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Crossing the arms confuses the clocks: Sensory feedback and the bimanual advantage

Breanna E. Studenka · Kinga L. Eliaz · David I. Shore · Ramesh Balasubramaniam

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Abstract The bimanual advantage refers to the finding that tapping with two fingers on opposite hands exhibits reduced timing variability, as compared with tapping with only one finger. Two leading theories propose that the bimanual advantage results from the addition of either sensory (i.e., enhanced feedback) or cognitive (i.e., multiple timekeeper) processes involved in timing. Given that crossing the arms impairs perception of tactile stimuli and modulates cortical activation following tactile stimulation, we investigated the role of crossing the arms in the bimanual advantage. Participants tapped unimanually or bimanually with their arms crossed or uncrossed on a tabletop or in the air. With arms crossed, we expected increased interval timing variance. Similarly, for air tapping, we expected reduced bimanual advantage, due to reduced sensory feedback. A significant bimanual advantage was observed for the uncrossed, but not the crossed posture in tabletop tapping. Furthermore, removing tactile feedback from taps eliminated the bimanual advantage for both postures. Together, these findings suggest that crossing the arms likely impairs integration of internal

(i.e., effector-specific) and external (i.e., environment-specific) information and that this multisensory integration is crucial to reducing timing variability during repetitive coordinated bimanual tasks.

Keywords Bimanual tapping · Interval timing · Synchronization · Timing variability · Multisensory perception

Introduction

Prominent models of sensorimotor interval timing postulate that internal clocks meter out time intervals that specify the onsets of movement (e.g., tapping). Participants maintain a given pace by making small corrections to clock- and motor-induced errors (Repp & Su 2013; Wing & Kristofferson, 1973a). The significant role of feedback in continuous interval timing is supported by findings that increasing tactile, auditory, or visual feedback specific to timing decreases temporal variability (Aschersleben & Prinz, 1995; Drewing, Stenneken, Cole, Prinz, & Aschersleben, 2004). Furthermore, timing with two effectors exhibits smaller temporal variability, as compared with only one (Drewing, Hennings, & Aschersleben, 2002; Hellmuth & Ivry, 1996). Several researchers have suggested that two hands time better than one due to the addition of inputs or outputs to the timing system. While it is clear that timing is better with two hands than with one, we challenge the notion that improvements in timing result from the basic addition of more input or more output. Specifically, we had participants perform a continuous interval-timing task while using a posture known to impair discrete temporal perception (crossed hands; Shore, Spry, & Spence, 2002; Yamamoto & Kitazawa, 2001). We explore the notion that the bimanual advantage results from the unique pairing of input and output related to the same motor command and argue for the

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incorporation of cognitive, motor planning, and feedback mechanisms into models of continuous sensory–motor timing.

Precision in continuous timing

Temporal precision refers to a person's ability to perceive and reproduce a given interval duration. Consistency of timing is measured by computing the variability of the intervals in a series of taps. Variability is often further decomposed into component sources of variance, one due to an internal timekeeper and one due to motor requirements.

According to the classic timing model (Wing & Kristofferson, 1973a), two processes contribute to overall timing variability. An internal clock process measures out regular intervals, and a motor implementation process translates these signals to begin each tapping movement. Variability in a time series of intertap intervals (V) is thought to reflect both clock (C) and motor implementation (M) variability ($V = C + 2M$). Because clock and motor variance are assumed to be independent, the lag one covariance of each time series approximates the motor variance (see Wing & Kristofferson, 1973a). The clock, or central, component of variability is calculated as twice the motor variance subtracted from the total variance. Behavioral (Keele & Ivry, 1987; Keele, Pokorny, Corcos, & Ivry, 1985; Wing & Kristofferson, 1973a, 1973b) and neurological (Ivry & Keele, 1989; Ivry, Keele, & Diener, 1988) studies of tapping support the separable and independent nature of these two sources of variance; each is uniquely influenced by experimental manipulations of temporal and motor aspects of timing.

