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SYNCHRONIZATION ERROR OF DRUM KIT PLAYING WITH A METRONOME AT DIFFERENT TEMPI BY PROFESSIONAL DRUMMERS

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THE PRESENT STUDY EXAMINED THE SYNCHRONIZATION error (SE) of drum kit playing by professional drummers with an auditory metronome, focusing on the effects of motor effectors and tempi. Fifteen professional drummers attempted to synchronize a basic drumming pattern with a metronome as precisely as possible at tempi of 60, 120, and 200 beats per minute (bpm). In the 60 and 120 bpm conditions, the right hand (high-hat cymbals) showed small mean SE (~2 ms), whereas the left hand (snare drum) and right foot (bass drum) preceded the metronome by about 10 ms. In the 200 bpm condition, the right hand was delayed by about 10 ms relative to the metronome, whereas the left hand and right foot showed small SE (~1 ms). The absolute values of SE were smaller than those reported in previous tapping studies. In addition, the time series of SE were significantly correlated across the motor effectors, suggesting that each limb synchronized in relation to the other limbs rather than independently with the metronome.

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Key words: sensorimotor synchronization, synchronization error, asynchrony, drum kit playing, drummers

SENSORIMOTOR SYNCHRONIZATION, the coordination of rhythmic movement with rhythmic sensory stimuli, is a universal human skill that is particularly relevant to music activities (Repp, 2005, 2006). Musicians must synchronize their actions with the audible and visible actions produced by other members in an ensemble. Jazz and popular musicians must, moreover, synchronize their actions with a click track during recording. Precise sensorimotor synchronization is especially required for drummers due to their central role as the rhythm section in a band. Therefore, drummers practice intensively on a daily basis to synchronize their drum kit playing with an auditory metronome. For researchers, such highly trained drummers provide an opportunity to investigate expert human sensorimotor synchronization (see Münte, Altenmüller, & Jäncke, 2002; Schlaug, 2001; Zatorre, Chen, & Penhune, 2007). For music instructors and performers, investigation of the degree of synchronization between drumming and metronome beats attained by professional drummers may provide useful goals for music education. However, researchers have not studied musicians playing in synchrony with a metronome in detail, despite the familiarity of this task to many musicians. Repp (2005, 2006) pointed out in his reviews of research on sensorimotor synchronization that playing music with a metronome seems to have been investigated only with regard to piano playing (Repp, 1999a).

Instead, for more than 100 years, researchers interested in sensorimotor synchronization have mainly investigated the synchronization of simple finger-tapping movements with a pacing signal (e.g., Dunlap, 1910; Johnson, 1898; Miyake, 1902). The precision of synchronization has been assessed by measuring the interval between the pacing signal and the onset of tapping, called synchronization error (SE) or asynchrony.[1] Previous studies found a psychologically and neurophysiologically interesting phenomenon—namely, that taps tend to precede tones by about 20–80 ms rather than being distributed symmetrically around the tone onsets (see Aschersleben, 2002, for a review). This tendency to anticipate, or negative mean asynchrony (NMA), is considered related to the subjectivity of synchrony in tapping,

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[1] The synchronization error (SE) or asynchrony is identified by a negative number when the tap precedes the tone and as positive otherwise. The mean and variability of SE within an experimental trial are usually regarded as dependent variables.

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because participants are generally unaware of it (Aschersleben, 2003). Although the underlying mechanisms are still not completely understood, some researchers have suggested that synchrony between finger tapping and the pacing signal must be established at the level of central representation for the two to be perceived as synchronous, concluding that the NMA results from the difference in neural processing time between tactile/kinesthetic and auditory information (for more detail, see Aschersleben, 2002).

A number of studies have investigated factors that influence the SE during tapping, such as the following: (1) experience of music training: musically trained participants showed smaller SEs than did untrained participants (Aschersleben, 2002; Repp, 1999b, 2003); (2) auditory feedback: the SE decreases when auditory feedback is made contingent on each tap (Aschersleben & Prinz, 1995); (3) motor effectors: the NMA increases during foot tapping compared to manual tapping (Aschersleben & Prinz, 1995; Aschersleben, Stenneken, Cole, & Prinz, 2002; Billon, Bard, Fleury, Blouin, & Teasdale, 1996); (4) tempo: the SE depends on the tempi of pacing stimuli and tapping movements, and upper and lower limits on the rate at which humans can synchronize their tapping movements with the stimuli have been recognized (Kolers & Brewster, 1985; Mates, 1994a, 1994b; Peters, 1989; Pressing, 1998; Repp, 2003).

All of these factors would be expected to have critical influences not only on the SE during tapping movements but also during drum kit playing by professional drummers. First, professional drummers have considerable music experience. Second, auditory feedback is a standard element of drumming performance. Third, drummers are required to play the drums with both hands and feet simultaneously. Fourth, drummers must synchronize their playing over a wide range of tempi during a music performance, although skill levels vary at different tempi. Consequently, we hypothesized that professional drummers are able to synchronize their drum kit playing to a metronome very precisely, but the degree of precision depends on the motor effectors and/or the tempi. The purpose of the present study was therefore to examine this hypothesis.

Method

Participants

Fifteen professional drummers (13 men and 2 women) participated in the experiment. All were right-handed; the handedness score, assessed using the Edinburgh Handedness Inventory (Oldfield, 1971), was 76.67 ± 21.43 (mean ± standard deviation) and ranged from 40 to 100. The mean age was 40.33 ± 8.28 years (range = 23–58). Participants began drum training at 13.80 ± 3.05 years of age (range = 6–17), and had 26.53 ± 9.53years of experience (range = 8–43). All were professional drum kit players who had released numerous CDs and performed many live concerts as members of professional bands or as support musicians for professional singers.

In accordance with the Declaration of Helsinki, the participants received clear explanations of the experimental procedure and submitted written informed consent prior to participation in the study. The experimental procedure was approved by the Ethical Committee of the Graduate School of Arts and Sciences of the University of Tokyo.

