The Effects of Stimulus Rate and Tapping Rate on Tapping Performance

Benjamin Rich Zendel, Bernhard Ross, & Takako Fujioka
Rotman Research Institute, Baycrest Centre, Toronto, Canada

When finger taps are synchronized with an isochronous click, it is known that tap-click asynchrony and its variability increase with the interonset interval (IOI). It remains unclear whether these results are due to the IOI or the intertap interval (ITI) duration. The present study examines how these two factors influence tapping performance by altering the tap-click ratio (i.e., 1:*n* tapping). It has been shown that holding the ITI constant while decreasing the IOI—so that extra clicks subdivide each tap—results in a reduction of tapping variability, described as a subdivision benefit (Repp, 2003). Two questions remain: Does asynchrony and variability increase with the ITI while holding the IOI constant? Does asynchrony decrease with the IOI while holding ITI constant? Using linear regression, both asynchrony and variability decreased with the IOI, with little additional effect of ITI. In contrast, when using ITI as a predictor, the contribution of IOI was significant, suggesting that IOI is the main determinant of tapping performance. In addition, an ANOVA revealed a disadvantage for 1:3 tapping, supporting a categorical distinction between duple and triple meters since 1:*n* tapping can engender the subjective feel of different metric structures.

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In music, rhythm refers to the temporal structure of acoustic events. Patterns of rhythmic events can be formed based on the interonset interval of successive rhythmic events (London, 2004). Listeners can infer the perception of a beat from a rhythmic event and then subjectively organize it into a hierarchy of stronger and weaker beats called meter (Jones & Boltz, 1989; Lerdahl & Jackendoff, 1983). The feeling of meter can arise from interactions between various acoustic features within the musical stream, such as timing, intensity, melody, and harmony (Hannon, Snyder, Eerola, & Krumhansl, 2004); however, perception of meter is a subjective phenomenon. Even when listening to identical isochronous sounds (e.g., metronome clicks), listeners can establish and maintain a subjective metric structure (Bolton, 1894; Brochard, Abecasis, Potter, Ragot, & Drake, 2003; Temperley, 1963).

Synchronizing movements with temporally predictable rhythmic stimuli, such as music or the conductor's baton, is called sensorimotor synchronization (SMS). Performing a SMS task consists of a number of cognitive processes. One must extract precise timing information from the environment, encode it, predict the time interval for the next action, and plan and execute the movement in time accordingly. SMS is important for many aspects of movement and perception, such as dancing or music performance, and has thus attracted researchers for over a century (for a review, see Repp, 2005).

One way to test performance of SMS in the auditory domain is to examine tapping performance in relation to an isochronous acoustic stimulus. Once a participant has become entrained to a transient isochronous auditory stimulus (hereto described as a 'click'), her taps tend to precede the click by anywhere from tens of milliseconds to just a few milliseconds (Aschersleben, 2002; Klemmer, 1967; Repp, 2003, 2005; Woodrow, 1932). This indicates that the tap is not a response to the previous or the current stimulus, but rather a prediction of the time interval to the next stimulus, based upon the encoding of the time interval between, at least, the previous two stimuli. The mean of multiple tap-click asynchronies can be used to describe the accuracy of the tapping performance, while the standard deviation of multiple tap-click asynchronies can be used to describe its variability (hereto described as mean-asynchrony and variability).

A second common finding of SMS research in the auditory domain is that the stimulus rate, or stimulus interonset interval (IOI), at which participants can synchronize in such a predictive and consistent manner has limits. The lower IOI limit (i.e., the fastest stimulus rate) is around 200 ms for adults who are not familiar

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with SMS tasks. Interestingly, this threshold can be as low as ~100 ms when subjects are trained (e.g., musicians) and can use multiple limbs (e.g., alternating taps from the left to the right hand; Pressing & Jolley-Rogers, 1997; Repp, 2005). The upper limit is less clearly defined. Early studies suggested that synchronization becomes more difficult when the IOI exceeds 1800 ms (Fraisse, 1982). More recent studies have demonstrated that participants can synchronize up to an IOI of 3500 ms, although IOIs above that were not tested (Repp & Doggett, 2007).

A third common finding of auditory SMS research is that within a window between the upper and lower limits, tap-click asynchrony and variability increase as IOI increases (Kolers & Brewster, 1985; Peters, 1989). Specifically, tapping variability is generally proportional to the IOI, suggesting that the relationship between tapping variability and IOI follows Weber's law (Peters, 1989). On the other hand, tapping asynchrony tends to increase with IOI; however, there are some nonlinearities within this relationship (Repp, 2003). Together, these findings suggest that performance of predictive and synchronized tapping depends on the stimulus rate, as long as there is a 1:1 tap to click ratio.

However, in a 1:1 tapping task, it is impossible to determine whether increased asynchrony and variability are due to the increased IOI *or* ITI. To investigate the separate influence of IOI and ITI, one has to vary one of the factors, while the other is held constant. This can be accomplished by varying the tap-click ratio such that participants tap to every second, third, or n^{th} click (1:*n* tapping). Surprisingly, only a few studies have investigated how tapping performance varies in this task (Repp, 2003, 2007; Semjen, Schulze, & Vorberg, 1992). Repp (2003) first examined how the lower IOI limit was influenced by using a 1:*n* tapping task. He found that for IOIs below 200–250 ms the variability increased during 1:*n* tapping compared to 1:1 tapping (termed as a "subdivision cost"), whereas for IOIs above 200–250 ms, tapping variability decreased (termed as a "subdivision benefit"). Accordingly, he termed the IOI range of 200–250 ms range as the "cost-benefit transition point." He associated his results with metric processing as a combination of "internal clocks" or oscillators, each entraining a separate level of periodicity in the metric hierarchy (Large & Kolen, 1994; Povel & Essens, 1985). When the IOI is above the cost-benefit transition point, the oscillator encoding the ITI benefits from the oscillator encoding IOI; in other words, the added clicks between each tap reduce tapping variability. In addition, because the 1:*n* tapping task requires encoding of at least two temporal periodicities (IOI and ITI) in parallel, the ITI must be at least double the lower IOI limit (for 1:1 tapping) to benefit from 1:*n* tapping modes, and, if the ITI falls below this point, tapping performance should deteriorate (London, 2002). Interestingly, the cost-benefit transition point was different for 1:2 tapping (IOI = ~200 ms) compared to 1:3 tapping (IOI = ~250 ms), suggesting an additional influence of the number of subdivisions on tapping performance.

Another study by the same author tested if different strategies of entrainment to rhythmic stimuli differentially influence tapping performance (Repp, 2007). To test this possibility the tap-click ratio was varied from 1:1 to 1:9. Again, Repp focused on the lowest IOI that could be synchronized to, and compared this limit in two conditions. First, 1:*n* tapping tasks were performed in a repeating cyclical pattern that encouraged "internal clock" processing. Second, participants were asked to tap to the n^{th} click of a sequence that did not repeat. The author hypothesized that this would encourage a counting strategy. The results showed that in the cyclical tapping condition, synchronizing to lower IOIs was particularly difficult when the tap-click ratio was 1:5 and 1:7 compared to 1:2, 1:3, 1:4, and 1:8, whereas, results in 1:2, 1:4, and 1:8 were similar. On the other hand, in the counting condition, such a categorical difference among different *n* was absent. These findings support the idea that cyclical 1:*n* tapping tasks likely employ multiple internal clocks or oscillators, and that such metric hierarchies can be categorized into distinct groups according to the ratio of these oscillators.