The bimanual advantage

Overall variance and, in particular, the clock variance tend to be reduced when participants tap synchronously with two effectors, as compared with when only one effector is used (Drewing & Aschersleben, 2003; Drewing et al., 2002; Drewing et al., 2004; Hellmuth & Ivry, 1996). Several researchers have postulated theories to explain this reduced variability. The multiple-timekeeper model of bimanual advantage proposes a coupling of internal timekeeping mechanisms, which produces a reduced clock variance (Hellmuth & Ivry, 1996; Ivry & Richardson, 2002). The main assumptions of this model follow from the classic timing model proposed by Wing and Kristofferson (1973a) for a single effector. Alternatively, the reduced variance could be accounted for by the addition of sensory feedback when two effectors make contact with the tapping surface, as opposed to one (Drewing & Aschersleben, 2003).

The multiple timer model

According to the formalized “multiple timer model” (Ivry & Richardson, 2002), a separate clock signal is generated for each effector (the right and left index fingers), and these clock signals are combined prior to initiation of movement. This coupling, or gating, process also serves to initiate the next clock signal in a series of repetitive timed movements. Hellmuth and Ivry (1996) cited reduced variability of timed intervals when both hands were used, as compared with when only one hand was used, and attributed this to the central (clock) as opposed to the motor implementation component of variability. Behavioral data support the hypothesis that coupling timing variability for two hands approximates an average of the two independent timing signals (Hellmuth & Ivry, 1996). The resultant variability of two averaged clock signals is smaller than that of one signal alone, resulting in reduced variability at the motor output level of timed movement.

The enhanced sensory feedback hypothesis

An alternate account of the bimanual advantage posits that timing improves as a result of additional sensory feedback received from two effectors, as opposed to one. The feedback hypothesis is supported by several studies showing that changing feedback to a finger on one hand influences timing variability in the opposite hand (Drewing & Aschersleben, 2003; Drewing et al., 2002). During bimanual timing, a reduction in feedback to the participant's left finger increased overall clock variance, as compared with when both hands touched the table surface (Drewing et al., 2002). In another study, when auditory feedback was present for only right-hand taps, the bimanual advantage was not as strong as when both hands received auditory feedback from taps (Drewing & Aschersleben, 2003). Furthermore, a significant multi-effector advantage was seen when the index and middle fingers from one hand, versus only the index or middle finger, were used to time intervals, suggesting that the bimanual advantage is a phenomenon of multiple, but not necessarily contralateral, sources of feedback (Drewing et al., 2002). Increased sensory feedback may act in two ways to improve timing accuracy: improved detection of timing errors may lead to on-line correction, or increased feedback may improve prediction of the sensory consequences of future movement goals (see Drewing & Aschersleben, 2003).

Crossed-hand effect

Successful interaction with the environment hinges on the ability to accurately target actions in time and space. As the limbs move from location to location, the brain must constantly update their current position to compute the optimal trajectory

to a new location. This updating process involves both visual and proprioceptive feedback (Bolognini & Maravita, 2007; Viswanathan, Fritz, & Grafton, 2012) and is challenged when the hands are placed across the body midline (Nicoletti, Umiltà, & Ladavas, 1984; Riggio, Gawryszewski, & Umiltà, 1986; Shore et al., 2002; Yamamoto & Kitazawa, 2001). Because perception of the limbs' spatial locations is influenced by visual and proprioceptive feedback, it stands to reason that temporal aspects of movement might also be influenced by conflicts between representations of external (e.g., visual) and internal (e.g., proprioceptive) space. Exactly how the timing of continuous actions depends upon the spatial orientations and locations of the limbs has not been explored in the timing literature.

The ability to judge which of two stimuli occurred first (i.e., temporal order judgment) and the ability to discriminate where and how many stimuli occurred (i.e., sensory discrimination) are impaired when the arms are crossed (Cadieux, Barnett-Cowan, & Shore, 2010; Cadieux & Shore, 2013; Craig, 2003; Craig & Belser, 2006; Nicoletti et al., 1984; Shore et al., 2002; Wada, Yamamoto, & Kitazawa, 2004; Yamamoto & Kitazawa, 2001; Yamamoto, Moizumi, & Kitazawa, 2005). Participants are slower in responding to a visual stimulus presented next to one or the other hand when their arms are crossed (i.e., for the crossed posture, a visual stimulus on the right side of the body near to the left hand signaled a left-hand response; Nicoletti et al., 1984). Judging the temporal order of two tactile stimuli (e.g., mechanical stimulation of the skin near the tip of the ring finger) is also impaired when the hands are crossed (Yamamoto & Kitazawa, 2001). With uncrossed arms, participants could accurately detect which hand was stimulated first (84 % of the time) when stimuli were about 74 ms apart. When their arms were crossed, participants confused the temporal order of stimuli for intervals shorter than about 300 ms. Shore et al. (2002) also found increased temporal order judgment differences between uncrossed (34 ms) and crossed (124 ms) arms.