Apparatus

A drum kit consisting of high-hat cymbals (14-inch diameter, Sabian), a snare drum (14-inch diameter, Carbon-Ply-Maple Series, Pearl), and a bass drum (22-inch diameter, Reference Series, Pearl) was located in front of the participants (see Figure 1). The height and position of the drum kit were adjusted to fit each participant, enabling them to sit comfortably while holding the drum sticks. Before conducting the experiment, we informed the participants about the apparatus as follows: "We prepared drum kit, throne, sticks, and pedals for the experiment. If you feel uncomfortable using an unfamiliar apparatus, please bring your own." Fourteen drummers used a pair of sticks (190STH Standard Hickory, Pearl) prepared by the experimenter, while one drummer used his own sticks (118H Maple, Pearl). Thirteen drummers used a bass pedal (P-2000 Eliminator Series, Pearl) prepared by the experimenter, and two drummers brought their own pedals (made by DW,

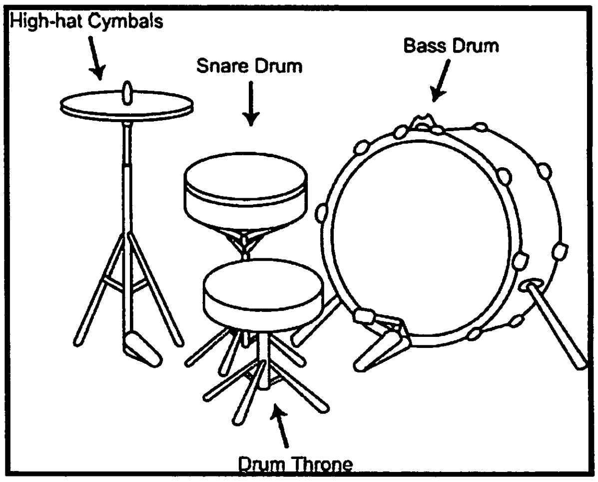

FIGURE 1. Schematic of drum kit setting.

model number was not recorded). For the high-hat cymbals and the snare drum, microphones were set 10 cm above each instrument. For the bass drum, a microphone was inserted through a 10-cm diameter hole opened on the front drumhead of the bass drum. A metronome (DB-88, BOSS) was used as a pacing signal.

The signals of the microphones and the metronome were amplified (M1204, ATL), mixed (LS9-16, YAHAMA), converted from analog to digital at a frequency of 48,000 Hz (Fire Wire 410, M-Audio), and recorded on a personal computer (iBook G4, M9846J/A, Apple) using ProTools software (M-Powered v7.3, Digidesign). The mixed sounds of the drum kit and the metronome were fed back to the participants through head phones (MDR-CD900ST, SONY).

Procedure

The participants were instructed to play a basic drumming pattern (see Figure 2) with the pacing metronome at three tempi in turn: 60, 120, and 200 beats per minute (bpm), or interonset intervals (IOI) of 1000, 500, and 300 ms. On the first and third beat, the participants were required to hit the high-hat cymbals and the bass drum simultaneously with the right hand and foot, respectively, whereas on the second and fourth beat, they were required to hit the snare drum and the high-hat cymbals simultaneously with the left and right hand, respectively (see Figure 2). Note that the right hand played four times faster either than the left hand or right foot. For example, in the 200 bpm condition, the right hand was played every 150 ms while the left hand and right foot were played every 600 ms. The participants started to play the drum kit after the metronome sound was fed back for 2, 4, and 8 bars (i.e., 8.0, 8.0, and 9.6 s) in 60, 120, and 200 bpm conditions, respectively. They were asked to synchronize the sound of their drum playing to that of the metronome as precisely as possible for 65 s.

Data Analysis

The data across 65 s were truncated to eliminate the last 5 s, and the 60-s data from the start of playing were analyzed for each participant (i.e., 60, 120, and 200 beats were analyzed in the 60, 120, and 200 bpm conditions, respectively). Typical recorded sound waves of the metronome and the drum kit are shown in the left panels of Figure 3. The upper part of the left panels indicates the mixed sounds of the bass drum and the high-hat cymbals, and the lower part indicates those of the snare drum and the high-hat cymbals. As shown in the figure, the sound of the high-hat cymbals (relatively high-frequency components) overlapped that of the bass or snare drum (relatively low-frequency components). To extract the bass- or snare-drum sound from the mixed sounds, the mixed sounds were low-pass filtered using a bidirectional fourth-order Butterworth low-pass filter with a cut-off frequency of 1,000 Hz (see middle panels in Figure 3). The mixed sounds were also high-pass filtered using a bidirectional fourth-order Butterworth high-pass filter with a cut-off frequency of 20,000 Hz to extract the high-hat-cymbals' sound. The bidirectional filter was used to cancel phase delays.

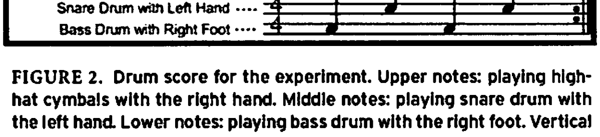

FIGURE 2. Drum score for the experiment. Upper notes: playing high-hat cymbals with the right hand. Middle notes: playing snare drum with the left hand. Lower notes: playing bass drum with the right foot. Vertical arrows indicate the timing of metronome sounds.

In order to detect sound onset, an envelope was calculated from the filtered signal by using the Hilbert transform as follows:

$$\mathrm{E}(t)=\sqrt{x(t)^2+\tilde{x}(t)^2}, \tag{1}$$

where $\mathrm{E}(t)$ is the envelope, $\tilde{x}(t)$ is the filtered signal, and $\tilde{x}(t)$ is the Hilbert transform of $x(t)$ that can be written as the convolution integral of $x(t)$ with $\frac{1}{\pi t}$ as $\tilde{x}(t)=x(t)*\frac{1}{\pi t}$ (Choi & Jiang, 2008; Feldman, 2008). The calculated envelope was shown as thick lines in the right panels of Figure 3. We defined the onset of the metronome as the time at which the envelope exceeded 10% of the maximum amplitude of each sound burst (see vertical broken lines on the envelope of metronome sound in Figure 3). The detections were performed by a custom written program using Matlab software (version 7.6, Mathworks). Standard deviation (*SD*) of the IOI of the metronome sound detected by the automatic program was less than 0.10 ms.