There are, however, two unresolved questions about the factors that influence tapping performance in metrically subdivided tapping. First, it is not clear whether the subdivision benefit observed in tapping variability for 1:*n* tapping tasks is only related to the shorter IOIs compared to the 1:1 tapping task. In Repp (2003), the variability for 1:*n* tapping was actually larger than what would be expected in 1:1 tapping at the same IOI. For example, the tapping variability for 1:2 tapping with an ITI of 1200 ms (i.e., IOI = 600 ms) was ~27 ms, larger than that of ~22 ms for 1:1 tapping (i.e., ITI & IOI = 600 ms). While this tendency seems consistent across the various ITIs in his data, he examined only short IOIs, mostly below 400 ms. This narrow range of ITIs made it difficult to determine the separate influence of IOI and ITI. Consequently, the influence of ITI across the same IOI has not been clearly determined for a wide range of IOIs within the synchronization limits.

Second, it is unclear whether the tap-click asynchrony is also influenced by having different ITIs in 1:*n* tapping tasks. While both tapping asynchrony and variability decreased as ITI was shortened in the previous study (i.e., faster tapping; Repp, 2003, Figures 4 & 5), the actual benefit of 1:*n* tapping compared to 1:1 tapping with the same ITI was only statistically analyzed and described in detail for tapping variability. The author mentioned that the large interindividual variability might have resulted from the heterogeneity of skill levels of his participants including nonmusicians and musicians with different levels of experience in SMS tasks. If participants were more homogenous, the tap-click asynchrony may also exhibit systematic effects of subdivision as reduced asynchrony compared to the asynchrony observed in 1:1 tapping, which could be described as another form of "subdivision benefit."

The current study was therefore designed to examine the effects of IOI and ITI on tapping performance, using a 1:*n* tapping paradigm (n = 1, 2, 3, or 4). We hypothesized that testing musicians with similar levels of training experience would reduce interindividual variability in tapping performance, thus allowing us to examine the effects of IOI, ITI, and their interactions for both tapping asynchrony and its variability over a wide range of rates. Specifically, the interval range was chosen to be above the cost-benefit transition point described by Repp (2003) so that we could assume a subdivision benefit for the variability in all of our conditions. To test the influence of these factors, we employed two types of statistical analyses. First, we used an ANOVA that included the factors Tap-click ratio and either IOI or ITI for selected sets of conditions. Second, we examined linear regression models using either IOI or ITI as a predictor for time, and Tap-click ratio, n, as a second predictor to determine the impact and relationship of both factors. These two analyses explain different aspects of the data. The ANOVA allows for a systematic comparison of how different tap-click ratios influence tapping performance at each level of the IOI or ITI. The regression analysis allows for a global analysis of how increasing the IOI or ITI by varying the tap-click ratio influences tapping performance over a wide range of IOIs and ITIs. Also, the regression analysis allows us to include data points from IOIs or ITIs even if a matching IOI/ITI condition for different tap-click ratios was above or below the synchronization limits for 1:1 tapping (e.g., ITI of 260 ms cannot be examined for 1:3 [IOI = 86.6 ms] or 1:4 [IOI = 65 ms] tapping because the corresponding IOI would be much lower than the synchronization limit). We expected tapping asynchrony and its variability to increase with IOI, which would be consistent with previous research (Kolers & Brewster, 1985; Peters, 1989). We also expected that tapping asynchrony and its variability would increase with ITI, because regardless of the tap-click ratio, ITI covaries with IOI. Furthermore, the regression analysis allowed us to extrapolate trends outside of the IOIs tested. Here we expect that this extrapolation of the regression line to IOIs below the cost-benefit transition point will support the subdivision benefit for tapping variability described in Repp (2003). Finally, we expected systematic differences in 1:3 tapping compared to the other conditions, as numerous studies have demonstrated a categorical distinction between duple and triple meter (Drake 1993; Fujioka, Zendel, & Ross, 2010; Repp, 2003).

Method

PARTICIPANTS

We recruited eight right-handed musicians (20-31 years of age, 2 females) who met the following inclusion criteria after a telephone screening: (1) advanced level of formal music training (above Grade 8 level in Royal Conservatory of Music, undergraduate degree in music, or equivalent), and (2) currently playing a musical instrument for over 10 hours per week. All participants read and signed informed consent forms according to guidelines established by the University of Toronto and Baycrest Centre before participation in the study.

STIMULI

Auditory stimuli were 250 Hz clicks of 10 ms duration that were presented in an isochronous stream. Every twelfth tone was of a higher frequency (1000 Hz). These high tones were used to cue the starting point to participants such that all the individuals tapped to the same target clicks within each 12-click cycle (Figure 1a). All stimuli were presented at 65 dB sound pressure level via insert earphones (ER3A, Etymotic Research, Inc., Elk Grove Village, IL, USA) in both ears. Across all the conditions, the stimuli were kept identical except for the IOI. Tap-click ratio was manipulated through the 1:*n* tapping task described below, and illustrated in Figure 1a.

TASK

Tapping performance was tested in a sound-attenuated room in which a participant sat down in a comfortable chair, wore insert earphones, and tapped on a computer mouse fixed on a table in front of the chair. Participants were told that isochronous click stimuli would be presented at different IOIs in separate blocks. Here we define a trial as a tap synchronized with a single auditory stimulus, and a block as a series of trials where clicks were presented at a constant IOI while participants maintained the same subdivision by tapping to every n^{th} click throughout. The tap-click ratios tested were 1:1, 1:2, 1:3, and 1:4. Accordingly, this ratio defined ITI as $n \times$ IOI (Figure 1b, c), where n was equal to the number of clicks per tap. The combinations of IOI or ITI and tap-click ratio that were tested are listed in Tables 1a and 1b. The tables are laid out in this manner to illustrate the balanced design necessary for conducting an ANOVA based on either IOI or ITI (described below in *Data Analysis*). It is important to note that six of the twelve blocks listed in Table 1a are redundant with blocks in Table 1b (indicated with superscripted numbers). These six blocks were only tested once, and the data were used for both the ANOVAs based on IOI and ITI. Thus, there were 18 unique conditions in total. The order of blocks was randomized across participants. This required one one-hour testing session for each participant.

When starting each block, the participant listened to the clicks until she or he could anticipate the next click as well as the timing according to the prescribed target click, then the participant started tapping to the next high tone as a starting cue (Figure 1a). Participants were further instructed to use the right index finger for tapping on the left-most button of a three-button optical computer mouse (Dell, Round Rock, TX, USA) in synchrony with the target click. Before starting any blocks participants practiced the procedure until both the experimenter and participant felt that taps were reliably and accurately synchronized to the clicks. During the practice, the experimenter advised participants to make quick transient taps while lifting the finger quickly after hitting the button so that the upward movement of the mouse button could not be used as a separate level of subdivision. While the button press on the mouse produced a quiet mechanical sound, the insert earphones filtered outside noise, virtually eliminating the audibility of the mouse button.

TABLE 1a. IOIs Used for Each Tap-Click Ratio and its Relationship to ITI.