In most tasks demonstrating a reduction in temporal order judgment for the crossed-arms posture, the required response involved both temporal and spatial discrimination (i.e., participants indicated for which hand a stimulus had been perceived first). However, the crossed-arms posture also elicited nonspatial discrimination deficits. When participants had to judge whether a vibro-tactile stimulus presented to only one hand was one or two pulses while ignoring visual distractors, responses were faster (17 ms), and participants made significantly fewer errors (3.6 %) when the arms were uncrossed than when they were crossed (Holmes, Sanabria, Calvert, & Spence, 2006). These findings indicated that crossing the arms impaired the ability to interpret the time between sensory inputs.

Deficits in temporal discrimination and speeded responses when the arms are crossed have been attributed to confusion between proprioceptive and visual representations of the task goal (Riggio et al., 1986; Shore et al., 2002). These deficits in

temporal order judgment, as well as in nonspatial temporal discrimination, when the arms are crossed seem to involve a partial remapping of tactile stimuli to the ipsilateral versus the contralateral hemisphere, which might have implications for tasks that involve feedback control. Using fMRI, Lloyd, Shore, Spence, and Calvert (2003) found that tactile stimulation of the right hand when it was crossed over the body midline led to greater activation in the right hemisphere, as opposed to the left hemisphere, when the eyes were closed. Greater activation in the ipsilateral versus the contralateral hemisphere indicated that the tactile stimuli presented to the crossed hand were represented by the hemisphere responsible for processing the external, rather than the internal, representation of the hand position. Furthermore, when the eyes were open, activation shifted to the contralateral hemisphere, similar to when the arm was not crossed over the body midline, signifying the role of vision in mapping stimuli to the same hemisphere as the limb receiving it. These findings support the notion that, when the arms are crossed, speeded responses and temporal order judgments are impaired due to confusion over where the hands are represented in external versus internal space. While previous work on the impact of crossing the arms has examined discrete temporal discrimination, we sought to extend these findings to a qualitatively different measure of temporal precision—continuous interval timing. As such, we examined the impact of crossing the arms on timing behavior, using a classic continuation finger-tapping task (Wing & Kristofferson, 1973a).

On the basis of the theories of continuous interval timing and sensory deficits in discrete timing when the arms are crossed, we set out to investigate the influence of crossing the arms on continuous interval timing. To our knowledge, this is the first study documenting the influence of crossed arms on continuous sensory-motor timing. In order to examine the influence of crossed arms on continuous interval timing, we had participants perform continuation tapping with and without crossed arms. Additionally, due to the significant role of sensory feedback in deficits related to crossing the arms and in aiding the bimanual advantage in continuous interval timing, we included a condition where tactile feedback was reduced (i.e., air tapping). We explore the implications of several possible outcomes below in relation to the crossed-hands effect and the two theories of bimanual advantage in timing.

The following experiment had two aims. First, does crossing the arms—a manipulation known to impair discrete temporal judgment—impair temporal precision in continuous timing (i.e., reduced bimanual advantage)? If so, this might also tell us something about the underlying mechanisms responsible for the bimanual advantage. We hypothesized that if crossing the arms reduces the bimanual advantage, we would see little difference between unimanual and bimanual clock variance when the arms were crossed. Our

second aim was to test the general tenet of models of bimanual advantage, that two is better than one. We hypothesized that if the bimanual advantage results strictly from two feedback signals or two timekeepers, we should see that crossing the arms does not reduce the bimanual advantage in timing. Any finding of reduction in bimanual advantage when the arms were crossed would indicate some confusion either between the clock signals metering out intervals or from the feedback signals resulting from movement. This would indicate that the bimanual advantage in continuous interval timing involves the pairing of feedback or clock signals to specific effectors and does not result from the general addition of output or input. Furthermore, because the main influence of the crossed-hands posture is a reduction in temporal discrimination, a reduction in tactile feedback (i.e., air tapping) was aimed at helping delineate the role of tactile feedback in any sensory–motor deficits caused by the crossed-hands posture.

