

In previous studies on accentuated tapping, Billion, Semjen, and Stelmach (1996) reported significant correlations between the peak force of the accentuated tap and the duration of the preceding and succeeding interresponse intervals. In several experimental manipulations, the authors identified a shorter than average IRI before the PF of an accentuated tap and a longer than average IRI following the accentuated tap. Although the present study differed in that there was no intentional accentuation, the question of whether the same correlations were observed in IRIs around higher than average peak forces was still relevant. In cross-
correlations calculated for lags -3 to 3, we did not detect such significant correlations. Those effects were probably attenuated either because there were smaller differences in successive peak forces or because they were not intentionally modulated.

EXPERIMENT 2

Experiment 1 gave first indications of an interaction between force and timing constraints in a rhythmic tapping task paced by metronome frequencies. Interaction effects were found between the two variability measures of force as a function of tapping period such that impact forces were maintained in a more steady way at higher frequencies than at lower ones. Force variability was lowest when participants were allowed to select their most comfortable frequency. Because we did not manipulate force level explicitly in Experiment 1, possible effects of magnitude of force on timing performance could not be addressed. To examine the possible impact of force constraints on timing variability, in Experiment 2 we prescribed three levels of target force. Continuing with the same experimental set-up, participants were given target force levels but were allowed to tap at their preferred frequencies.

Method

Participants

Six participants (3 men and 3 women), all graduate students between 23 and 27 years of age, volunteered for the experiment. None of them had taken part in Experiment 1. All participants were right-handed and free of any history of injury to either hand or wrist. Prior to the experiment, they were instructed about the nature of the experiment, about which they signed a consent form in accordance with regulations from the Human Ethics Committee at The Pennsylvania State University.

Apparatus

The experimental apparatus was identical to the one used for Experiment 1. In Experiment 2, the required target force level was presented to the participants as a thin red horizontal line on the monitor. The target line was visible before the beginning of each trial and remained visible throughout the trial, together with the impact forces produced by the participants. As such, participants had immediate visual feedback about the accuracy of their peak forces. There was no pacing at a metronome frequency, and therefore participants did not wear headphones.

Procedure and Design

As in Experiment 1, participants were instructed to tap unimanually on the drum pad by initiating the rhythmic movement from their wrist joint. Again they were instructed to move the hand and fingers as a single unit, but we used no external devices to restrain the finger and hand joints. Each participant performed four randomized practice trials at the beginning of data collection. Each trial lasted 50 s. The total data collection lasted 30 min.

Participants performed three target force levels at 5 N, 10 N, and 15 N, as well as one condition in which they were instructed to tap at their preferred force level with no visual target present. The magnitudes of the target forces were chosen on the basis of average results obtained in Experiment 1, where an overall mean of 12.74 N was recorded. We selected the three target force values to approximately bracket the preferred levels of force. For all conditions, the instruction emphasized that the force levels should be achieved as accurately and as uniformly as possible. The experiment was performed in two blocks consisting of eight trials each; all pairings of target force condition and hand occurred exactly once in each block. Within each block, the order of the target force conditions was pseudo-randomized, with the provision that participants alternate the tapping hand on each trial in order to avoid fatigue. Because no significant differences were found between the two strain gauges in Experiment 1, the drum pads were no longer switched between the two blocks.

Data Analysis

The data analysis routines were identical to the ones used in Experiment 1.

Results and Discussion

Peak Force

The trial averages of peak force were computed from the series of PF values and submitted to a 4 (target force) \( \times 2 \) (hand) \( \times 2 \) (repetition) ANOVA. The highly significant main effect for target force corroborated the finding that the participants were successful in producing three different imposed peak force levels, \( F(3, 15) = 40.55, p < .0001 \). Because the two hands did not differ in their force values, we show in Table 4 the individual participants' PF values computed as the average across the four (hand \( \times \) repetition) repetitions for each target force condition. The mean of the self-chosen PF was 12.94 N, a value similar to the finding in Experiment 1. Four participants exhibited a self-selected force level that was very close to the force level that they produced in the high target force condition. The ANOVA rendered no other significant effects.

