Effects of Stick Use on Bimanual Coordination Performance During Rapid Alternate Tapping in Drummers

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The aim of this study is to establish the effects of stick use on rhythmic bimanual coordination in drummers. Eighteen drummers performed a rapid antiphase coordination task using their fingers and handheld drumsticks. We found no significant differences in the speed of tapping between finger and stick-use tapping, while stick-use tapping had a larger peak force and smaller variability in coordination pattern than finger tapping. As a consequence, the quotient of the number of taps divided by the variability of coordination pattern, named the bimanual performance quotient, was higher for stick-use tapping than for finger tapping. A significant correlation was found between years of drumming experience and the bimanual performance quotient for both finger and stick-use tapping, but not between the years of drumming experience and the degree of improvement in the bimanual performance quotient with stick use relative to finger tapping. These results indicate that stick use enhances drummers’ bimanual coordination during rapid alternate tapping, whereas the degree of improvement with stick use does not depend on drumming experience.

Keywords: tool use, musicians, training, variability

Tools extend human abilities, allowing people to do things they cannot do unaided and making tasks easier to perform (Galer, 1989). The ability to use tools helps to define human uniqueness and has long been a focus in the study of human evolution (Berthelet & Chavaillon, 1993; Gibson & Ingold, 1993). Recently, tool-use ability has also attracted the attention of neuroscientists, and tool use has been confirmed to have a critical effect on the sensorimotor system (Johnson-Frey, 2003, 2004; Maravita & Iriki, 2004; Pillard, 1993).

Since ancient times, the stick has been one of the simplest tools used by humans to play percussion instruments. Drumming behavior is also seen in great apes such as chimpanzees and gorillas; however, they do not play music with handheld sticks but rather drum on their bodies or other resonant structures using their hands as a component of their complex dominance or aggressive displays.
Fujii and Oda (Fitch, 2006). This implies that playing music using sticks is a characteristic unique to humans, and that humans achieve highly organized musical performance by applying the effects of stick use. From the point of view of motor control, using sticks is predicted to have critical effects on bimanual coordination because it leads to changes in both mechanical properties of upper limbs (e.g., increased mass, moment of inertia, and stiffness) and sensory information (e.g., tactile, auditory, and kinesthetic feedback information). However, there is no study investigating the effects of stick use on bimanual drumming performance.

In our previous study examining the performance of rapid periodic drumming, the performance variables such as speed of tapping and peak tapping force were used to assess tapping speed and intensity, respectively (Fujii & Oda, 2006). In addition, the previous studies on human bimanual coordination have used the measure called relative phase (i.e., phase difference between the left and right hand) to assess stability and accuracy of bimanual coordination performance (see reviews by Kelso 1995; Swinnen & Wenderoth, 2004). For example, standard deviation (SD) of the relative phase was used for an index of the coordination stability; mean relative phase, as well as absolute difference between actual relative phase and intended relative phase, named absolute constant error, was used for an index of coordination accuracy (e.g., Murian, Deschamps, Bourbousson, & Temprado, 2008). Considering that tools extend human abilities (Galer, 1989), we hypothesized that stick use has not negative but positive effects on some of the performance variables: stick use should enhance movement speed, tapping intensity, coordination stability, and/or coordination accuracy during bimanual movement. Thus, the primary purpose of the current study is to establish the effect of stick use on these performance variables of bimanual coordination in drummers. We therefore examined the differences in performance between two bimanual tapping tasks—“finger tapping” and “stick-use tapping”—in which drummers were asked to tap with the left and right fingers in one task condition and with handheld sticks in the other condition. In both conditions, drummers were asked to produce an alternating (antiphase) coordination pattern.

Previous studies have also revealed that bimanual coordination performance is influenced by individual experiences regarding manual training (Summers, 2002; Summers, Ford, & Todd, 1993; Zanone & Kelso, 1992). Because bimanual coordination is necessary for playing a musical instrument, one might expect musical experience to affect coordination constraints. Indeed, previous behavioral and brain studies support the link between musical experience and bimanual coordination: musicians show stable bimanual coordination when performing (Verbeul & Geuze, 2004; Yamanishi, Kawato, & Suzuki, 1980) as well as adaptive changes in related sensorimotor areas of the brain compared with nonmusicians (Haslinger et al., 2004; Jancke, Shah, & Peters, 2000; Schlaug, 2001). Since these previous studies on musicians focused on the experience of playing musical instruments such as keyboard and string instruments, the need exists to ascertain whether drumming experience/training also affects bimanual coordination during performance. In addition, whether the degree of improvement in the bimanual performance with stick use is dependent on an individual’s drumming experience/training should be clarified. Thus, the secondary purpose of the current study is to investigate the relationship between years of drumming experience/training and bimanual performance as well as the relationship between years of drumming
Effects of Stick Use on Bimanual Coordination