Method

Participants

Previous studies indicating a significant difference between unimanual and bimanual timing have included from 12 to 30 participants (Drewing & Aschersleben, 2003; Helmuth & Ivry, 1996). In this study, 25 right-handed university students (9 male, 16 female) with a mean age of 23.9 years participated. One participant was excluded from analysis due to an inability to produce cycles of movement at the appropriate pace (mean greater than 600 ms; Helmuth & Ivry, 1996; Ivry, Richardson, & Helmuth, 2002). Informed consent procedures were approved by the McMaster human research ethics board.

Apparatus and tasks

The crossed-hands posture deficits in discrete temporal judgments might be due to confusion in pairing sensory information with the appropriate effector. In other words, even though a stimulus is presented to the right hand, because it occurs in left external space, it may be represented in the right hemisphere of the brain (Lloyd et al., 2003). Lloyd et al., however, saw representation of tactile stimuli in ipsilateral space only when participants did not have vision of their stimulated limb. To diminish the impact of a participant forming an a priori representation of the external space during the first timing condition, which has been shown to affect the crossed-hands temporal order judgment deficit (Cadieux & Shore, 2013), a blindfold was placed over the participant's eyes before he/she entered the room. Participants were seated at a 75-cm-high table. Two strips of masking tape were placed approximately shoulder width

apart and approximately a forearm's length from the front edge of the table to serve as a guide in keeping the arms and fingers in the same spatial location throughout the experiment. Participants performed tapping in three conditions: table tapping with the blindfold applied outside the room, table tapping with the blindfold applied inside the room, and air tapping with the blindfold applied inside the room. For the table-tapping condition, the participant placed his or her hands on the table with his/her fingers hovering over the two strips of masking tape. For the air-tapping condition, the participant placed his or her hands on a wooden platform, with his/her fingers hovering over two holes (squares cut out of the wood; see Fig. 1). Participants were instructed to tap to the tabletop or to the "level of the tabletop" and, during air tapping, not to contact the sides of the cut-out squares. Two different effector types were used for each condition: right (dominant) hand unimanual tapping and bimanual tapping. Both effector types were performed with the arms crossed and with the arms uncrossed. For the crossed-arms posture, the right arm was always crossed over the left arm. Specifically, each participant placed the left arm through the best-fitting padded PVC pipe (9, 10, or 11.5 cm in diameter) and his/her right arm rested on top of this PVC pipe. Solid blocks were placed under the participant's elbows and hands to ensure maximal comfort and that all taps occurred in the sagittal plane. For all trials, the participant tapped in synchrony with a metronome for 30 beats (400 ms apart), after which he/she produced approximately 30 additional taps. Noise-isolating headphones (Sennheiser HAD 200) playing white noise were worn for all trials.

Procedure

The experimenter met the participant outside the laboratory, where the experiment was explained and consent was obtained.

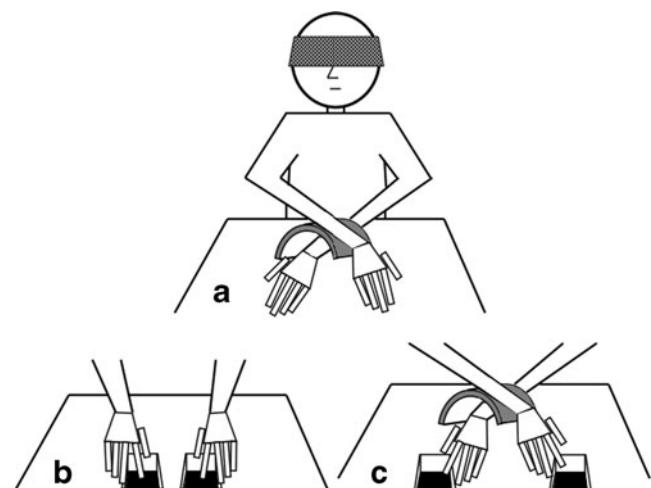


Fig. 1 Experimental setup for **a** crossed table tapping, **b** uncrossed air tapping, and **c** crossed air tapping. The right arm was crossed over the pipe for both table and air tapping