Variability of Peak Force

The same 4 \( \times 2 \times 2 \) ANOVA just discussed revealed that \( SD(PF) \) increased significantly with increasing target force values, \( F(3, 15) = 22.05, p < .0001 \). Post hoc Tukey comparisons detailed that all pairwise differences between the three target force and the self-selected force conditions were significant; the only exception was that the self-chosen condition was not different from the 15-N condition. The mean \( SD(PF) \) values were 1.22 N at the 5-N target force, 1.71 N at the 10-N force, 2.00 N at the 15-N force, and 1.81 N at the self-selected target force. Given the vari-
TABLE 4
Mean Peak Force Values (PF, in Newtons) and Their Standard Deviations SD(PF), in the Four Force Conditions Produced by the 6 Participants In Experiment 2

<table>
<thead>
<tr>
<th>Target</th>
<th>Participant 1</th>
<th>Participant 2</th>
<th>Participant 3</th>
<th>Participant 4</th>
<th>Participant 5</th>
<th>Participant 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PF</td>
<td>SD(PF)</td>
<td>PF</td>
<td>SD(PF)</td>
<td>PF</td>
<td>SD(PF)</td>
</tr>
<tr>
<td>5 N</td>
<td>5.52</td>
<td>1.08</td>
<td>6.21</td>
<td>1.38</td>
<td>5.12</td>
<td>1.25</td>
</tr>
<tr>
<td>10 N</td>
<td>10.75</td>
<td>1.42</td>
<td>10.95</td>
<td>1.83</td>
<td>9.88</td>
<td>1.87</td>
</tr>
<tr>
<td>15 N</td>
<td>14.94</td>
<td>1.57</td>
<td>16.27</td>
<td>2.15</td>
<td>15.10</td>
<td>2.31</td>
</tr>
<tr>
<td>Self-selected</td>
<td>14.99</td>
<td>1.55</td>
<td>16.42</td>
<td>2.06</td>
<td>14.18</td>
<td>2.04</td>
</tr>
</tbody>
</table>

*Note.* The values are averages across four trials, two performed with the left hand and two performed with the right hand, respectively.

![Figure 4](image)

**FIGURE 4.** Mean values of coefficients of variation of peak force, CV(PF), plotted against the mean target forces in the 5-N, 10-N, and 15-N target force conditions, and the self-selected force condition for all 6 participants in Experiment 2. The self-selected condition has been inserted on the basis of each participant's self-selected force level.

The distribution of mean PF values around the target force value, the data of SD(PF) were also regressed against their respective mean PF. Each individual participant showed a significant linear regression, with $r^2$ values ranging between .45 and .77, except Participant 6, who had $r^2 = .01$. Those results are in agreement with trends seen previously in discrete movements (Schmidt et al., 1979), isometric movements (Newell & Carlton, 1985), and rhythmic movements (Inui et al., 1998). In comparison with the results of Inui and colleagues, the present relationship was considerably more stringent because we tightly prescribed the force levels. In addition, the ANOVA also yielded a significant hand effect, showing that the dominant hand displayed less variability across all four conditions, $F(1, 5) = 7.76, p < .05$.

Next, an ANOVA conducted on the coefficients of variation of peak force CV(PF) rendered the main effects for target force and hand as significant: target force, $F(3, 15) = 24.88, p < .0001$; hand, $F(1, 5) = 15.37, p < .05$. As Figure 4 shows, CV(PF) displayed a systematic decrease with increasing target force. Following the same convention introduced above, the dark columns were rank-ordered on the basis of the participants' self-selected force level. Not only was that effect significant across the entire data set, it was also displayed by all individual participants. Using
pairwise Tukey tests, we found that the difference between the hands in $CV(PF)$ was significant for all target force values, although the dominant hand showed less variability at all target forces. The joint observation of an increase in $SD(PF)$ with a decrease in $CV(PF)$ is contrary to Weber's law but is in line with findings in discrete isometric force control (Carlton & Newell, 1993).

It is important to highlight that the analysis of $SD(PF)$ and $CV(PF)$ in the individual participants revealed that the self-selected conditions ordered with the systematic relationship seen in the target force conditions. As we have already argued, assuming that the oscillatory movement of the hand is a stable oscillation assembled for the task, one could expect tapping with a comfortable impact force to correspond to the intrinsically preferred mode of performance and, hence, to be accompanied by the lowest level of fluctuations. Similar to our expectations concerning the $IRI$ data of Experiment 1, that expectation was not confirmed. Rather, absolute magnitudes of impact force appeared to determine the level of accuracy.