For the drum kit sounds, we first detected the time of peak amplitude of each sound burst and then the onset times were designated in reference to the peak time. The onsets of the bass and snare drum were detected from the envelope of low-pass filtered drum sound, and those of the high-hat cymbals were detected from the envelope of high-pass filtered sound. The onset was defined as the time at which the sound amplitude exceeded 10% of the maximum amplitude of the sound burst and was below the threshold for 74 points (i.e., 2 ms) before the onset point. The detected onsets are shown in Figure 3 as vertical broken lines on the envelopes of drum kit

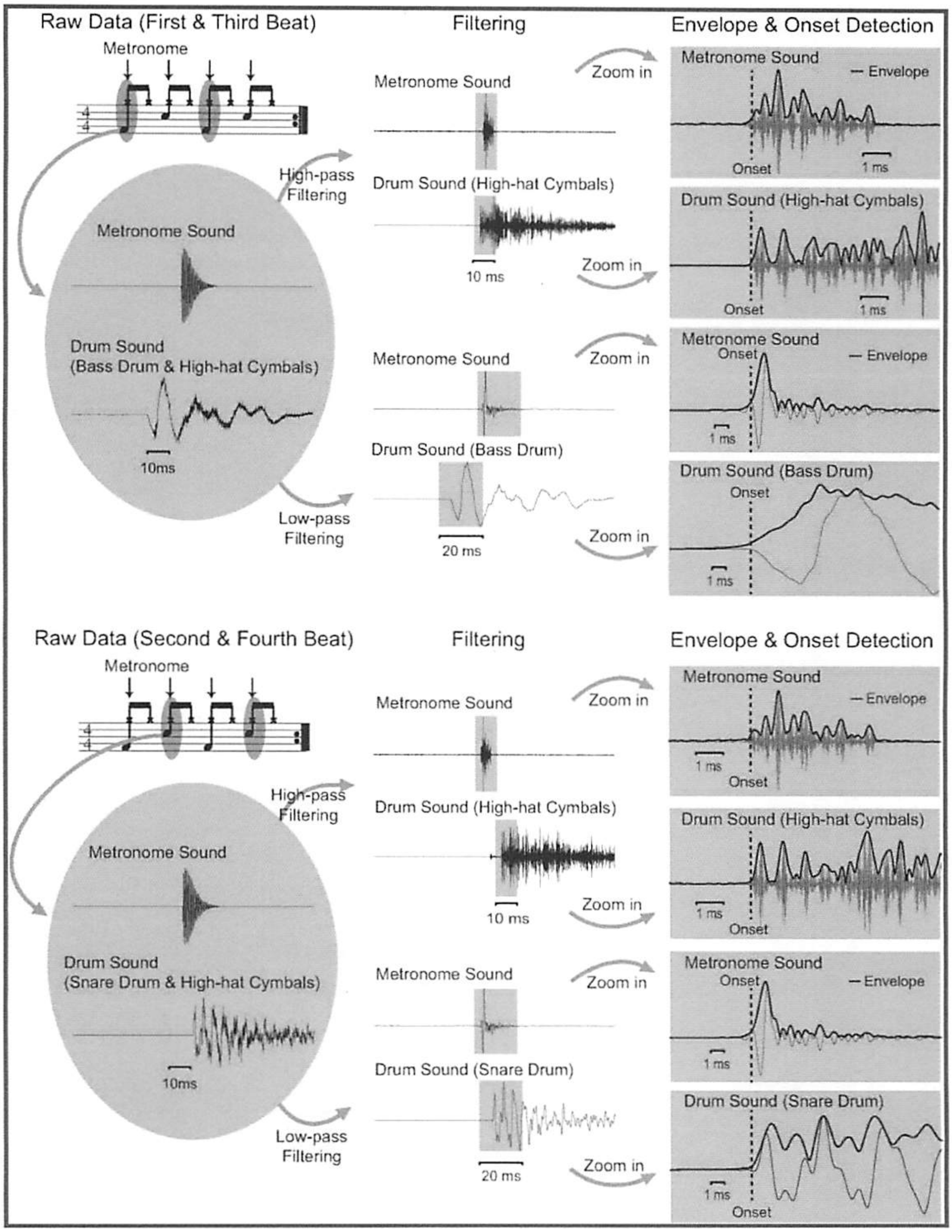

FIGURE 3. Example of recorded sound of metronome and drum kit (left panels). The upper part of the left panels indicates the sound data on the first and third beat, while the lower part indicates that on the second and fourth beat. The recorded drum kit sounds were low-pass filtered to extract the bass- or snare-drums' sound, and high-pass filtered to extract the high-hat cymbals' sound (middle panels). The same filters were applied for the metronome sounds. In order to detect sound onsets, envelopes were calculated from the filtered signals (right panels). Vertical dashed lines indicate the onsets of the sounds detected from the envelopes.

sounds. When the filtering technique did not completely separate drum kit sounds and therefore the automatic program failed to detect the onset, we determined it manually. The percentage of manual analysis was less than 0.13% for the sounds of bass and snare drum and less than 6.00% for the sounds of high-hat cymbals. The percentage of manual analysis for the high-hat cymbals was somewhat larger than that for the bass and snare drum because the high-pass filtered drum sound sometimes still included the sound components derived from the hitting of the snare drum.

The onset of each drum kit sound relative to that of the metronome was defined as the synchronization error (SE). That is, the SEs of high-hat cymbals were calculated as the difference in the onset between the high-pass filtered metronome and drum kit sounds, and the SEs of the bass and snare drum were calculated as the difference between the low-pass filtered metronome and drum kit sounds. The value was negative when the onset of the drum sound preceded that of the metronome and positive when the drum onset lagged behind the metronome. We calculated the mean, *SD*, and percentage of variation of the SE (ratio of the *SD* of SE to the IOI of metronome) of each drum kit sound over 60 s for each participant.

Statistics

The mean, *SD*, and percentage of variation of SE were subjected to 3 × 3 two-way repeated-measures analysis of variance (ANOVA). The factors were motor effectors (right hand, left hand, and right foot playing high-hat cymbals, snare drum, and bass drum, respectively) and metronome tempi (60, 120, and 200 bpm, corresponding to 1000, 500, and 300 ms IOI, respectively). When there was a significant interaction, one-way repeated-measures of ANOVA and multiple comparisons using the Bonferroni procedure were conducted for each factor.

Results

Typical Example

The typical distribution of the SE of each motor effector at the three tempi for a professional drummer is shown in Figure 4. At the 60 and 120 bpm tempi, the SE of the right hand (high-hat cymbals) was distributed around the zero value, whereas those of the left hand (snare drum) and right foot (bass drum) were ahead of the metronome. At the 200 bpm tempo, the left hand and right foot showed relatively smaller SEs compared to the right hand, which was delayed relative to the metronome.