Tap-click ratio	1:1	1:2	1:3	1:4
IOI	ITI			
260 ms	260 ms	520 ms	780 ms[4]	1040 ms
390 ms	390 ms	780 ms[2]	1170 ms[5]	1560 ms[6]
780 ms	780 ms[1]	1560 ms[3]	2340 ms	3120 ms

TABLE 1b. ITIs Used for Each Tap-Click Ratio and its Relationship to IOI.

Tap-click ratio	1:1	1:2	1:3	1:4
ITI	IOI			
780 ms	780 ms[1]	390 ms[2]	260 ms[4]	195 ms
1170 ms	1170 ms	585 ms	390 ms[5]	292.5 ms
1560 ms	1560 ms	780 ms[3]	520 ms	390 ms[6]

Note: The conditions marked with 1-6 indicate the redundant blocks reported in Table 1a.

DATA RECORDING

The stimulus presentation and response recording were controlled by Presentation software (Version 13; Neurobehavioral Systems; Albany, California, USA) running on a Windows 2000 computer with an Intel Pentium 4 CPU. The timing of the taps and stimulus onset were recorded in separate log files for each block. The mouse button was sampled at a rate of 60 Hz, causing a quantization error uniformly distributed between 0 and 16 ms with a standard error of 0.725. A constant delay of 70 ms, caused by a switching device between the mouse and the computer (Avocent AMX5000/5111, Huntsville, Al, USA), was subtracted from all data points. This delay and error were determined by comparing the timing of an audio recording of the mouse clicks and the recorded time (in the log file) of the mouse clicks in a separate test. During the experiment, only successful taps were recorded in the log file, defined as any tap to a correct target click that was within ±50% of the stimulus IOI. All taps outside this window were rejected online. Each condition was tested with one block of 120 successful trials. Participants found the task quite easy, and only a few taps were actually rejected. Taps to the high tone presented as every 12th stimulus were also excluded from further analysis to avoid any possible confounds, such as effects of additional auditory processing required for its higher frequency or effects of a higher-order metrical grouping that might have resulted from the acoustic accent.

DATA ANALYSIS

Tap-click asynchrony was calculated by subtracting the timing of stimulus presentation from the timing of the response for each trial. Thereafter, the average of this difference within each block was the mean tap-click asynchrony, or simply, tapping asynchrony. The variability of tapping was the standard deviation of the tap-click asynchronies across trials for each block. For these two dependent variables, we used two different statistical approaches to examine the effects of IOI and ITI as well as the tap-click ratio. First, we conducted an ANOVA for selected subset of the data, and then a backward stepwise linear regression analysis for the entire dataset.

We used four within-subjects repeated measures ANOVAs to separately examine the effects of IOI and ITI on tapping performance. The first analysis compared the influence of IOI on tap-click ratio and utilized a 3 (IOI:

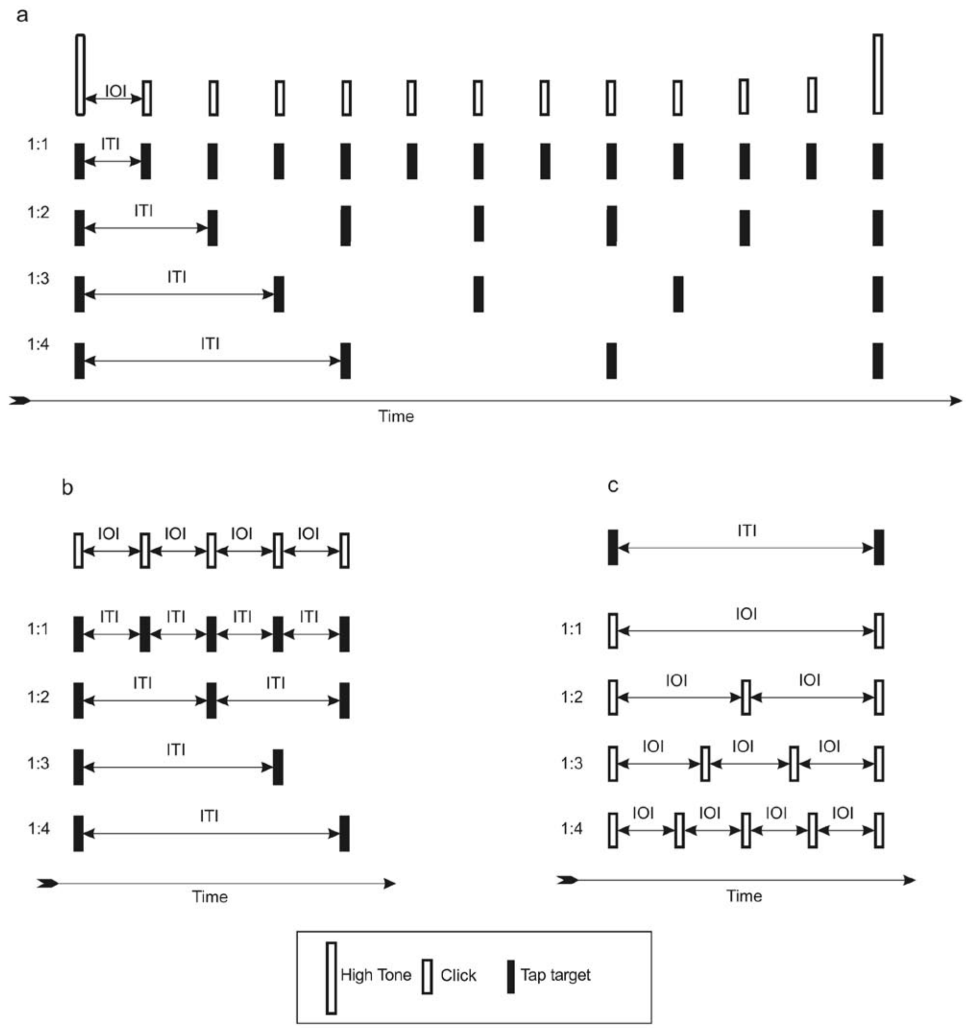

FIGURE 1. (a) Stimulus sequence of the 12-click repeating cycle (one high-pitched tone followed by 11 identical isochronous clicks) presented during the experiment and locations of the tap target with the designated tap-click ratio. (b) Relationship between ITI, IOI, and Tap-click ratio in the IOI-based analysis. IOI is illustrated along the top row to show how ITI varies with Tap-click ratio. For the IOI-based comparison, the conditions with the same IOI across different Tap-click ratios are compared. (c) Relationship between ITI, IOI, and Tap-click ratio in the ITI-based analysis. ITI is illustrated along the top row to show how IOI varies with Tap-click ratio. For the ITI-based analysis, conditions with the same ITI across different tap-click ratios are compared.

260 ms, 390 ms, 780 ms) by 4 (tap-click ratio: 1:1, 1:2, 1:3, 1:4; Table 1a) design, while the second analyzed the influence of ITI and tap-click ratio and utilized a 3 (ITI: 780 ms, 1170 ms, 1560 ms) by 4 (tap-click ratio; Table 1b) design. Both these analyses were calculated twice, first using tapping asynchrony and then tapping variability as the dependent variable, yielding four separate ANOVAs. As mentioned above, we used different subsets of conditions in the IOI and ITI analyses in which some conditions overlapped, as indicated in Tables 1a and 1b. Also, it is worthwhile to point out again that the covariance between IOI and ITI in this analysis is illustrated in Figure 1b (IOI) & Figure 1c (ITI).