**Interresponse Intervals and Their Variability**

To determine whether the specified target forces induced a specific timing structure on the participants' rhythmic performance, we computed the mean $IRIs$ and their variability measures in terms of $SD(IRI)$ and $CV(IRI)$ for each trial. Averaged across all participants, the mean $IRIs$ for the target forces 5 N, 10 N, and 15 N, and for the self-selected force were 318 ms, 327 ms, 329 ms, and 335 ms, respectively. The associated $SD(IRI)$ were 22 ms, 20 ms, 20 ms, and 19 ms, respectively. Although the 4 (target force) $\times$ 2 (hand) $\times$ 2 (repetition) ANOVA did not detect any systematic dependence of either $IRI$ or $SD(IRI)$ on target force, 2 participants nevertheless displayed a significant trend wherein $IRIs$ increased with increasing target force; that trend was weakly reflected in the overall means. For the regressions of $SD(IRI)$ on target force, the $r^2$s for the 2 participants were .43 and .38. Additionally, the ANOVA showed significantly different $SD(IRI)$ for hand, $F(1, 15) = 8.55, p < .01$, indicating that the nondominant hand showed higher variability throughout all target forces. That result corroborated the similar differences in regularity between the two hands on $SD(PF)$ found earlier.

The same three-way ANOVA performed on $CV(IRI)$ revealed that $CV(IRI)$ was systematically dependent on the target force level, $F(3, 15) = 5.48, p < .01$ (Figure 5). With Tukey post hoc analyses, we identified all pairwise contrasts as significant, with the one exception that $CV(IRI)$ in the self-chosen condition was statistically identical to the one for the highest target force. The second main effect on hand repeated the earlier observation that the dominant hand performed with a lower level of variability, $F(1, 15) = 20.50, p < .01$. In Figure 5, the overall analysis is split into the participants’ results. Again, the self-selected condition was

![FIGURE 5. Mean values of coefficients of variation of interresponse intervals, $CV(IRI)$, in all four target force conditions (5 N, 10 N, and 15 N, and self-selected) of Experiment 2. The self-selected condition has been inserted on the basis of each participant's self-selected force level.](image-url)
rank-ordered with the target force conditions according to the mean values that the participant chose across the four trials. It can be seen that in all participants the lowest force level was accompanied by the highest variability in timing. When participants self-selected their force levels, 3 of the 6 participants preferred forces higher than the 15-N condition; that condition was consequently accompanied by lower variability. Remember that in the instructions for performing the task, it was implied that the participants were to tap with a self-chosen rhythm that was as regular as possible.

Analysis of Sequential Aspects in the Time Series

As we had done in Experiment 1, the temporal correlations in the sequence of IRI$s and PF$s and their cross-correlations were evaluated. Autocorrelations of lag 1 in the IRI sequence showed significant positive correlations in 28 out of 96 trials (29%). The cut-off for significance was uniformly set to a conservative value of $r = .30$, although the number of observations varied because of the frequency participants chose. In some cases, autocorrelations of lag 2, and in a few cases even lags 3 and higher, were also positive at a 5% significance level. Those results signaled that participants tended to accelerate their tapping frequency throughout one trial. A complete set of trials of 1 participant is illustrated in Figure 6, which shows the sequence of IRI$s for each of the trials. Given that variability in PF was lower for shorter IRI$s, the acceleration in the tapping may have reflected the participants’ attempt to improve their tapping accuracy.

We explored the relationship between PF and the adjacent IRI value by computing cross-correlations between PF and IRI, using the same lags as in Experiment 1. Following Billion, Semjen, and Stelmach (1996), a negative correlation for lag 0 and a positive correlation for lag 1 should be expected. Those predictions were confirmed only in a small number of trials, however, and no other consistent pattern was found. That finding was unexpected because the results had been shown to be very robust in tapping sequences with individual tap accentuation. Evidently, the intentional increase of peak force is necessary for such preparatory action. On the other hand, in rhythmic isometric actions as well, similar time-force correlations have been found (Keele et al., 1987). We conjecture that compared with the free effector trajectory in dynamic performance, which allows many possible compensatory modulations of the trajectory, there was less room to extricate kinematic from kinetic parameters in Keele’s experimental protocol.