Mean Synchronization Error

The group means of the within-trial mean synchronization error (MSE) are shown in Figure 5. The values for the right hand were −2.49, 0.00, and 10.07 ms in the 60, 120, and 200 bpm conditions, respectively. Those for the left hand were −10.98, −5.45, and 0.22 ms, respectively; values for the right foot were −12.91, −8.91, and −0.70 ms, respectively. A two-way ANOVA showed significant interaction between motor effectors and metronome tempi, $F(4, 56) = 3.16, p < .05, \eta^2 = 0.18$. The main effects of both motor effectors and metronome tempi were significant, $F(2, 28) = 32.60, p < .001, \eta^2 = 0.70$ and $F(2, 28) = 6.55, p < .01, \eta^2 = 0.32$, respectively. One-way ANOVAs for each metronome tempo showed that there were significant differences among the motor effectors in all of the metronome conditions, $F(2, 28) = 24.24, p < .001, \eta^2 = 0.63$, $F(2, 28) = 22.49, p < .001, \eta^2 = 0.62$, and $F(2, 28) = 29.26, p < .001, \eta^2 = 0.68$, in the 60, 120, and 200 bpm conditions, respectively. Posthoc analysis revealed that the MSE of the right hand (high-hat cymbals) was significantly larger than that of the left hand (snare drum, $p < .01$) and the right foot (bass drum, $p < .001$) in all of the metronome conditions. There was no significant difference between the MSE of the left hand and right foot in the 60 and 200 bpm conditions, while in the 120 bpm condition, the MSE of left hand was significantly larger than that of the right foot. One-way ANOVAs for each motor effector showed that there were significant differences among the metronome conditions in all of the motor effectors, $F(2, 28) = 7.49, p < .01, \eta^2 = 0.35$, $F(2, 28) = 5.15, p < .05, \eta^2 = 0.27$, and $F(2, 28) = 6.59, p < .01, \eta^2 = 0.32$ in the right hand, left hand, and right foot, respectively. Posthoc analysis revealed that the MSE of 200 bpm was significantly larger than that of 60 bpm ($p < .05$) and 120 bpm ($p < .05$) in the right hand and foot. In the left hand, the MSE of 200 bpm was significantly larger than that of 60 bpm ($p < .05$).

Variability of Synchronization Error

The group mean of the within-participant *SD* of SE is shown in Figure 6A. A two-way ANOVA showed significant interaction between motor effectors and metronome tempi, $F(4, 56) = 3.47, p < .05, \eta^2 = 0.20$. The main effects of both motor effectors and metronome tempi were significant, $F(2, 28) = 4.36, p < .05, \eta^2 = 0.24$ and $F(2, 28) = 22.06, p < .001, \eta^2 = 0.61$, respectively. One-way ANOVAs for each metronome tempo showed significant difference among motor effectors in the 60 and 200 bpm conditions, $F(2, 28) = 3.73, p < .05, \eta^2 = 0.21$ and $F(2, 28) = 4.78, p < .05, \eta^2 = 0.26$, respectively.

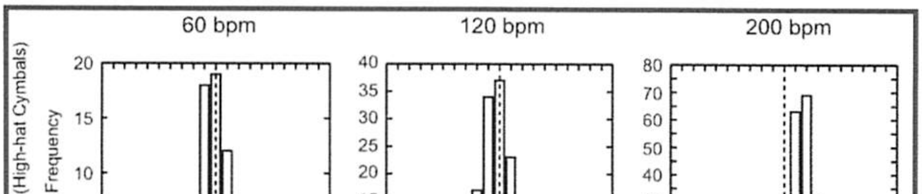

FIGURE 4. Typical distribution of synchronization error (SE) in drum kit playing by a professional drummer. White bars in upper panels = SE of right hand or high-hat cymbals. Grey bars in middle panels = SE of left hand or snare drum. Dark bars in lower panels = SE of right foot or bass drum. Left, middle, and right panels correspond to 60, 120, and 200 bpm conditions, respectively.

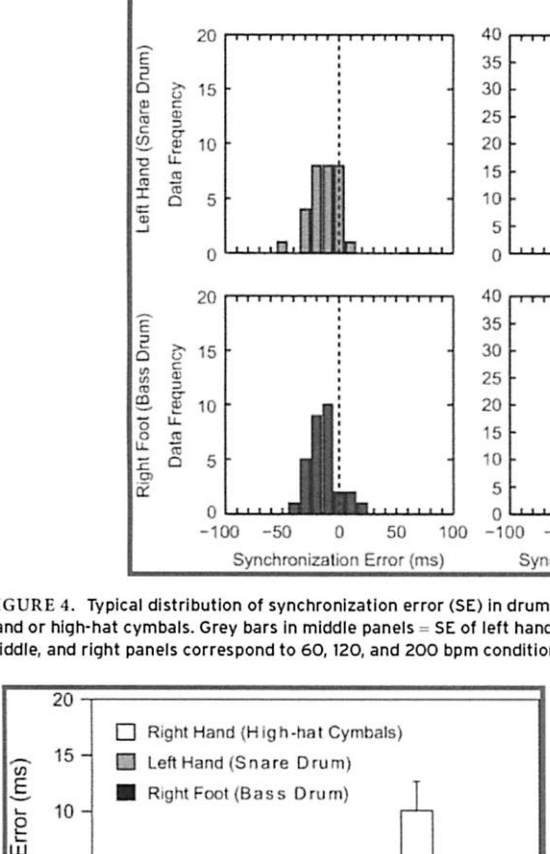

FIGURE 5. Mean synchronization error (MSE). Error bars indicate between-participants standard error ($n = 15$).

However, posthoc analysis did not detect any significant difference among the motor effectors for both of the tempi. One-way ANOVAs for each motor effector showed that there were significant differences among the metronome conditions for all of the motor effectors, $F(2, 28) = 14.92$, $p < .001$, $\eta^2 = 0.52$, $F(2, 28) = 17.14$, $p < .001$, $\eta^2 = 0.55$, and $F(2, 28) = 28.07$, $p < .001$, $\eta^2 = 0.67$ in the right hand, left hand, and right foot, respectively. Posthoc analysis revealed that the *SD* of SE at the 60 bpm tempo was significantly larger compared to that at 120 ($p < .001$) and 200 bpm ($p < .01$) for the left hand and right foot. For the right hand, the *SD* of SE at the 60 bpm tempo was significantly larger than that at 120 bpm ($p < .001$).

The group mean of the within-participant percentage of variation of SE is shown in Figure 6B. Two-way ANOVA showed significant interaction between motor effectors and metronome tempi, $F(4, 56) = 4.12$, $p < .01$, $\eta^2 = 0.23$. The main effects of both motor effectors and tempi were significant, $F(2, 28) = 4.89$, $p < .05$, $\eta^2 = 0.26$ and $F(2, 28) = 71.04$, $p < .001$, $\eta^2 = 0.84$, respectively.