Methods

Participants
The participants were 18 drummers (mean age = 26.7 years, \(SD = 8.1\), 14 men and four women). They began drum training at an average age of 15.9 years (\(SD = 4.0\)) and had an average of 8.9 years of drumming experience (\(SD = 9.6\)). The duration of drumming experience/training ranged from one month to 33 years. They were four professional drummers (9, 22, 29, and 33 years of drumming experience) and 14 students at a special music school (one month to 11 years of drumming experience), usually playing rock, popular, or jazz music. All participants were right-handed, as determined using the Edinburgh Handedness Inventory (Oldfield, 1971). The mean laterality quotient between the participants was 93.9 (\(SD = 8.5\)). In accordance with the Declaration of Helsinki, the participants received a clear explanation of the experimental procedure and submitted written informed consent before 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 and Tasks
The height and position of a drum throne was adjusted to allow each participant to sit on it comfortably. Two strain-gauge force transducers (LUR-A-1KNSAI, KYOWA), the tapping surface of which were covered by sponge rubber, were in front of the participants. We used the sponge rubber as tapping surface because it absorbed the vibration making the moment of the tap clear and therefore easily determined.

The experimental task was a rapid antiphase coordination task requiring the participants to tap the force transducers alternately as fast and as accurately as possible for 12 s. We employed the task because it is consistent with the most basic drumming behavior. The task was conducted under two conditions: the finger and stick-use tapping conditions. Under the finger-tapping condition, the participants were asked to extend the left and right index finger while the remaining fingers were curled into a fist. They were then instructed to perform rapid antiphase tapping using the index fingers. They were instructed to use wrist flexion–extension movements while keeping their other joints as fixed as possible. Under the stick-use tapping condition, the participants held a drumstick (118M, Hiro Tsunoda Model, Pearl) in their left and right hands with their palms facing down, and were instructed to perform rapid antiphase tapping using the sticks. Again, they were instructed to use the wrist flexion–extension movements while keeping their other joints fixed as much as possible. Similar wrist flexion-extension movements were used for both conditions. We instructed the participants to use wrist movements in both conditions because the drummers in our previous study (Fujii & Oda, 2006) reported that they mainly used wrist movements during rapid periodic drumming. After the participants had practiced under the two conditions experience/training and degree of improvement in the bimanual performance with stick use.
for a few minutes, experimental measurements were conducted. Each condition consisted of three trials and the order of the conditions was counterbalanced among the participants.

Data Analysis

The signal of the force transducers was amplified (SA-100D, TEAC), converted from analog to digital at 1000 Hz, and recorded on a personal computer. A typical example shows the tapping data for 500 ms during both the finger and the stick-use tapping (see Figure 1). The data across 12 s were truncated to eliminate start-up effects and periods of final slowing; that is, data collected during the first 1.5 s and the last 0.5 s were omitted, and only the data collected during the middle 10 s were analyzed. The number of taps for 10 s was calculated for each trial from the signal of the force transducers. For each tap, the peak amplitude of the signal was termed the peak force and the mean peak force over 10 s was calculated for each trial. Although we used the sponge rubber as a tapping surface, some vibration components after tap still remained in the signal of the force transducers in

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**Figure 1** — Typical examples of recorded force data during finger (upper part) and stick-use tapping (lower part). Vertical broken lines indicate the detected moments of the tap. $RL$ denotes time interval from a right-hand tap to a left-hand tap, while $LR$ indicates that from a left-hand tap to a right-hand tap.
the stick-use tapping task (see lower panel in Figure 1). To determine the appropriate threshold to detect the moment of the tap, we tried the thresholds from 5% to 30% by 5% amplitude of the peak force. Because we visually confirmed that the thresholds above 15% correctly detected each tap onset without detecting the vibration components, the 15% threshold was employed in the current study. The detected tap onsets are shown in Figure 1 as vertical broken lines. After determining the tap timing, the relative phase $\phi$ was calculated by the equation

$$\phi = RL / (RL + LR) \times 360$$

(1)