In sum, in this experiment additional evidence emerged in support of the hypothesis that force and timing constraints in a rhythmic tapping task interact. Although there was no connection between the absolute magnitudes of PF and preferred IRI, an additional link between timing and force production was found in the decrease in timing variability CV(IRI) associated with increases in target force. That result is in agreement with the finding that, under the instruction to minimize timing variability, participants also chose PF levels that were closest to the highest target force.

![Figure 6](https://example.com/figure6.png)

**FIGURE 6.** All trial sequences of interresponse intervals (IRIs) of 1 representative participant. The graph shows the acceleration of IRIs throughout each of the trials.
level. Furthermore, in a considerable number of cases the presentation of the rigorous force constraints had the effect of preventing participants from maintaining a constant mean IRI. The mean IRI tended to drift systematically toward shorter mean IRIs over the course of the trial. That observation is directly linked to the finding of Experiment 1 that force variability decreased at faster tapping rates. It thus appears as if participants accelerated in order to reduce their variability in the series of peak forces.

**EXPERIMENT 3**

Thus far, in Experiment 1 we demonstrated that the imposition of even very loose force constraints upon a rhythmic task had consequences for the force variability of the movement such that force variability decreased at faster tapping rates. In a complementary fashion, Experiment 2 provided evidence that controlled force constraints give rise to change in the variability of rhythmic timing such that the variability decreased for higher peak forces. In Experiment 3, we explored directly once more the interaction between force and timing constraints by imposing explicit constraints on both timing and force production simultaneously.

**Method**

**Participants**

Six participants (4 men and 2 women; age range 22–28 years) from the University population participated voluntarily. None of them had participated in Experiments 1 or 2.

Five were right-handed and 1 left-handed. None reported previous injuries to their wrists and forearms.

**Apparatus and Task**

The experimental station for this experiment was identical to the one used for the previous two experiments.

**Procedure**

As in the preceding two experiments, participants were instructed to tap rhythmically, moving primarily at their wrist joint while keeping the hand and fingers as a fixed unit. Target frequencies were presented by the same auditory metronome signal used in Experiment 1, and target forces were displayed as they were in Experiment 2.

**Experimental Conditions**

Participants were given both frequency and force targets for each trial. The target periods were the same as those used in Experiment 1 (333 ms, 500 ms, and 1,000 ms, and self-paced) and the force targets were the same as those of Experiment 2 (5 N, 10 N, 15 N, and self-selected) in a fully crossed 4 (target period) × 4 (target force) × 2 (hand) × 2 (repetition) within-participant design. Because of the larger number of trials, the data were collected in two sessions, which occurred, in most cases, within 24 hr of each other. In each session, participants performed under every combination of force, period, and hand condition once. The conditions were presented in pseudo-randomized order, with

![Figure 7](image)

**FIGURE 7.** Overall means of all participants, showing coefficients of variation of interresponse intervals, CV(IRI), decreasing with higher force levels in Experiment 3. The average of the self-selected force conditions was 10.6 N, and CV(IRI) rank-ordered with the prescribed force.
the proviso that the right and the left hands alternate in succeeding trials. As before, trials were 50 s in duration.

Data Analysis

The data collection and analyses procedures in Experiment 3 were the same as in Experiments 1 and 2. For each trial, the mean values of the trial sequence of produced peak forces $PF$, produced interresponse intervals $IRI$, and their respective standard deviations $SD(PF)$, and coefficients of variation $CV(PF)$, were calculated and submitted to the analysis of variance.