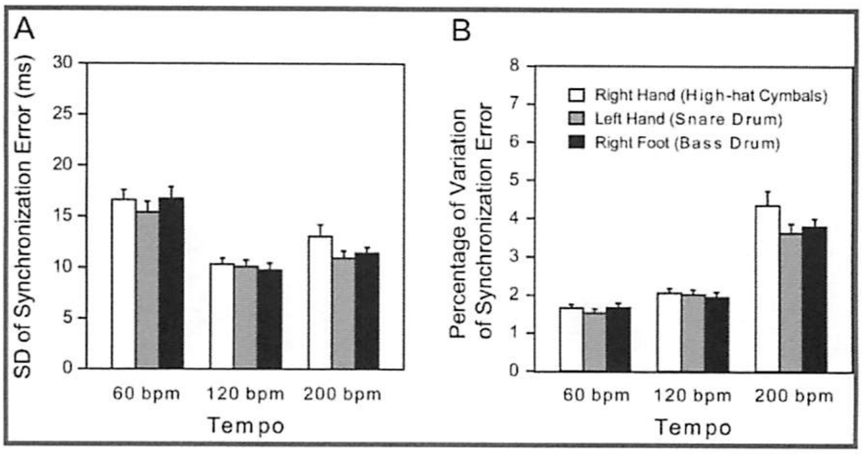

FIGURE 6. A. Standard deviation (*SD*) of synchronization error. B. Percentage of variation of synchronization error (SE). The percentage of variation of the SE was calculated as the ratio of the *SD* of SE to the interonset interval of the metronome. Error bars indicate between-participants standard error ($n = 15$).

One-way ANOVAs for each metronome tempo showed significant difference among the motor effectors in the 60 and 200 bpm conditions, $F(2, 28) = 3.76, p < .05, \eta^2 = 0.21$ and $F(2, 28) = 4.80, p < .05, \eta^2 = 0.26$, respectively. However, posthoc analysis did not detect any significant difference among the motor effectors. One-way ANOVAs for each motor effector showed that there were significant differences among the metronome conditions for all of the motor effectors, $F(2, 28) = 44.08, p < .001, \eta^2 = 0.76$, $F(2, 28) = 61.37, p < .001, \eta^2 = 0.81$, and $F(2, 28) = 83.57, p < .001, \eta^2 = 0.86$ for the right hand, left hand, and right foot, respectively. Posthoc analysis revealed that the percentage of variation of SE in the 200 bpm condition was significantly larger than that in the 60 ($p < .001$) and 120 bpm ($p < .001$) conditions for all of the motor effectors. The percentage of variation of SE in the 200 bpm condition was about twice as large as that in the 60 and 120 bpm conditions.

Percentage of Playing an Instructed Note Pattern

During the measurement of the 200 bpm condition, participants seemed to have difficulty playing the eighth note pattern with the right hand. We therefore tested whether the participants correctly played the instructed score shown in Figure 2. When we calculated the percentage that each participant played an instructed note (see Table 1), we observed that the instructed notes were correctly played with the left hand (snare drum) and right foot (bass drum). On the other hand, the instructed notes

TABLE 1. Percentage of Playing Instructed Note Shown in Figure 2 with Right Hand, Left Hand, and Right Foot at 60, 120, and 200 bpm tempi.

	60 bpm			120 bpm			200 bpm		
Drummer ID	right hand	left hand	right foot	right hand	left hand	right foot	right hand	left hand	right foot
D1	100.00	100.00	100.00	100.00	100.00	100.00	4.52	100.00	100.00
D2	100.00	100.00	100.00	100.00	100.00	100.00	24.12	100.00	100.00
D3	100.00	100.00	100.00	100.00	100.00	100.00	58.29	100.00	100.00
D4	100.00	100.00	100.00	100.00	100.00	100.00	70.85	100.00	100.00
D5	100.00	100.00	100.00	100.00	100.00	100.00	83.42	100.00	100.00
D6	100.00	100.00	100.00	100.00	100.00	100.00	83.42	100.00	100.00
D7	100.00	100.00	100.00	100.00	100.00	100.00	85.93	100.00	100.00
D8	100.00	100.00	100.00	100.00	100.00	100.00	88.44	100.00	100.00
D9	100.00	100.00	100.00	100.00	100.00	100.00	93.97	100.00	100.00
D10	100.00	100.00	100.00	99.16	100.00	100.00	95.48	100.00	100.00
D11	100.00	100.00	100.00	100.00	100.00	100.00	95.98	100.00	100.00
D12	100.00	100.00	100.00	100.00	100.00	100.00	98.99	100.00	100.00
D13	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
D14	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
D15	100.00	100.00	100.00	98.32	100.00	100.00	100.00	100.00	100.00
Mean	100.00	100.00	100.00	99.83	100.00	100.00	78.89	100.00	100.00

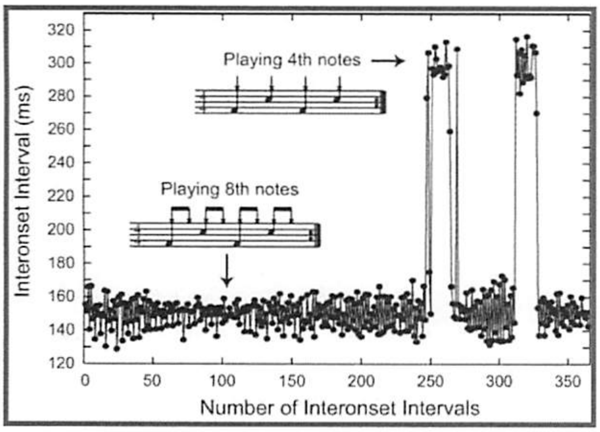

FIGURE 7. Typical example of the interonset interval (IOI) detected from the sound of high-hat cymbals (right hand) at 200 bpm tempo by a professional drummer. The drummer sometimes played fourth notes (IOI of 300ms) instead of eighth notes (IOI of 150ms) in the latter half of the trial.

were not played correctly with the right hand (high-hat cymbals), especially at the 200 bpm tempo; the mean percentage of playing an instructed note was 78.89%. This resulted from participants' inability to endure playing eighth notes (i.e., IOI of 150 ms) with the right hand; instead, they reduced their speed and played quarter notes (i.e., IOI of 300 ms) when they could no longer keep up their original pace (see Figure 7). In fact, 12 of the 15 participants were unable to continue playing eighth notes during the entire 200 bpm trial (D1-D12 in Table 1). The percentage of playing the instructed eighth notes was less than 90% for 8 of the 15 participants (D1-D8 in Table 1).