Second, we used four backward stepwise linear regression analyses to explain the entire dataset (i.e., data from *all* conditions were used). Each analysis determined the effect of Time (IOI or ITI) on Tapping performance (tapping asynchrony or variability), yielding four separate analyses. For each regression analysis, the factor Time (IOI or ITI) was included as a continuous variable, while the factor Tap-click ratio was transformed into a continuous variable via three dummy-coded variables. Accordingly, the interaction between Time and Tap-click ratio was analyzed by including three additional variables, each of which was a product of the Time factor and each of the Tap-click ratio variables (i.e., 1:2 × Time, 1:3 × Time, 1:4 × Time). Given that there are only three degrees of freedom in this analysis (i.e., number of conditions minus 1), only three variables can be used to code the four conditions. Therefore, the 1:1 tapping condition was used as the condition to which the other three conditions were compared.

Thereafter, we used the backward stepwise procedure to examine how each of the three factors predicted variance in the dependent variable (TP: tapping performance: tapping asynchrony or variability). In the first step we constructed a full regression model (Eq. 1) that included three independent factors: Time (T: IOI or ITI), Tap-click ratio (TCR:1:2, 1:3, 1:4), and the interaction between Time and Tap-click ratio (T × TCR, henceforth called "the interaction").

$$\textit{Full model}: \mathrm{TP} = \mathrm{T} + \mathrm{TCR} + (\mathrm{T} \times \mathrm{TCR}) \qquad (1)$$

Second, a partial regression model that only included the factor Time (Eq. 2) was compared to the full model to test if removing the other two factors decreased the *R*-squared value (effect size). A significant change in *R*-squared value indicates an independent contribution of Tap-click ratio and/or the interaction to the overall effect size. The *F*-statistic was used to examine whether this change was statistically significant.

$$\textit{Model T}: \mathrm{TP} = \mathrm{T} \qquad (2)$$

If Model T was significantly different from the full model, a third model (Eq. 3) that used Time and the Tap-click ratio, but not the interaction, was compared to the full model to determine whether the Tap-click ratio or the interaction contributed to the overall effect. Here, a significant reduction in *R*-squared value would indicate that the interaction made a significant contribution to the full model, while a nonsignificant effect would indicate that Tap-click ratio and not the interaction made a significant contribution to the full model.

$$\textit{Model T(TCR)}: \quad \mathrm{TP} = \mathrm{T} + \mathrm{TCR} \qquad (3)$$

For each variable included in the full model, beta weights that explain the magnitude of difference from that variable to the comparison condition (1:1 tapping; Table 2a-d) were calculated. For the three variables that make up the Tap-click ratio factor (i.e., TCR (1:2), TCR (1:3) & TCR (1:4)), the beta weight is the difference in the intercept of the regression line compared to the 1:1 tapping condition. For the three variables that make up the interaction term (i.e., (T(IOI *or* ITI) × TCR(1:2), (T(IOI *or* ITI) × TCR(1:3) & (T(IOI *or* ITI) × TCR(1:4), the beta weight is the difference in the slope of the regression line compared to the 1:1 tapping condition. Significance of these metrics was assessed using a *t*-test. For all statistical tests, the level of significance was set to $\alpha = .05$.

Results

COMPARISON BY ANOVA

For the IOI-based comparison on tapping asynchrony (Figure 2a), the ANOVA revealed main effects of both Tap-click ratio, $F(3, 21) = 4.71$, $p < .05$, $\eta_p^2 = .40$, and IOI, $F(2, 14) = 9.01$, $p < .01$, $\eta_p^2 = .56$, with no interaction between the two factors. Pairwise comparisons revealed that the main effect of Tap-click ratio was due to larger asynchronies in the 1:3 condition compared to those in the other three conditions ($p <.05$ for all comparisons). The main effect of IOI was observed because tapping asynchrony was largest when the IOI was 780 ms compared to when it was 390 ms and 260 ms ($p < .05$ for both comparisons).

For the comparison based on ITI, the ANOVA revealed a main effect of Tap-click ratio, $F(3, 21) = 6.54$, $p < .01$, $\eta_p^2 = .48$, on tapping asynchrony (Figure 2b). Pairwise comparisons revealed that tapping asynchrony decreased from the 1:1 condition to the 1:2, and from 1:2 and 1:3 conditions to the 1:4 condition ($p < .05$ for both comparisons). However, the 1:3 condition was not significantly different from the 1:2 condition, indicating that smaller asynchronies cannot be entirely explained by the increased number of clicks between each tap. The main effect of ITI and the interaction with Tap-click ratio were not significant.

For tapping variability in the IOI-based comparison (Figure 2c), the ANOVA revealed main effects for both Tap-click ratio, $F(3, 21) = 11.04$, $p < .01$, $\eta_p^2 = .61$, and IOI, $F(2, 14) = 31.37$, $p < .01$, $\eta_p^2 = .82$; however, they did not interact. The main effect of Tap-click ratio was due to the increased variability in the 1:2, 1:3, and 1:4 conditions compared to the 1:1 condition ($p < .01$ for all comparisons). In contrast, no differences between the 1:2, 1:3, and 1:4 conditions were significant. For the main effect of IOI, pairwise comparisons revealed that variability was highest at 780 ms IOI compared to 260 ms and 390 ms ($p < .01$ for both comparisons).

For the ITI-based comparison of tapping variability (Figure 2d), main effects were found for both Tap-click ratio and ITI, $F(3, 21) = 35.71$, $p < .01$, $\eta_p^2 = .84$ and $F(2, 14) = 13.21$, $p < .01$, $\eta_p^2 = .65$, respectively. Pairwise comparisons revealed that the main effect of Tap-click ratio was caused by a decrease in variability for both the 1170 ms and 1560 ms ITI conditions from the 1:1 condition to the 1:2 condition ($p < .01$ for both), and a further decrease in variability from the 1:3 condition to the 1:4 condition ($p < .05$ for both). There was no decrease in