Results and Discussion

Interresponse Intervals and Their Variability

The mean $IRI$ values attained for the target period conditions, when collapsed across all experimental conditions, confirmed that participants generally tapped at the periods specified by the metronome. That expected result was evidenced by a $4 \times 4 \times 2 \times 2$ (unpaced trials) ANOVA, $F(3, 45) = 128.89, p < .0001$. The overall average $IRI$ values in the three timing conditions were 998 ms, 499 ms, and 332 ms. The self-chosen period was 381 ms, with individuals ranging between 282 ms (Participant 6) and 640 ms (Participant 3). A significant interaction was also obtained between period and force, $F(9, 45) = 2.92, p < .01$; the interaction was obtained because in the unpaced trials participants tapped with longer periods when they had to produce the higher target forces. That observation was seen as a significant trend in 5 out of 6 participants (regression slopes differed from zero). Whereas the dependence between the magnitudes of peak force and period was not significant in Experiments 1 and 2, it should also be kept in mind that the main effect for target force was not significant.

As in the preceding two experiments, interactions between the force and the time domain were primarily observed in the fluctuations of $IRI$ and $PF$, rather than in the absolute mean values. When the same $4 \times 4 \times 2 \times 2$ ANOVA was performed on $SD(IRI)$, a main effect for period repeated the finding of Experiment 1 that variability increased with the duration of the interresponse interval, $F(3, 15) = 20.25, p < .0001$. The $SD(IRI)$ averages across participants and conditions were 54 ms (1000-ms period), 26 ms (500-ms period), 19 ms (333-ms period), and 22 ms (self-selected period). Furthermore, in the second repetition, $SD(IRI)$ decreased from 32 ms to 29 ms in their overall means, $F(1, 5) = 29.06, p < .01$. No other effects were significant. More important, $SD(IRI)$ did not show any dependence on the target force.

Using the $CV(IRI)$ as an additional variability estimate in the ANOVA, however, we identified a systematic decrease in $CV(IRI)$ with specified target force, $F(3, 45) = 3.68, p < .05$ (Figure 7). In pairwise Tukey comparisons, we identified all differences as significant except the self-selected force condition (mean = 10.6 N), which did not differ significantly from the 10-N condition. When that effect was
scrutinized for the four period conditions separately, we found that the 333-ms and the self-paced conditions produced the effect clearly, whereas the 500-ms and 1,000-ms conditions did not show the same strong modulation. Although not extremely strong, that result replicated the effect obtained in Experiment 2 (compare with Figure 5). No other effect was significant. One additional main effect in the ANOVA on repetition revealed that the second trial in each condition showed a lower value of CV(R(T)), F(1, 45) = 21.66, p < .01. The latter finding appeared to reflect improvement in participants' performances.

Magnitude and Variability of Peak Force

The mean peak force estimates reflected the following not unexpected systematic dependencies: Besides the strong main effect of target force, F(3, 15) = 70.77, p < .0001, there was a weakly significant interaction between target force and repetition. That finding points to the fact that the three target force conditions were overshot initially but approached the target more accurately in the second repetition. Also, the self-chosen force dropped by approximately 1 N in the second repetition. Consistent with previous findings, the peak force values for the dominant hand were higher in all force conditions than those of the nondominant hand, F(1, 5) = 7.65, p < .05.

More informative were the results for the variability estimates. First, SD(PF) again followed the expected relation in that it increased with target force, F(3, 15) = 35.96, p < .0001. When the self-chosen condition was ordered in magnitude with the specified force conditions, the variability measure replicated the previously found systematic ranking. That increase appeared across participants and across target periods, as depicted in Figure 8. The main effect for hand signified that the nondominant hand's tapping was accompanied by less variability, F(1, 5) = 36.74, p < .01. However, the lower variability was partially a result of the lower mean peak forces produced by the nondominant hand, as indicated by the previous finding. The interaction between force and hand was also significant, F(3, 15) = 13.23, p < .001, indicating higher PF values for the dominant hand.

By analyzing CV(PF) in the same manner, we obtained a similar set of effects. Consistent with the findings of Experiment 2, CV(PF) decreased as target force increased, F(3, 15) = 20.87, p < .0001, and the nondominant hand was associated with significantly higher variability, F(1, 5) = 10.41, p < .05.

Of central concern are the results that connect the kinetic with the temporal measures. In corroboration of the force–time interaction found in Experiment 1, participants displayed a systematic increase in SD(PF) with increasing period of movement, F(3, 15) = 9.00, p < .01. However, we concluded from post hoc Tukey tests that the significant main effect was brought about by a significant pairwise difference between the 1,000-ms condition and all of the other pacing conditions, and there were no pairwise differences between other conditions. By examining CV(PF) and its
relation to target period, we obtained a main effect for period, $F(3, 15) = 22.38, p < .0001$. Figure 9 illustrates the finding that the variability in tapping force, measured as $CV(PF)$, tended to be highest for the slowest tapping rate. The interaction between force and period was also significant, $F(9, 45) = 4.05, p < .001$. That effect captured the fact that in the highest target force, tapping at a fast rate lowered the variability in the sequence of peak forces.