As for those eight participants, we examined the effect of the change in the played notes on the MSE, *SD* of SE, and percentage of variation of SE (see Figure 8). Thus, we conducted a two-way ANOVA using the factors of played notes (eighth and fourth notes) and motor effectors (right hand, left hand, and right foot). We found no significant interaction, $F(2, 14) = 0.36$, *n.s.*, $\eta^2 = 0.05$, $F(2, 14) = 0.97$, *n.s.*, $\eta^2 = 0.12$, and $F(2, 14) = 0.97$, *n.s.*, $\eta^2 = 0.12$ in the MSE, *SD* of SE, and percentage of SE, respectively. We also found that changes in the notes played had no significant effect, $F(1, 7) = 0.11$, *n.s.*, $\eta^2 = 0.02$, $F(1, 7) = 1.37$, *n.s.*, $\eta^2 = 0.16$, and $F(1, 7) = 0.28$, *n.s.*, $\eta^2 = 0.16$ in the MSE, *SD* of SE, and percentage of SE, respectively (see Figure 8).

Correlation of Synchronization Error Among the Motor Effectors

Figure 9 shows a typical example of the time series of SE for the right hand and foot on the first and third beat and those for the left and right hand on the second and fourth beat at 60, 120, and 200 bpm tempi, respectively. As shown in the figure, the pattern of the time series was similar across the limbs at each tempo. When we calculated Pearson's correlation coefficients between the time series of the right hand and foot, all of the participants showed significant values (r ranged from 0.21 to 0.98, $p < .05$). They also showed significant correlations between the time series of the left and right hand (r ranged from 0.48 to 0.99, $p < .05$).

The group mean of the correlation coefficient is shown in Figure 10. A two-way ANOVA with the factors of metronome tempi (60, 120, and 200 bpm) and limb combinations (the right hand and foot; the left and right hands) showed significant interaction, $F(2, 28) = 5.64$, $p < .01$, $\eta^2 = 0.29$. The main effects of both metronome tempi and limb combinations were significant, $F(2, 28) = 26.79$, $p < .001$, $\eta^2 = 0.66$ and $F(1, 14) = 60.46$, $p < .001$,

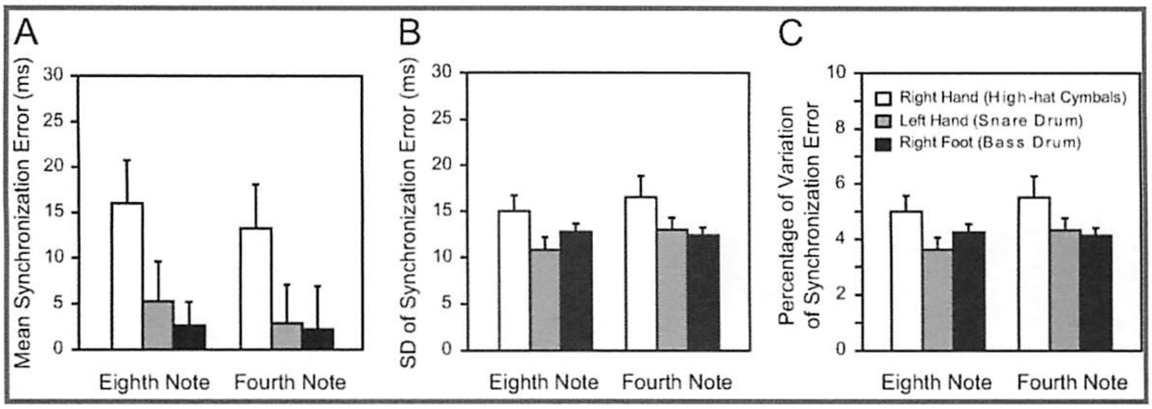

FIGURE 8. A. Mean synchronization error (SE). B. standard deviation (*SD*) of SE. C. Percentage of variation of SE while playing eighth and fourth notes with the right hand at 200 bpm tempo. Error bars indicate standard error among eight drummers whose percentage of playing the instructed note was less than 90% in Table 1.