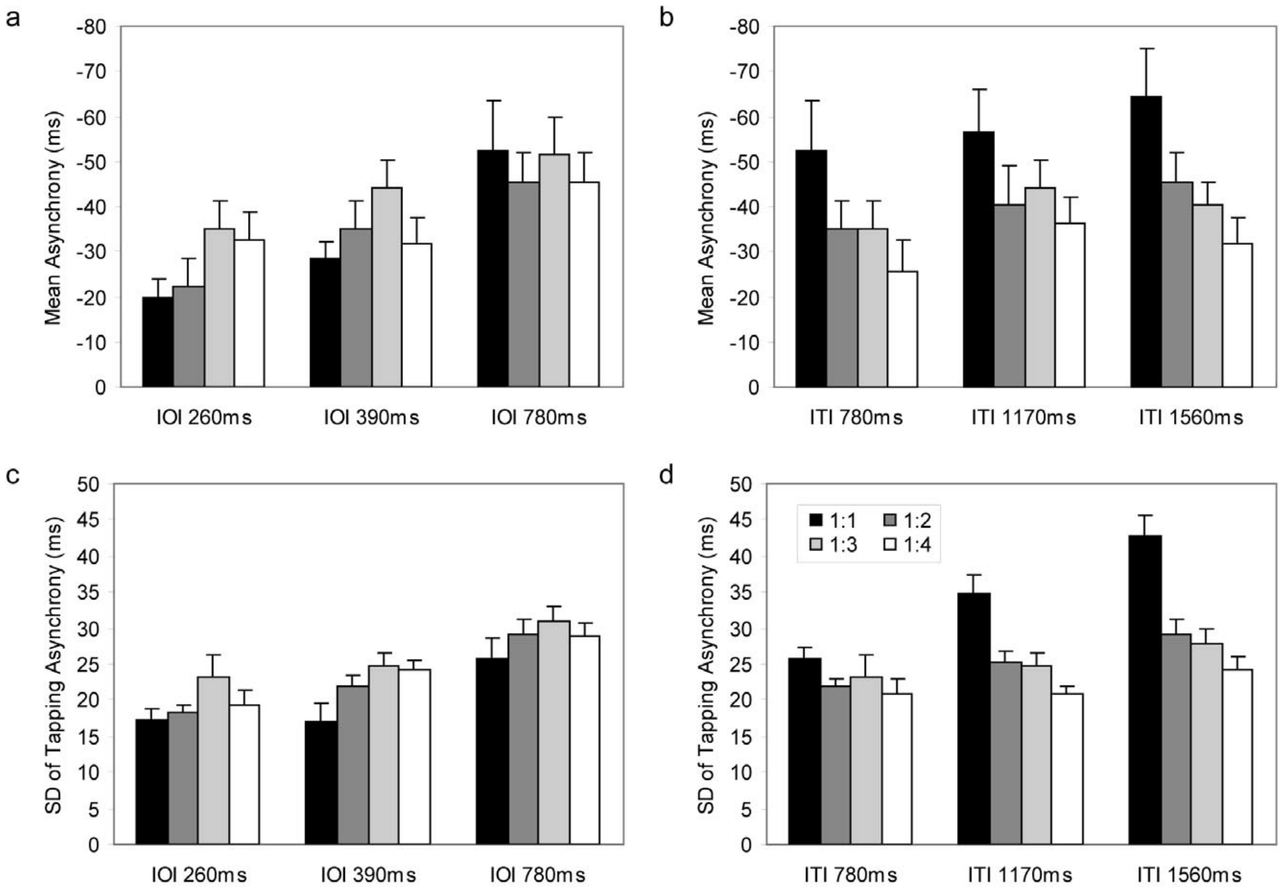

FIGURE 2. Tapping asynchrony and variability measured by standard deviation of the asynchrony in the sets of conditions analyzed by ANOVA. (a) Mean asynchrony as a function of IOI and tap-click ratio. (b) Mean asynchrony as a function of ITI and tap-click ratio. (c) Tapping variability as a function of IOI and tap-click ratio. (d) Tapping variability as a function of ITI and tap-click ratio. Error bars represent 1 standard error of the mean. Note that for Figures 2a and 2b negative values are plotted up so the direction of decreasing asynchronies is consistent with the direction of decreasing tapping variability in Figures 2c and 2d.

variability from the 1:2 to 1:3 conditions. Pairwise comparisons revealed the source of the main effect for ITI; there was a significant increase in tapping variability from the 780 ms condition to the 1560 ms condition ($p < .05$). An interaction between the two factors, $F(6, 42) = 4.61$, $p < .05$, $\eta_p^2 = 0.40$, was caused by the effects of Tap-click ratio in both the 1170 ms and 1560 ms ITI (both $p < .01$) but not in the 780 ms ITI condition.

REGRESSION ANALYSIS

For both tapping asynchrony and variability, we compared full and partial regression models using the factors of Time (based on IOI or ITI) and Tap-click asynchrony. The results of this comparison are summarized in Table 2, while Figure 3 illustrates the full regression models for both tapping asynchrony and variability.

First, we used IOI as the independent variable for Time and conducted a comparison between the *Full model* and *Model T* of the tapping asynchrony data (see Table 2a). This comparison yielded no significant decrease in *R*-squared value, meaning that Tap-click ratio did not significantly account for any additional variance in the data. As seen in Figure 3a, the slopes and intercepts of the regression lines are similar, which is supported statistically by nonsignificant beta weights for the variables that make up the factor Tap-click ratio and the interaction factor (see Table 2a-2). Further analysis was not necessary because both Tap-click ratio and its interaction with Time do not add predictive value to the model (hence the n/a in Table 2a).

Next, we used the ITI to compare the *Full model* to *Model T* for tapping asynchrony (see Table 2b). This comparison yielded a significant decrease in the *R*-squared value, $F(6, 136) = 5.07$, $p < .01$, indicating that Tap-click ratio accounted for a significant portion of the variance in the *Full model*. In addition, the comparison between the *Full model* to *Model T(TCR)* revealed a significant decrease in the *R*-squared value, $F(3, 136) = 4.62$, $p < .01$, suggesting that the effect of Tap-click ratio was due to differences in the slopes of the regression lines (Figure 3b). As shown in Table 2b-2, *t*-tests on the beta weights for the interaction terms were significant for 1:3 and 1:4 tapping, meaning that the slopes of the regression lines for 1:3 and 1:4 are different from the 1:1 condition.

For tapping variability, we first used IOI as the independent variable for Time and compared the *Full model* to *Model T* (see Table 2c). This comparison yielded a significant decrease in *R*-squared value, $F(6, 136) = 3.77$, $p < .01$. In the next step, the comparison between *Model T(TCR)* and the *Full model* revealed no significant decrease in *R*-squared value ($p > .10$), indicating that there is no effect of Tap-click asynchrony on the slope of the regression lines (Figure 3c). The effect of Tap-click ratio must therefore be due to differences in their intercepts. As seen in Table 3c-2 *t*-tests on the beta weights for each Tap-click ratio condition indicate that the intercepts of the 1:3 and 1:4 conditions are different from the 1:1 condition.

Finally, we used ITI and compared the *Full model* to *Model T* to for tapping variability (see Table 2d). This analysis yielded a significant decrease in the *R*-squared value from the *Full model* to *Model T,* $F(6, 136) = 22.60$, $p < .01$, indicating that Tap-click ratio accounted for a significant portion of variance in the data. In the next step the decrease in *R*-squared from the *Full model* to *Model T(TCR)* was also significant, $F(3, 136) = 24.74$, $p < .01$. This suggests that, similar to the asynchrony data, the effect of Tap-click ratio resulted in differences in the slopes of the regression lines. As seen in Figure 3d, the slopes are less steep as Tap-click ratio decreases, which is supported statistically in Table 2d-2, where *t*-tests on the beta weights for each interaction term indicate that the slopes of the regression lines for 1:2, 1:3, and 1:4 conditions are different from the 1:1 condition.

Finally, we tested whether the difference in the pattern of results for the IOI and ITI based analyses resulted from using different ranges for each of these variables (IOI:195 – 1560 ms, ITI: 260 – 3120 ms). We recalculated the entire regression analysis by including only overlapping IOI and ITI conditions (IOI: 260 – 1560 ms, ITI: 260 – 1560 ms). This did not change the pattern of results from those described above, suggesting that the influence of IOI and ITI was consistent across the conditions that we tested.