Taken together, all results concerning the interrelation between force and time measures confirmed the results found in Experiments 1 and 2. Most important, the results made no difference between the self-selected conditions and the conditions where peak force or period was prescribed. That finding shows that feedback had no effects. The only new effect was the trend that longer periods tended to covary with higher forces in self-selected conditions.

**Analysis of Sequential Effects in Tapping Sequence**

To determine the effects of the dual task constraints on the correlational structure of the tapping sequence, we again autocorrelated the trial sequences of $IR$ and $PF$ with lags up to order 5. Analyses of $IR$ indicated that in the paced trials the $IR$ showed significant negative autocorrelations at lag 1. That finding, however, demonstrated only that deviations from the metronome-specified periods were corrected for in the adjacent $IR$. More interesting were the consistently positive autocorrelations for lag 1 and higher in the unpaced trials, repeating the observation of both Experiments 1 and 2. All 6 subjects showed a significant tendency to speed up the tapping interval (see Figure 6). Autocorrelations performed on the $PF$ sequences yielded no consistent pattern of results. Regardless of the pacing conditions, the autocorrelations hovered around zero, showing that the variability of $PF$ had no detectable structure.

Finally, in the cross-correlations we aimed to identify dependencies between $PF$ and $IR$. There were individual trials that showed positive correlation coefficients for lag 1, indicating that high $PF$ were followed by longer $IR$. However, the proportion of the total number of such trials was less than 10% of the entire data set. Because those significant correlations occurred across all target force and target period conditions, the trends are difficult to interpret. Contrary to results of Babilon, Semjen, and Stelmach (1996), none of the subjects showed any hint of a negative cross-correlation at a lag −1.

**GENERAL DISCUSSION**

Rhythmic tapping has become established as the prevailing paradigm for examining the mechanisms and limitations of the perception and production of temporal intervals (Collyer & Church, 1998; Keele, Pokorny et al., 1985; Michon, 1967). A number of different tapping protocols have been employed in which the pacing conditions (with and without metronome), the effects used for tapping, the complexity of the temporal structure, and the accentuation of individual taps have been varied. The literature is to some degree spurred by the anecdotal observations that performers such as piano players and drummers can subtly produce subtly varying temporal intervals between key strokes or contacts. Indeed, in view of those skills, it is often professed that the control of timing must be independent from the control of force because, for instance, a piano player can play the same piece of music at any desired volume. On the other hand, accentuation, that is, the control of the impact force, is an inextricable facet of how the piano player or drummer creates aesthetic expression. The question examined here was whether the impact force is independent from the concomitant temporal variations or whether there are interdependencies between the production of force and the temporal structure of the movement sequence. In the overwhelming majority of finger-tapping studies, only the temporal intervals between contacts have been of interest; and as a result, the contact forces that the taps produce have been ignored.

The assumption of independence of timing from force control is in stark contrast to the almost trivial fact that timing and development of force are tightly intertwined. To produce a given movement amplitude at varying movement times, one must scale the accelerating or decelerating force impulses. To produce a more forceful movement, the central nervous system must recruit more motor units or implement frequency modulation, or both, leading to, for example, an increase in the rise time to peak force. Specific demonstrations of the interdependence between temporal and force parameters have been obtained in tasks involving isometric forces where the shape of the impulse and the characteristics of the force–time curve were precisely prescribed and monitored (Carlton, Kim, Liu, & Newell, 1993). In addition, if the rhythmic tapping action is assumed to be an oscillatory system, then one has to make specific adjustments to the kinematics especially during the downward stroke in order to produce the desired acceleration and, hence, impact force. The impact event itself is also a critical perturbation to the otherwise smooth oscillation. How does the system deal with such perturbations?