The symbol $RL$ denotes the time interval from a right-hand tap to a left-hand tap, while $LR$ indicates the time interval from a left-hand tap to a right-hand tap. The symbol $\phi$ denotes 180 degrees ($^\circ$), when participants taps alternated in a perfect antiphase coordination, while $\varphi$ indicates 0 or 360$^\circ$, when taps were precisely simultaneous. Although there is an equivalent equation possible: $LR / (LR + RL) \times 360$, we adopted Equation 1 because the two equations generate similar results for the antiphase pattern (see, Verheul & Geuze, 2003). We calculated the mean relative phase (mean $\varphi$), the absolute difference between the actual relative phase and the intended 180$^\circ$ relative phase termed the absolute constant error, and the standard deviation of the relative phase ($SD \varphi$) over 10 s for each trial. To assess the degree of performance achieved in the present task requiring rapid and stable bimanual coordination, we developed a dependent variable named the bimanual performance quotient. The bimanual performance quotient was calculated as the quotient of the number of taps divided by the $SD \varphi$. The bimanual performance quotient becomes larger when the number of taps is higher and/or when the $SD \varphi$ becomes smaller; that is, the more quick and stable the performance, the larger the bimanual performance quotient becomes.

The dependent behavioral variables were the number of taps, the mean peak force, the mean $\varphi$, the absolute constant error, the $SD \varphi$, and the bimanual performance quotient. The number of taps, mean peak force, mean $\varphi$, absolute constant error, and $SD \varphi$ were averaged over the three trials for each participant. The bimanual performance quotient was calculated from the averaged number of taps and $SD \varphi$ for each participant. Comparisons between the finger and the stick-use tapping were tested using paired $t$ tests when the data fulfilled the prerequisites for conducting parametric analyses (Kolmogorov–Smirnov test for normal distribution and Levene test for homogeneity of variances). If the data did not fulfill the prerequisites for parametric analyses, differences between the finger and the stick-use tapping were analyzed using the Wilcoxon matched-pairs signed-ranks tests. Effect sizes using Cohen’s $d$ were calculated for all the comparisons. We examined the correlation of the bimanual performance quotient with the years of drumming experience/training. In addition, we calculated the percent of improvement in the bimanual performance quotient with stick use (i.e., the proportion of the bimanual performance quotient for stick-use tapping to that of finger tapping). We also examined the correlation between the years of drumming experience/training and the percent of improvement in the bimanual performance quotient with stick use. Correlations were assessed using Pearson’s and Spearman’s correlation coefficients. A $p < .05$ was accepted as significant.
Results

The statistical analysis revealed no significant differences between finger and stick-use tapping in the number of taps ($t_{17} = -1.53, \text{ns, } d = 0.18$), the mean $\varphi$ ($t_{17} = -0.95, \text{ns, } d = 0.30$), and the absolute constant error ($z = -1.33, \text{ns, } d = 0.27$; see Figure 2). However, a significant difference was observed between finger and stick-use tapping in the mean peak force ($z = -3.72, p < .001, d = 0.98$) and the SD $\varphi$ ($z = -3.07, p < .01, d = 0.74$); stick-use tapping had larger peak force and smaller variability in the relative phase compared with finger tapping. As a consequence of the smaller SD $\varphi$, stick-use tapping had a larger bimanual performance quotient than finger tapping ($t_{17} = 3.01, p < .01, d = 0.64$).

Significant correlations using Pearson’s correlation coefficients were detected between years of drumming experience/training and the bimanual performance quotient in both finger and stick-use tapping (finger tapping, $r = .71, p < .01$; stick-use tapping, $r = .61, p < .01$; see Figure 3). Significant correlations were still detected in both finger and stick-use tapping when using Spearman’s correlation coefficient (finger tapping, $r = .53, p < .05$; stick-use tapping, $r = .51, p < .05$). The mean percent of improvement in the bimanual performance quotient with stick use was 41.21 ± 51% (mean ± SD between participants). No significant correlation was observed between years of drumming experience/training and the percent improvement in the bimanual performance quotient with stick use (Pearson’s correlation coefficient, $r = -0.18, \text{ns}$; Spearman’s correlation coefficient, $r = -0.36, \text{ns}$; see Figure 4).

Discussion

Effect of Stick Use

Our primary purpose is to establish the effects of stick use on some performance variables of bimanual coordination in drummers. Thus, we compared the performance of rapid antiphase finger and stick-use tapping. We found no significant differences between finger and stick-use tapping in the number of taps, the mean $\varphi$, and the absolute constant error, which suggests that stick use has only a minor effect on tapping speed and coordination accuracy. In contrast, we found significant differences between the finger and stick-use tapping in the mean peak force, the SD $\varphi$, and the bimanual performance quotient. Stick-use tapping had greater peak force, higher stability in relative phase, and a higher bimanual performance quotient compared with finger tapping. Thus, our hypothesis that stick use enhances drummers’ bimanual coordination performance was confirmed in these performance variables (i.e., mean peak force, the SD $\varphi$, and the bimanual performance quotient). We indicate that stick use has a major effect on the force profile and the stability of the bimanual coordination patterns during rapid alternate tapping in drummers.