Discussion

The primary findings in the present study were: (1) ANOVA and regression analyses consistently revealed improved tapping performance (smaller mean tap-click asynchrony and reduced variability) as both the IOI and ITI decreased. (2) In the regression analysis using the IOI as an independent factor, the effect of Tap-click ratio was not significant. Furthermore, this analysis provided the best model to explain the variance of the tapping data. (3) In the ANOVA that compared different tap-click ratios with an identical IOI or ITI, the results for tapping performance in the 1:3 condition were different than what would be predicted based on linear differences between the 1:2 and 1:4 conditions.

Tapping performance improved as both IOI and ITI decreased, consistent with previous studies (Kolers & Brewster, 1985; Peters, 1989). This likely reflects the effect of IOI because for both tap-click asynchrony and its variability, the regression model based on IOI predicted the most variance in tapping performance. If the ITI had made a unique contribution to tapping performance beyond the contribution of the IOI, differences in the regression lines for the IOI-based analysis would have been present given that in the IOI-based analysis each level of tap-click ratio had a different ITI. Our findings demonstrated that tapping performance was mainly related to the IOI.

In the regression analysis, for both tapping asynchrony and variability, the best model to predict tapping performance occurred when time was referenced to the IOI. This was best illustrated by the *R*-squared value (effect size) in the partial regression models that only included Time as a factor (*Model T*). The effect size was much larger for the IOI based analyses compared to the ITI based analyses, as seen in Table 2. These are important differences because when the full model was used, both IOI and ITI analyses had identical effect sizes (because the data set was identical, only the independent factor Time was different), indicating that IOI accounts for a greater portion of the variance compared to ITI. This pattern of effect sizes was similar for the ANOVA analyses, as indicated by the partial eta-squared values (η_p^2). However, the ANOVA analyses only included a subset of the data; thus, these metrics were considered to be more reliable in the regression analyses.

Within the range of IOIs tested, both dependent measures were proportional to the size of the IOI. Moreover, different tap-click ratios, and thus longer ITIs, showed little influence on tapping performance. The IOI-based analysis did not require the inclusion of tap-click ratio or its interaction with time (IOI in this case) to account for the variance in the model, whereas the ITI-based analysis required both. This trend was similar for both tap-click asynchrony in addition to tapping variability, and the improvement in performance for both measures was mainly due to the shorter IOI in subdivided conditions.

TABLE 2a-1. Dependent Variable: Asynchrony (Time: IOI).

Model	*R* Statistic	*R*-Squared	*R*-Squared Change	*F* change	*df*	*p*
Full	.50	.25	.25	6.48	7, 136	.00**
T	.47	.23	·03	0.77	6, 136	.59
T(TCR)	n/a					

Note: The full and partial models for tapping asynchrony when regressed with IOI as the measure of time. *$p < .01$; **$p < .001$

TABLE 2a-2. Regression coefficients.

Variable	Unstd. Beta	Std. Error	Std. Beta	*t*-test	*p*
(Constant)	-16.11	6.25		-2.58	.01
T(IOI)	-0.03	0.01	-0.54	-5.21	.00**
TCR(1:2)	1.06	11.49	0.02	0.09	.93
TCR(1:3)	-12.78	11.43	-0.24	-1.1	.27
TCR(1:4)	-7.44	9.08	-0.15	-0.82	.41
T(IOI) × TCR(1:2)	-0.01	0.02	-0.08	-0.38	.70
T(IOI) × TCR(1:3)	0.01	0.02	0.05	0.28	.78
T(IOI) × TCR(1:4)	0.01	0.02	0.05	0.36	.72

Note: Regression coefficients for the full model are in a-1. *$p < .01$; **$p < .001$

TABLE 2b-1. Dependent Variable: Asynchrony (Time: ITI).

Model	*R* Statistic	*R*-Squared	*R*-Squared Change	*F* change	*df*	*p*
Full	.50	.25	.25	6.48	7, 136	.00**
T	.29	.08	.17	5.07	6, 136	.00**
T(TCR)	.42	.17	.08	4.62	3, 136	.00*

Note: The full and partial models for tapping asynchrony when regressed with ITI as the measure of time. *$p < .01$; **$p < .001$

TABLE 2b-2. Regression coefficients.

Variable	Unstd. Beta	Std. Error	Std. Beta	*t*-test	*p*
(Constant)	-16.11	6.25		-2.58	.01
T(ITI)	-0.03	0.01	-1.03	-5.21	.00**
TCR(1:2)	1.06	11.49	0.02	0.09	.93
TCR(1:3)	-12.78	11.43	-0.24	-1.12	.27
TCR(1:4)	-7.44	9.08	-0.15	-0.82	.41
T(ITI) × TCR(1:2)	0.01	0.01	0.27	1.2	.23
T(ITI) × TCR(1:3)	0.02	0.01	0.73	2.74	.01*
T(ITI) × TCR(1:4)	0.03	0.01	0.98	3.58	.00**

Note: Regression coefficients for the full model are in b-1. *$p < .01$; **$p < .001$

TABLE 2c-1. Dependent Variable: Tapping Variability (Time: IOI).

Model	*R* Statistic	*R*-Squared	*R*-Squared Change	*F* change	*df*	*p*
Full	.78	.6	.60	29.65	7, 136	.00**
T	.73	.54	.07	3.77	6, 136	.00*
T(TCR)	.77	.6	.01	0.73	3, 136	.54

Note: The full and partial models for tapping variability when regressed with IOI as the measure of time. **p* < .01; ***p* < .001

TABLE 2c-2. Regression coefficients.

Variable	Unstd. Beta	Std. Error	Std. Beta	*t*-test	*p*
(Constant)	10.29	1.66		6.18	.00
T(IOI)	0.02	0.00	0.89	11.95	.00**
TCR(1:2)	2.91	3.06	0.15	0.95	.34
TCR(1:3)	8.95	3.04	0.46	2.94	.00*
TCR(1:4)	6.54	2.42	0.36	2.70	.01*
T(IOI) × TCR(1:2)	0.00	0.01	0.00	0.01	.99
T(IOI) × TCR(1:3)	-0.01	0.01	-0.15	-1.04	.3
T(IOI) × TCR(1:4)	-0.01	0.00	-0.13	-1.14	.26

Note: Regression coefficients for the full model are in c-1. *p* < .01; ***p* < .001

TABLE 2d-1. Dependent Variable: Tapping Variability (Time: ITI).

Model	*R* Statistic	*R*-Squared	*R*-Squared Change	*F* change	*df*	*p*
Full	.78	.60	.60	29.65	7, 136	.00**
T	.46	.21	.40	22.60	6, 136	.00**
T(TCR)	.62	.39	.22	24.74	3, 136	.00**

Note: The full and partial models for tapping variability when regressed with ITI as the measure of time. **p* < .01; ***p* < .001

TABLE 2d-2. Regression coefficients.