Our major goal in the present series of experiments was to examine whether timing and its variability would be modified when the impact force of the repeated taps was controlled. In Experiment 1, the effects of the explicit instruction to produce a constant impact force on the variability in rhythmic timing in a wrist-tapping task were examined. The sequence of peak forces was displayed online and provided feedback about the produced impact force as well as visual orientation to the participant. Experiment 2 complemented the first study in that target forces were prescribed as goal lines that were presented to the participant on a monitor. In addition, the participants were instructed to maintain a constant rhythm at the chosen pace. The conditions of Experiment 3 provided a combination of those force and time task prescriptions. We conjectured that the temporal accuracy would be influenced by impact force and that the structure of variability in the interresponse
intervals would be affected by variations in the produced peak forces.

The major thrust of the analyses was on mean performance within a trial, and performance averages and variability estimates served as the main dependent measures. In a second set of analyses, we examined the tap-to-tap structure, searching for changes in the temporal structure of each trial. In the first two experiments, where either tapping force or period was prescribed, leaving tapping period and force unconstrained, respectively, participants did not show any preferences for pairing impact forces with intertap intervals. In fact, the range of mean peak forces displayed by the participants in the metronome-paced trials of Experiment 1 was considerable (1.7 N to 26.9 N). In addition, the range of self-chosen tapping frequencies under given force targets was also unsystematic but was less variable across participants. All participants tapped at periods ranging approximately between 200 and 800 ms, a period that is close to the natural frequency of the wrist. It was only in the self-paced conditions of Experiment 3 that a trend appeared in 5 participants, showing that longer periods were accompanied by higher forces. Overall, the results from the mean data suggest that force and time are independent, just as Keele and colleagues have shown in a series of articles (Keele et al., 1987). Moreover, the striking difficulty that participants had in achieving a constant sequence of peak forces, in contrast with their ease of reproducing the intertap intervals specified by the metronome, enhances the impression that the control of force and the control of timing are governed by different mechanisms (cf. Inui et al., 1998).

A different picture emerged, though, when the variability measures of the series of temporal intervals and impact forces were examined. In agreement with the two lines of literature on force and time control, the band of fluctuations around the mean performance, measured in standard deviations, increased with the magnitudes of the produced peak forces and periods. Conversely, the Weber's fraction, or coefficient of variation, decreased concomitantly, negating the original hypothesis of Weber (1843). In Experiments 1 and 3, SD(iri) increased with increasing IRI, but CV(iri), the Weber fraction, decreased under the same conditions. Experiments 2 and 3 showed a similar pattern in the variability of force production. SD(pf) increased as PF increased, but CV(pf) decreased with increasing PF. Those observations held in conditions where both force and period were prescribed and in conditions where only time or force was prescribed. Both of those results are similar to well known findings in discrete movement and isometric force tasks (Carlton & Newell, 1993; Schmidt et al., 1979; Wing, 1980), but they have not been identified previously in rhythmic tapping.

Against this backdrop of familiar results, two further novel interrelations were identified. First, the variability in the intertap intervals, for both the self-selected and prescribed forces, decreased with higher target peak forces. That effect, however, was discerned only in the normalized measure of IRI variability, CV(iri). The recurrent effect can be linked to the observation that the self-chosen peak forces were closer to the highest prescribed forces. Participants may thereby have optimized their timing accuracy. Second, the variability in force production was lower for faster tapping rates. That effect was demonstrated in both SD(pf) and CV(pf). The second finding also seemed to provide a rationale for the frequent observation that in unpaced trials participants tend to speed up their tapping rate. An interpretation of that finding could be that they accelerated their tapping rate to improve their accuracy in the train of impulses.