The participant was blindfolded prior to entering the laboratory and were walked around for approximately 1 min before being seated at the table. Each trial consisted of 30 intervals (400 ms) of synchronization (80-ms duration tones, 860 Hz), followed by approximately 30 additional taps. Following the completion of a trial, the participant was provided feedback (the goal interval duration and the produced interval duration) and 10 s of rest. If the participant's mean interval duration was above 425 ms or below 375 ms, the experimenter reminded the participant to stay on pace. The participant performed three conditions consisting of four blocks of six trials each. After completion of each condition, the participant took his/her blindfold off and rested until he/she felt ready to continue. The session lasted approximately 75 min.

Design

Tasks were performed in a 3 (condition: table tapping blindfold outside, table tapping blindfold inside, and air tapping blindfold inside) \times 2 (posture: crossed vs. uncrossed) \times 2 (effector type: right unimanual vs. bimanual) design. The table-tapping blindfold outside condition was always performed first, and the order of the other two conditions was counterbalanced across participants. Task order within a condition (right-hand unimanual uncrossed, right-hand unimanual crossed, bimanual uncrossed, and bimanual crossed) was blocked in a Latin square design and was kept constant within the participant across conditions.

Data collection and reduction

Kinematic data were collected using a Vicon Nexus motion capture system (VICON Motion Systems, Oxford, U.K.). Vicon markers (14 mm in diameter) were placed on the participant's right and left index finger, knuckle, wrist, and elbow. Data were sampled at 250 Hz. Data from the finger marker of the right hand was used to score intertap duration and variability in interval production. The end of each cycle was scored on the basis of a graphical routine in MATLAB (Mathworks, Natick, MA). The time series of inferior–superior movement for tapping was plotted, and cycle end points were marked at points when the movement toward the table reached 3 % of maximal velocity. An experimenter plotted the time series of tapping data in the z dimension (inferior/superior) with cycle end points overlaid, and verified that each end point was accurate.

All dependent variables were calculated only for the continuation portion of the trial. Each cycle duration was calculated as the time from the end of one tap to the end of the next tap. This series of cycle durations was detrended, removing any within-trial drift. Because cycle duration variability increases as cycle duration increases, we calculated variability of the overall time series as the standard deviation of the time series of cycle durations divided by the mean (coefficient of

variation). Of 1,728 total trials, 24 had missing data (1 %) and could not be used in the analysis. Of the 1,704 remaining trials, 259 (15 %) were not used for the Wing and Kristofferson (1973a) decomposition of clock variance, due to the cycle duration time series having a positive lag one covariance. Averages for cycle duration and coefficient of variation were calculated per trial and then averaged over the 6 trials per task per participant. The values for clock variance were calculated on the basis of the Wing and Kristofferson (1973a) derivations for trials that had negative or zero lag one covariance (1,445 trials). According to the model proposed by Wing and Kristofferson (1973a), variability in producing timed intervals comes from two sources, the internal timekeeper and the motor implementation ($I_n = C_n + M_n - M_{n-1}$, where I_n is equal to the interval duration produced, C_n is equal to the interval duration produced by the internal timekeeper, M_n is equal to the motor implementation delay following the clock signal, and M_{n-1} is equal to the duration of the previous delay). Furthermore, the variance of the interval produced is equal to the clock variance plus 2 times the motor variance. Because these two processes are modeled as independent, and because successive clock and motor delay intervals are also modeled as independent, the covariance between the interval duration time series and the same time series shifted by one (lag one autocovariance) is set equal to the motor implementation variance multiplied by -1 . An estimate of the clock variance can then be derived by subtracting the estimate of the motor implementation variance from the total variance. The main assumption of the Wing and Kristofferson model is that successive intervals are independent and, therefore, the time series will exhibit negative lag one autocovariance. Therefore, only trials that exhibit negative lag one covariance can be used to calculate the estimate of the motor variance and, subsequently, the clock variance.