Variable	Unstd. Beta	Std. Error	Std. Beta	*t*-test	*p*
(Constant)	10.29	1.66		6.18	.00
T(ITI)	0.02	0.00	1.71	11.95	.00**
TCR(1:2)	2.91	3.06	0.15	0.95	.34
TCR(1:3)	8.95	3.04	0.46	2.94	.00*
TCR(1:4)	6.54	2.42	0.36	2.71	.01*
T(ITI) × TCR(1:2)	-0.01	0.00	-0.58	-3.51	.00**
T(ITI) × TCR(1:3)	-0.02	0.00	-1.27	-6.57	.00**
T(ITI) × TCR(1:4)	-0.02	0.00	-1.67	-8.37	.00**

Note: Regression coefficients for the full model are in d-1. **p* < .01; ***p* < .001

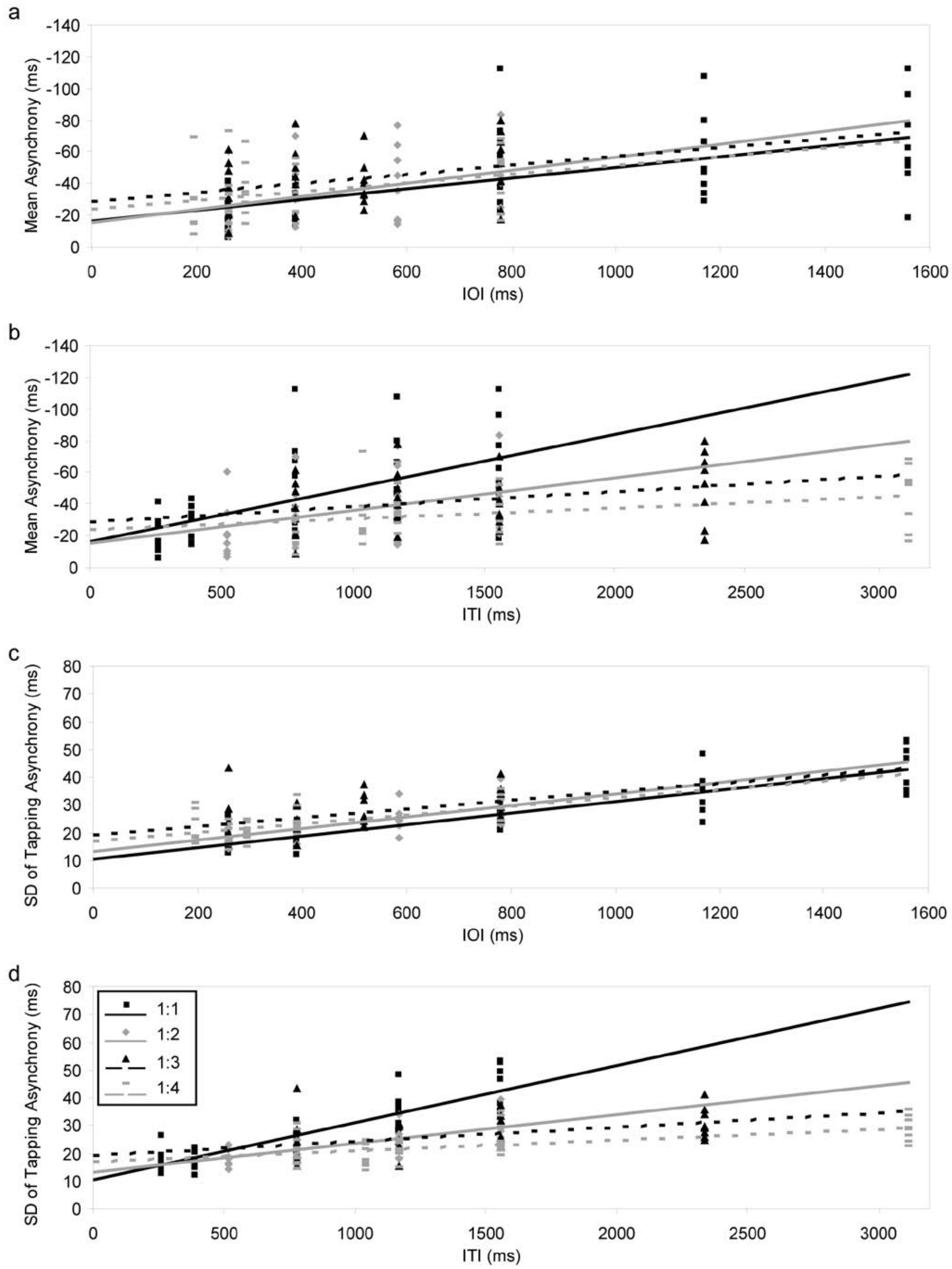

FIGURE 3. Regression models of tapping asynchrony and its variability as a function of tap-click ratio and time. (a) Tapping asynchrony as a function of IOI for different tap-click ratios. (b) Tapping asynchrony as a function of ITI for different tap-click ratios. (c) Tapping variability as a function of IOI for different tap-click ratios. (d) Tapping variability as a function of ITI and tap-click ratios. Note that for asynchrony data in Figures 3a and 3b negative values are plotted up so the direction of decreasing asynchronies is consistent with the direction of decreasing tapping variability in Figures 3c and 3d.

In terms of using the regression to predict cost-benefit transition points for tapping variability, our data are in agreement with the data from Repp (2003). In the ITI-based analysis, as shown in Figure 3d, the 1:2, 1:3, and 1:4 regression lines crossed the 1:1 regression line around 200 ms. This implies that below this point tapping variability would be larger for 1:2, 1:3, and 1:4 tapping compared to 1:1 tapping. These points are similar to the subdivision cost-benefit transition point described in Repp (2003), in which a limited range of short IOIs was used.

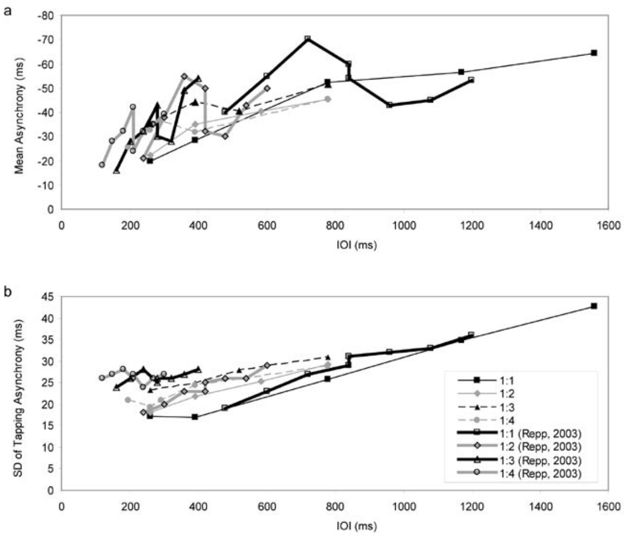

FIGURE 4. The current data and the data reported by Repp (2003). Note that the data from Repp (2003) were collected in two separate experiments, in which there are two data points for one IOI in each tap-click ratio condition (for details see Repp, 2003). (a) Tapping asynchrony as a function of IOI. (b) Tapping variability as a function of IOI.

In terms of the relationship to different tap-click ratios, the results of the tap-click asynchrony data showed a similar pattern to tapping variability. Although this trend was also present in Repp's dataset (Figure 4a; data were visually extracted from Figures 4 & 5 in Repp, 2003), it was not described in detail. Thus, our data confirmed that both asynchrony and variability decrease with the IOI. In addition, our data appear to predict a cost-benefit transition point for 1:3 and 1:4 tapping. When comparing different tap-click ratios at the same ITI, the regression lines for 1:3 and 1:4 tapping cross the 1:1 regression line (Figure 3b), resulting in an increased tapping asynchrony at lower stimulus rates and decreased tapping asynchrony at higher stimulus rates. This pattern of results suggests that subdividing a tap with extra clicks lowers the mean asynchrony above a certain threshold.