Numerous bimanual coordination studies have shown that relative phase variability increases when oscillation frequency increases (see Kelso, 1995). Since no significant difference was detected in the number of taps (i.e., movement frequency) between the finger and stick-use tapping in the current study, the
Figure 2 — Bimanual coordination during finger (white bars) and stick-use tapping (black bars). *Significant at $p < .01$. Error bars represent between-participant standard deviations ($n = 18$). Mean $\varphi$, mean relative phase; $SD \varphi$, standard deviation of the relative phase.
difference in the SD $\varphi$ between finger and stick-use tapping was not caused by movement frequency but by stick use. Bimanual coordination patterns have been confirmed to result from influential constraints associated with both motor output and sensory input (Swinnen & Wenderoth, 2004). On the processing-output side, holding sticks leads to changes in the mechanical properties of the motor effectors, such as increased mass, moment of inertia, and stiffness. These mechanical changes would produce a large action and reaction force at impact, observed as the large peak force in the current study. The increased mass and length due to the stick use would also change eigenfrequency of the effectors (see, Kugler & Turvey, 1987; Treffner & Turvey, 1996). However, no significant difference was detected
in the movement frequency between the finger and stick-use tapping in the current study. This might be because the tapping movements were different from simple limb swinging movements.

On the processing-input side, holding sticks leads to changes in sensory information, such as tactile, auditory, and kinesthetic feedback information. When people touch something with a tip of a handheld tool, they feel the contact at the tool’s tip, although it is actually sensed by somatosensory receptors on the hand holding the tool (Iriki, Tanaka, & Iwamura, 1996; Yamamoto & Kitazawa, 2001). Because the force profile for stick-use tapping was much sharper than that for finger tapping (see Figure 1), stick-use tapping may provide clearer tactile feedback information about the tap timing. Similarly, the larger impact force can produce a louder sound, providing clearer auditory feedback information. In addition, changes to the mechanical properties of the motor effectors caused by holding the stick (e.g., increased mass, moment of inertia, and stiffness) leads to enhanced kinesthetic information. We suggest that these transformations of perceptual information due to stick use led to more stable bimanual coordination in the current study.

Studies on the evolution of music suggest that instrumental music is at least 40,000 years old and probably even older, and that music had the role of prelinguistic communication, or protolanguage (Fitch, 2006). In line with the idea that music is a means of communication, the large impact force and the stable bimanual performance produced by the stick observed in the current study may be helpful in sending rich communicational signals. Thus, we suggest that stick use enhanced the evolutionary development of musical communication in humans.

**Effect of Drumming Experience/Training**

Several studies indicate that bimanual coordination performance is influenced by individual experiences regarding manual training (Summers, 2002; Summers, Ford, & Todd, 1993; Zanone & Kelso, 1992). Thus, our secondary purpose is to investigate the relationship between years of drumming experience/training and bimanual coordination performance as well as the relationship between years of drumming experience/training and degree of improvement in the bimanual performance with stick use. In the current study, significant correlations were observed between years of drumming experience/training and the bimanual performance quotient for both finger and stick-use tapping: the greater the drumming experience, the more rapid and stable the bimanual performance. Consistent with previous bimanual coordination studies on keyboard and string players (Verheul & Geuze, 2004; Yamanishi, Kawato, & Suzuki, 1980), we suggest that drummers had improved their bimanual coordination performance in the process of musical practice. However, no significant correlation was seen between years of drumming experience/training and the percentage of improvement in the bimanual performance quotient with stick use. This indicates that the degree of improvement in bimanual coordination using a stick during a performance does not depend on the number of years of drumming experience. Both beginners and professionals benefit from stick use.

A limitation of the current study is that all the participants in this study were drummers—inexperienced nonmusicians were not included. In future studies, it is
needed to confirm whether the present findings in the experienced drummers are consistent in inexperienced nonmusicians. It will provide further insight into the effect of tool use on human motor behavior.

**Conclusion**

We suggest that stick use enhances drummers’ bimanual coordination during rapid alternate tapping. We also posit that the degree of improvement in bimanual coordination performance with stick use does not depend on the number of years of drumming experience/training. Our evidence indicates that the effects of stick use allow drummers to accomplish highly coordinated performances.

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**References**