Statistical analysis

ANOVAs were run on cycle duration, coefficient of variation, and motor and clock variance, using the factors of condition (blindfold applied outside tapping, blindfold applied inside tapping, and air tapping), posture (uncrossed vs. crossed), and effector type (unimanual vs. bimanual). For descriptive statistics (cycle duration and coefficient of variation), the full data set with all trials was used for the statistical analysis. For the clock and motor variance, the data set with trials removed was used. Due to our main aim of assessing the significance of the bimanual advantage within each condition and posture, we also performed contrasts within the main ANOVA on unimanual versus bimanual clock variance within the table tapping uncrossed (both blindfold conditions were modeled), table tapping crossed, air tapping uncrossed, and air tapping crossed tasks. In addition, two post hoc contrasts were performed on the main effect of condition for clock variance in order to verify the

presence or absence of an effect of viewing the external space prior to moving in it and to verify that air tapping had greater clock variance than did table tapping. The p -value signifying significance for all contrasts was reduced to .008 according to a Bonferoni correction for multiple comparisons.

Results

Descriptive statistics

All descriptive means are presented in Table 1. Significant effects are reported below. Participants produced accurate cycle durations (see Table 1), with no effect of condition, $F(2, 46) = 0.39, p = .68$, or posture, $F(1, 23) = 0.92, p = .35$. Cycle durations were slightly longer for unimanual (403 ms, $SD = 10.1$ ms) than for bimanual (400 ms, $SD = 8.6$ ms) tapping, $F(1, 23) = 6.70, p = .02$. Coefficient of variation was greater for air (6.31, $SD = 1.85$) than for table (5.29, $SD = 1.40$) tapping, as supported by a significant main effect of condition, $F(2, 46) = 24.21, p < .0001$, and a significant post hoc contrast between air and table conditions, $F(1, 46) = 181.00, p < .0001$. Motor variance was higher for air (179.8 ms^2 , $SD = 137$) than for table (148.9 ms^2 , $SD = 119$) tapping, supported by a significant main effect of condition, $F(2, 46) = 3.57, p = .04$, and a significant contrast between table and air conditions, $F(1, 46) = 10.73, p = .002$. Motor variance was also higher for crossed (164.1 ms^2 , $SD = 132$) than for uncrossed (154.4 ms^2 , $SD = 120$) postures, $F(1, 23) = 11.76, p = .002$.

Clock variance

Crossing the hands induced a significant increase in overall clock variance over the uncrossed posture (300 ms^2 , $SD = 248$ ms^2 , vs. 267 ms^2 , $SD = 181$ ms^2), $F(1, 23) = 4.32, p = .05, \eta_p^2 = .16$ (see Fig. 2). Clock variance was greater for unimanual (320 ms^2 , $SD = 220$ ms^2) than for bimanual (249.7 ms^2 , $SD = 209$ ms^2) tapping, supporting an overall bimanual advantage, $F(1, 23) = 9.10, p = .006, \eta_p^2 = .28$. A significant effect of condition, $F(2, 46) = 13.81, p < .0001, \eta_p^2 = .38$, reflected greater clock variance for the air-tapping (396.6 ms^2 , $SD = 305$ ms^2) than for the table-tapping (229.1 ms^2 , $SD = 124$ ms^2) condition, $F(1, 46) = 99.97, p < .0001$. There was no difference in clock variance between the blindfold outside and blindfold inside table-tapping conditions, $F(1, 46) = 0.09, p = .76$. There were also no significant interactions between effector type and posture, $F(1, 23) = 1.51, p = .23, \eta_p^2 = .06$, effector type and condition, $F(2, 46) = 0.13, p = .88, \eta_p^2 = .006$, and effector type, posture, and condition, $F(1, 46) = 0.06, p = .94, \eta_p^2 = .003$. There was a small interaction between condition and posture, $F(1, 46) = 3.29, p = .05, \eta_p^2 = .13$.