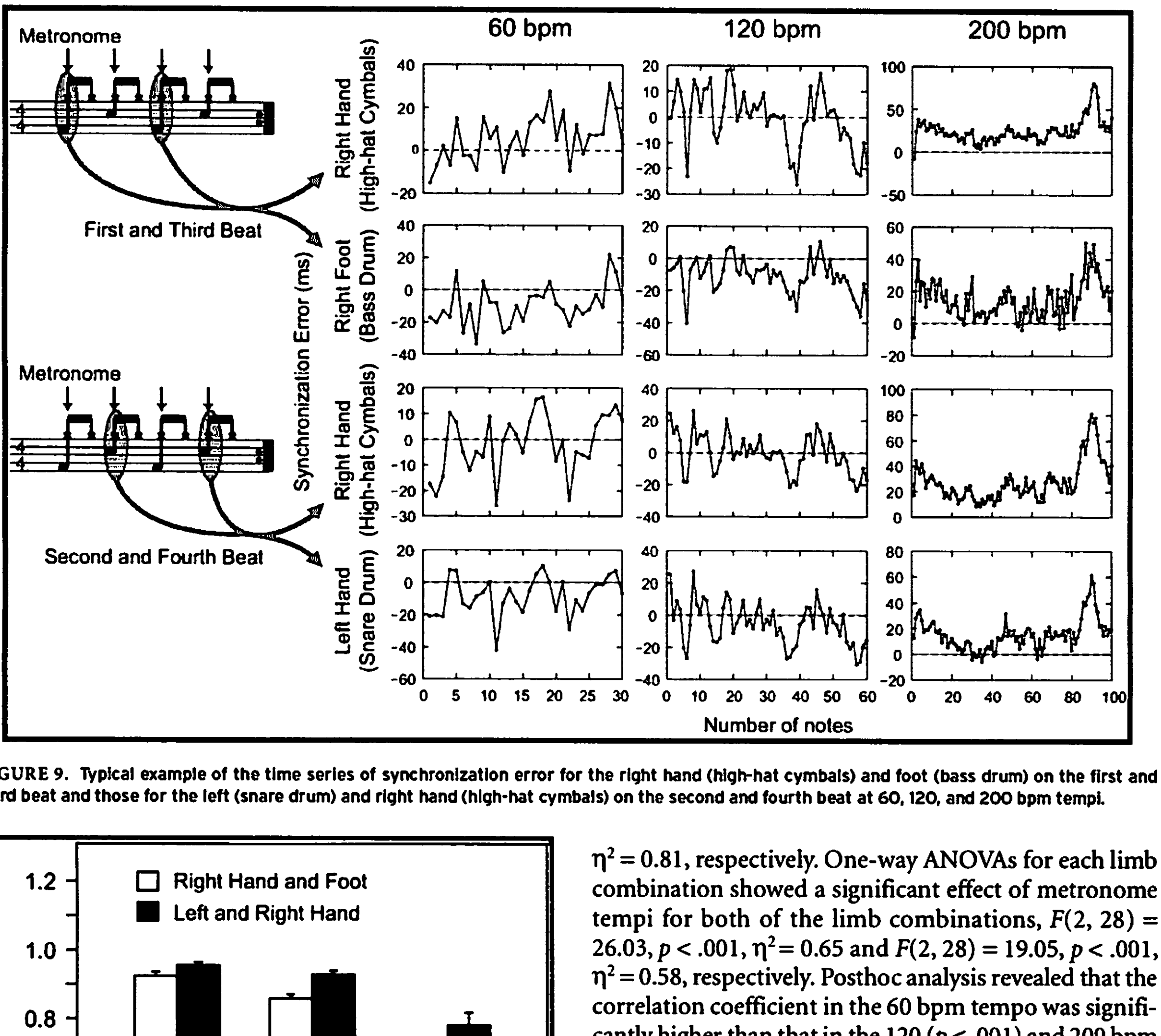

FIGURE 9. Typical example of the time series of synchronization error for the right hand (high-hat cymbals) and foot (bass drum) on the first and third beat and those for the left (snare drum) and right hand (high-hat cymbals) on the second and fourth beat at 60, 120, and 200 bpm tempi.

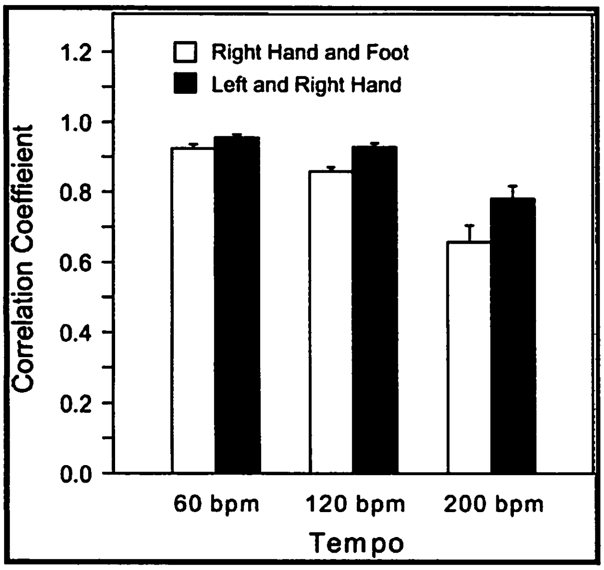

FIGURE 10. Group mean of Pearson's correlation coefficient calculated from the time series of synchronization error at 60, 120, and 200 bpm tempo, respectively. White bars = correlation coefficient between the right hand and foot on the first and third beat. Black bars = correlation coefficient between the left and right hand on the second and fourth beat. Error bars indicate between-participants standard error ($n = 15$).

$\eta^2 = 0.81$, respectively. One-way ANOVAs for each limb combination showed a significant effect of metronome tempi for both of the limb combinations, $F(2, 28) = 26.03, p < .001, \eta^2 = 0.65$ and $F(2, 28) = 19.05, p < .001, \eta^2 = 0.58$, respectively. Posthoc analysis revealed that the correlation coefficient in the 60 bpm tempo was significantly higher than that in the 120 ($p < .001$) and 200 bpm tempi ($p < .001$) for the combination of the right hand and foot. The correlation coefficient in the 60 bpm tempo was significantly higher than that in the 200 bpm ($p < .01$) for the left and right hand combination. The correlation coefficient between the left and right hand was significantly higher than that of the right hand and foot for all the metronome conditions ($p < .01$).

Discussion

Absolute Value of Synchronization Error

We hypothesized that professional drummers are able to synchronize their drum kit playing to a metronome very precisely, but the degree of precision depends on the motor effectors and/or the tempi. In the present study, the group means of the MSE ranged from −13 to 10 ms (see Figure 5). The absolute values of the MSE were smaller than those reported in previous tapping studies, in which the MSE was typically about −20 to −80 ms (see Aschersleben, 2002). The absolute values of MSE in the present study were smaller even when compared to the finger tapping study by Gërard and Rosenfeld (1995), who found an MSE of −25 ms in the professional percussionists of the Conservatoire de Paris. As predicted, the relatively small MSE in the present study can be attributed to the experience of the participants and the intensive practice needed to develop and maintain professional skill, as well as to the explicit auditory feedback of the drum kit. In addition, the effect of using a drumstick might affect the relatively small MNA in the present study, since holding sticks leads to changes in sensory information such as tactile, auditory, and kinesthetic feedback information (Fujii & Oda, 2009a, 2009b).

In the present study, the percent of variation of SE was around 2% in the 60 and 120 bpm conditions, whereas it was around 4% at the 200 bpm tempo (see Figure 6). Previous tapping studies showed that a musically trained and practiced individual achieved a 2% variation of SE, whereas the percentage of variation was typically at least twice as large for novice participants (see, e.g., Pressing & Jolley-Rogers, 1997; Repp & Penel, 2002). The 2% variations in 60 and 120 bpm conditions in the present study were comparable to those for the skilled participants in previous studies, and the 4% variation in the 200 bpm condition was comparable to that of unskilled participants. That is, the professional drummers in the present study showed relatively stable synchronization of drum kit playing with a metronome at a tempo of 60 and 120 bpm, while they showed unstable synchronization at 200 bpm.

For music instructors and students, the degree of precision in drum kit playing achieved by professional drummers (Figures 5 and 6) provides useful information for establishing goals for music education. Specifically, rough standards of performance for professional drummers would be an MSE of about 10 ms and 2% variation of SE for low (~60 bpm) and middle (~120 bpm) frequencies and 4% variation of SE for a very high frequency (~200 bpm).

Effect of Motor Effectors and Tempi on Mean Synchronization Error

Consistent with our hypothesis, we found the presence of significant main effects for both motor effectors and tempi on MSE during drum kit playing. In the 60 and 120 bpm conditions, the right hand showed almost no asynchrony, whereas the left hand and right foot showed negative mean asynchrony (NMA). In the 200 bpm condition, the right hand showed positive mean asynchrony (PMA), whereas the left hand and right foot showed almost no asynchrony (Figure 5).