Although in these analyses we focused on the average measures across trials, that is, a sequence of approximately 50 to 150 taps, in another set of analyses we attempted to uncover interrelation effects across the sequence of individual taps. In a series of studies, Billon, Semjen, and Stelmach (1996) identified strong preparatory and follow-up effects surrounding a stressed tap. Initially the authors adopted an information-processing standpoint and argued that force modulation increased processing time and, hence, had effects on the interval as well. In later work, in which they also recorded the tapping trajectory and analyzed the variability of different kinematic landmarks of the cycle, the authors proposed a two-stage open-loop model of endpoint programming: Instead of a central clock that triggers tapping movements, which are then accompanied by variable delays, the authors found that the temporal intervals between taps were less variable than extrema in the trajectory, and, hence, they suggested that the endpoint, the time of tap contact, is programmed. Subsequently, spurred by results from a deafferented patient, they argued that the specific compensatory relations found in a fine-grained analysis of the finger kinematics are better understandable with an oscillator concept. That theoretical framework has the advantage that perturbations can be compensated without assuming feedback-based corrections. Also, as mentioned previously, the interconnection between force and time is a natural feature of such a model. Pick, Glencross, Barrett, and Love (1993) additionally found evidence that at least part of the temporal effects from force modulation is the result of mechanical factors. In their study, relatively higher and lower force levels for the accentuated tap were contrasted, and part of the effect seen in the IRI was found to be caused by mechanical factors; that is, IRI increased or decreased as a function of force level, and therefore the changes could not be attributed to processing time alone.

We conjectured that we might see similar effects in the spontaneous variations across different tap forces. However, those expectations were not confirmed in the tap-to-tap analyses of the three experiments. Cross-correlations calculated for a range of lags did not reveal systematic effects for either peak force or intertap interval. It is possible that in our experimental task the processing demands did not impose themselves onto the output, because the variations in peak forces were not voluntarily produced. On the other
hand, autocorrelations performed on PF sequences showed that changes in impact forces were found across sequences of two to four taps, indicating that the individual taps were not independently corrected. That finding means that the force adaptations from trial to trial are not entirely random. Last, positive autocorrelations in the IRI sequence showed that participants tended to accelerate their tapping frequency in the unpaced conditions.

One additional aspect that determined the choice of conditions was our interest in contrasting experimentally prescribed conditions against comfort conditions. The concept of oscillators has been introduced so that timing and accuracy in rhythmic movement sequences can be better understood (Billon, Semjen, Cole, & Gauthier, 1996; Daffertshofer, 1998; Large & Koller, 1994). If one assumes that the so-called internal clock is a self-sustained oscillator or an ensemble of oscillations, or that the effector system adopts properties of a task assembled oscillation (Kugler & Turvey, 1987), or both, one would expect that the un prescribe preferred mode of tapping should reflect the most stable mode of the oscillator system with the least amount of fluctuations. Contrary to those expectations, the experimental results showed that fluctuations were largely determined by the magnitude of the temporal interval and the magnitude of the impact force. Fluctuations or the level of inaccuracy appeared to reflect the resolution properties rather than the stability properties of the system. Another way to understand this fact is that in paced conditions feedback information about the error is available at every tap.

We conducted the present experiments primarily to identify whether there are interrelations between force and time demands that may influence the analysis of rhythmic timing. However, the results are viewed as a first step toward an oscillator account for rhythmic tapping. Therefore, we offer some speculations as to what kind of oscillator it may take to produce the desired effects. It should be noted that compared with other work on an oscillatory account of rhythmic limb movements (e.g., Collins & Richmond, 1994; Daffertshofer, 1998; Kay, Kelso, Saltzman, & Schöner, 1987), the present tapping task included one critical new aspect that made it different from all the other movements that have been examined in the literature concerned with oscillator models: an impact. A central question concerns what parameters of an oscillatory trajectory need to be manipulated if impact force is to be controlled. Is it amplitude or local kinematic features such as the velocity of the downward trajectory prior to contact that is modulated? If impact force at a specified location in the cycle is modulated by movement amplitude, then amplitude and frequency must be independent of each other, because tapping actions obviously require separation of frequency from force. However, that notion runs counter to the typical characteristics of a nonlinear oscillator, where amplitude becomes smaller at higher frequencies (e.g., Kay et al., 1987). Any further insight into those questions can be obtained only if data from movement kinematics are also available, and we therefore postpone more discussion for future research. Clear though is the fact that, despite the increasingly more frequent invocation of oscillators as constituents in the timing of rhythmic movements including tapping, the formal modeling of those movement sequences poses several new challenges.

In conclusion, variability in the temporal structure of tapping movements is affected by the impact forces produced during the tapping actions. That finding points to the interdependence of the contributions of force and time to rhythmic tapping. The implication for theory is that the timing of rhythmic tapping is not strictly a timing problem per se.

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