In the IOI-based analysis on tapping variability, there was only a subtle effect of ITI; increasing the ITI (thus increasing *n*) resulted in an increase in tapping variability for 1:3 and 1:4 tapping compared to 1:1 tapping. This can be seen in the intercepts of the regression lines for the 1:3 and 1:4 conditions compared to the 1:1 condition (Figure 3c, Table 2c-2). This tendency is similar to the data from Repp (2003). To illustrate this similarity we plotted the group mean data from both studies together in Figure 4b as a function of IOI, where data points from Repp (2003) were visually extracted from the publication (Figures 4 & 5, in Repp 2003). Importantly, this effect of increasing the ITI seemed to be only significant at low IOIs—as in our data and in the data from Repp (2003), the slopes of the 1:3 and 1:4 regression lines trend towards the 1:1 regression lines. Our ANOVA confirms this trend, as 1:1 tapping at any given IOI always resulted in the lowest tapping variability. This pattern of results suggests that lengthening the ITI has a very small influence on tapping variability that is limited to when IOIs are near the cost-benefit transition point. Thus, tapping variability is mainly determined by the IOI alone.

Our results have demonstrated that IOI is the strongest predictor for auditory SMS performance in the 1:*n* tapping task. When taps are subdivided by clicks, tapping performance improves for stimulus rates above the cost-benefit transition point. Interestingly, composers seem to have been aware of this because music with slower tempi tends to have deeper subdivisions, whereas the reverse is true for faster music, which probably eases performance of these pieces. For example, in Western music, a musical piece with adagio tempo uses more 32nd or 64th notes, thus providing finer subdivisions, than faster musical pieces marked as allegro or presto, in which more 8th or 16th notes are used. As a result, the shortest duration of individual notes across different musical pieces may well be confined within a narrow range, compared to the wide variety of tempi. In fact, before the advent of the metronome, composers used meter as a cue for the proper tempo (called *tempo giusto)*, which suggests that the actual note density in musical works with differing tempi may be similar (Brown, 1999). This probably reflects the fact that the perception of a slower tempo and motor synchronization to that slower tempo was aided by metric subdivision. The longest ITI in which all four metric conditions were tested in the present study was 1560 ms and, in this case, the accuracy between the 1:1 condition and the other tap-click ratios differed substantially (Figure 3b). Alternatively, an IOI of 780 ms can be synchronized in the 1:4 condition, in which the ITI is 3120 ms. The corresponding IOI was not used for the 1:1 condition because it becomes increasingly difficult to anticipate precisely when clicks would occur at this IOI. The current data demonstrate that participants can synchronize movements more consistently at a significantly slower rate when there are subdividing stimuli between the taps. A consequence of these subdivided stimuli is that the IOI decreases. When there are subdivided stimuli between taps, the internal clock can synchronize with a level of the metric hierarchy closest to the preferred beat rate or maximal pulse salience of around 600-700 ms (Parncutt, 1994). The preferred beat rate can be thought of as the default rate of the internal clock, and thus synchronizing to external stimuli around this rate is easier. Support for this comes from Hannon et al. (2004), who demonstrated that identical musical stimuli are more likely to be perceived as having a different accent structure based on the tempo. Importantly, the stronger accents were most likely to be perceived at an interval of 600 ms. However, other studies have shown that slow or fast music can engender the feeling of a beat that is well outside this range, and that there is large individual variation in preferred beat rate (McKinney & Moelants, 2006). The rigorous imposition of tapping in the current study, or the high level of musicianship in our participants may explain why we did not observe specific modulation of tapping performance around the preferred beat rate.

Our results for tapping performance in the 1:3 condition did not fall between those for 1:2 and 1:4 conditions (Figure 2), suggesting that increasing the number of stimuli between taps did not lead to improved tapping performance. In other words, compared to the 1:2 condition, the additional stimulus between each tap in the 1:3 condition did not provide an additional benefit. This result may be related to the categorical differences between binary and ternary metric processing, which has been shown to interact with musicianship and/or developmental stages in a number of studies. For example, Repp (2003) found that the cost-benefit transition point for 1:3 tapping was higher than that for 1:2 and 1:4 tapping. This pattern was not present in the current data set, perhaps because unlike Repp (2003), we did not test the IOIs close to or below the cost-benefit transition point. Drake (1993) found that children and adults without music training had difficulty reproducing rhythms based on triple meter but not duple meter. In her study, adult musicians performed better than nonmusicians in reproducing the triple meter rhythm, although performance was still not as good as in a duple meter condition. Furthermore, our recent work suggests that there are neurophysiological differences in the way the brain encodes duple and triple meters in musicians (Fujioka et al., 2010). The studies mentioned above tested people trained in the Western music tradition, in which ternary meter is used on a regular basis, although there are approximately twice as many works in binary meters compared to ternary meters (Huron, 2006). This cultural bias could explain the advantage in binary meter tasks. Another line of evidence also supports that the perception of different metric structures is influenced by cultural experience and not by the complexity of metric structure. It has been shown that even 6-month-old infants can detect errors in complex meters counted in sevens (i.e., 2+2+3 or 3+2+2), such as Balkan folk music (Hannon & Trehub, 2005). While North American adults could only detect the violations for simple duple meters, adults from Bulgaria or Macedonia, as well as North American 6-month-old infants, were able to detect structure violations for both simple and complex meters. It is important to note that in both cultural groups, the adults did not have music training. This suggests that the advantage for processing of duple meter may be the result of an enculturation process, which is thought to develop after 6 months of age.

Interestingly, it also has been reported that there are no differences in duple and triple meter tasks in expert Western musicians, suggesting that enculturation may not be the only factor in metric processing (Repp, 2007). These discrepancies regarding differences between duple and triple meters may be due to the difference in task type. Repp (2007) found that lower IOI limits for synchronization thresholds were similar in duple and triple meter tasks for musicians but not for nonmusicians. Another possibility is that processing duple meters might be biologically preferred regardless of cultural background. Future studies are necessary to examine relationships between cultural influence, specific music training, and the physiological underpinnings for the processing of different metric structures.

To conclude, we found that IOI is the main determinant of tapping performance for metric tapping tasks over a wide range of IOIs within the limits of auditory SMS. Also, we confirmed and extended earlier findings by showing that when comparing the data based on the interval between finger taps, tapping performance improves with metric subdivision for both tapping asynchrony and variability for IOIs above the cost-benefit transition point (approximately double the synchronization limit). The subdivision benefits for triple meter were smaller than what would be expected based on the increased number of stimuli per tap. This behavioral difference in metric processing for duple and triple meters could be related to the known bias towards binary meter in Western music that might have influenced the performance of our subjects with music training.

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Correspondence concerning this article should be addressed to Benjamin Rich Zendel, Rotman Research Institute, Baycrest Centre, 3560 Bathurst Street, Toronto, Ontario, M6A 2E1, Canada. E-mail: b.zendel@utoronto.ca

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