The difference between the right hand and foot in the present study is consistent with previous tapping studies that showed that foot tapping precedes hand tapping (Aschersleben & Prinz, 1995; Aschersleben et al., 2002; Billon et al., 1996). In most studies, the difference between hand and foot tapping has been explained by the nerve conduction hypothesis, which suggests that the NMA has its origins in differences in nerve conduction times between tactile/kinesthetic and auditory feedback. Due to this difference, the finger/foot tap has to precede the auditory click to establish synchrony at the level of central representations because sensory information from the tip of the finger/foot takes longer to travel to the brain than it does from the ear (see Aschersleben, 2002; Fraisse, 1980). In line with the nerve conduction hypothesis, foot tapping was considered to show larger NMA than hand tapping because the temporal delay between the actual and the perceived tap would be greater in foot tapping than in hand tapping due to the increased neural distance between motor effector and brain. Aschersleben and Prinz (1995) showed that the effect of increased neural distance in foot tapping persisted even when additional auditory feedback contingent on each tap was provided. Thus, in the present study, the difference in the NMA between the right hand and foot can also be explained by the nerve conduction hypothesis. However, this hypothesis does not explain the difference between the left and right hands, because the neural distance between the motor effectors and the brain are almost the same in such a case.

With regard to the more precise performance of the right hand compared to the left hand in the 60 and 120 bpm conditions, a possible explanation might appeal to functional asymmetry between the hands (or hemispheres). The resulting hypothesis would be that the participants were able to play more precisely with the right hand simply because they were right-handed. Studies of the relationship between music and the brain have suggested that the temporal features of music are processed predominantly in the left hemisphere (Zatorre & Belin, 2001). In addition, Pollok et al. (2008) showed that low-frequency repetitive transcranial magnetic stimulation (rTMS) applied over the left dorsolateral premotor cortex (dPMC) decreased tapping accuracy of both left and right hands, suggesting that the left dPMC controls timing abilities for both hands. Based on these previous findings, it may be possible to explain the relatively small NMA observed in the right hand as a function of the control by the left hemisphere of both right-hand movement and music temporality and thus of their close neurological connection.

The idea of a subdivision benefit proposed by Wohlschläger and Koch (2000) might explain both the difference between the left and right hand and that between the right hand and foot under the 60 and 120 bpm conditions in the present study. Wohlschläger and Koch (2000) showed that the NMA is reduced or eliminated when participants subdivide the inter-tap interval by adding movements or sounds between regular synchronized taps (see also Repp, 2003; Thaut, Rathbun, & Miller, 1997). In the present study, participants played the eighth note with the right hand and the quarter note with the left hand and right foot (see Figure 2); thus, the additional movements and sounds that intervened between the metronome clicks may have created more subdivision and reduced the NMA of the right hand compared to that of the left hand and right foot at the 60 and 120 bpm tempi.

Another possibility is related to the acoustic characteristics of the instrument sounds. As shown in Figure 3, duration from the onset to the peak amplitude of envelope (i.e., attack time) was relatively longer in the sounds of the bass and snare drums compared to that in the sound of high-hat cymbals. If the timing of instrument playing is represented in the brain not by the onset of sound but by another perceptual center (p-center) (Aschersleben, 2002; Morton, Marcus, & Frankish, 1976) that related to the attack time, the difference in acoustic characteristics might have affected the MSE in the present study.

In future studies, it would be interesting to investigate the MSE in other experimental conditions, such as where the high-hat cymbals, snare drum, and bass drum are played separately and in pairs, not just all three together. That will allow more definitive conclusions regarding the effects of subdivision and the hemispheric asymmetry on MSE during drum kit playing. In addition, the condition in which each effector plays the same instrument will be helpful to confirm the effect of acoustic characteristics on the MSE.

Performance at 200 bpm Tempo

At the 200 bpm tempo, the drummers in the present study could not endure playing eighth notes with the right hand, and instead played quarter notes (see Figure 7 and Table 1). This phenomenon can be interpreted in two ways as follows.

The first interpretation is based on the previous studies on rapid tapping; the maximum frequency at which the motor effectors are able to move is about 5–7 Hz, which corresponds to intertap intervals (ITIs) of 150–200 ms (Aoki, Furuya, & Kinoshita, 2005; Hermsdorfer, Marquardt, Wack, & Mai, 1999; Kimura & Davidson, 1975; Peters & Durding, 1978, 1979; Todor & Kyprie, 1980; Todor, Kyprie, & Price, 1982; Todor & Smiley-Oyen, 1987). Our previous studies also showed that the limit of drummers' rate of drumstick tapping was about 7 Hz or ITIs of 150 ms (Fujii, Kudo, Ohtsuki, & Oda, 2009; Fujii, Kudo, Shinya, Ohtsuki, & Oda, 2009; Fujii & Oda, 2006, 2009a, 2009b). In the present experiment, the eighth note in the 200 bpm condition corresponded to an IOI of 150 ms (the upper rate limit). Thus, the biomechanical constraints of the upper rate limit might have prevented players from maintaining eighth notes with the right hand throughout the trial at the 200 bpm tempo.

The second interpretation is based on the previous findings on the spontaneous transition of interlimb coordination pattern with an increase of movement frequency (see Kelso, 1995, for a review). For example, during polyrhythmic or multifrequency interlimb coordination, the coordination mode with a higher order ratio (e.g., 5:8) is performed with larger temporal variability than that with a lower order ratio (e.g., 2:3 or 1:2), and spontaneous transitions from higher to lower order ratio occur with an increase in the tempo of performance (e.g., Peper, Beek, & Wieringen, 1995). From the point of view of interlimb coordination, the change in the note played, from eighth to fourth, with the right hand might be interpreted as a spontaneous transition of the interlimb coordination pattern from the higher order ratio of 4:1:1 to the lower ratio of 2:1:1 (right hand, left hand, and right foot, respectively).

Interlimb Coordination

In the present study, the time series of SE was significantly correlated across the limbs, suggesting that each limb synchronized not independently to the metronome but in relation to the other limbs, which are in turn synchronized with the metronome. Moreover, the correlation coefficients among the limbs decreased with the increase of the metronome tempo (see Figure 10), indicating that the interaction among the limbs became weaker with the increase of the metronome tempo. This might be related to the more unstable synchronization performance, especially at the tempo of 200 bpm.

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