Due to a priori hypotheses regarding the difference between unimanual and bimanual tapping, we examined the bimanual advantage for the different postures within different

Table 1 Descriptive statistics

	Table 1				Table 2				Air							
	Uncrossed		Crossed		Uncrossed		Crossed		Uncrossed		Crossed		Uncrossed		Crossed	
	Unimanual	Bimanual	Unimanual	Bimanual	Unimanual	Bimanual	Unimanual	Bimanual	Unimanual	Bimanual	Unimanual	Bimanual	Unimanual	Bimanual	Unimanual	Bimanual
Cycle Duration (ms)	403 (12)	401 (7)	403 (11)	402 (9)	402 (9)	398 (7)	404 (9)	399 (7)	402 (11)	399 (11)	401 (11)	400 (10)	402 (11)	399 (11)	401 (11)	400 (10)
CV (%)	5.3 (1.4)	5.5 (1.5)	5.4 (1.6)	5.5 (1.5)	5.0 (1.6)	5.4 (1.3)	5.1 (1.0)	5.1 (1.3)	6.5 (1.9)	6.1 (1.7)	6.5 (2.0)	6.2 (1.9)	6.5 (1.9)	6.1 (1.7)	6.5 (2.0)	6.2 (1.9)
Clock Variance (ms^2)	291 (128)	190 (92)	252 (128)	206 (128)	248 (112)	178 (98)	256 (96)	212 (165)	403 (293)	304 (184)	472 (339)	408 (367)	403 (293)	304 (184)	472 (339)	408 (367)
Motor Variance (ms^2)	124 (101)	202 (153)	126 (74)	180 (124)	115 (125)	167 (110)	125 (116)	151 (123)	193 (148)	183 (134)	158 (146)	186 (124)	193 (148)	183 (134)	158 (146)	186 (124)

*CV stands for coefficient of variation

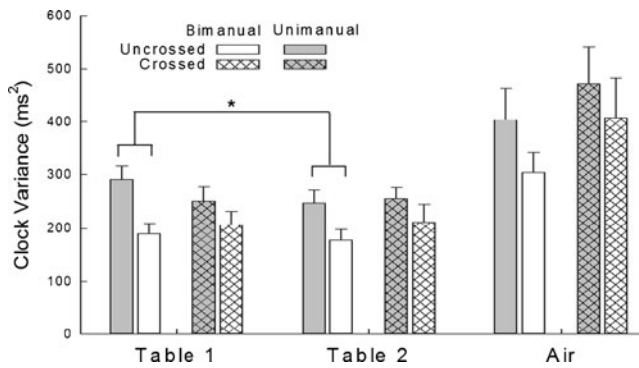


Fig. 2 Clock variance for uncrossed and crossed postures, for the unimanual and the bimanual conditions, and for table and air tapping

conditions. As was expected, a bimanual advantage was observed for uncrossed table tapping, $F(1, 46) = 8.37, p = .006$, but no significant ($\alpha = .01$) bimanual advantage was observed for crossed table tapping, $F(1, 46) = 2.29, p = .14$, uncrossed air tapping, $F(1, 46) = 5.68, p = .02$, or crossed air tapping, $F(1, 46) = 2.35, p = .13$.

Discussion

The first aim of this study was to document the role of crossing the arms on the accuracy of continuous interval timing. A significant increase in clock-related variability in timing when the arms were crossed indicates that crossing the arms does, to some extent, impair temporal precision in continuous interval timing. The second aim of this study was to challenge the main tenet of the two main theories of bimanual advantage: multiple inputs or multiple outputs lead to decreased timing variability. Specifically, for table tapping, we document a significant bimanual advantage for uncrossed, but not crossed, postures, indicating that the bimanual advantage does not result strictly from multiple feedback signals or multiple clock signals. Likely, the crossed-arms posture elicited an ipsilateral representation of feedback paired with a motor command from the contralateral hemisphere (cf. Lloyd et al., 2003), making it more difficult for participants to pair sensory feedback with the appropriate effector. Increased reaction time observed when the arms are crossed has been attributed to conflict between two internal representations of the sensory signal: a spatial-visual representation and an anatomical representation (Riggio et al., 1986; Viswanathan et al., 2012; see also Shore et al., 2002). The finding that the bimanual advantage was reduced for the crossed-hands posture indicates that mechanisms responsible for the bimanual advantage likely involve multisensory integration of limb-specific visuospatial information and feedback. These findings indicate that, in addition to detection and control of temporal aspects of movement and feedback, detection of spatial aspects of movement and

feedback is important for continuous interval timing. Likely crucial to producing accurately timed movements is the ability to pair feedback with the appropriate effector.

Furthermore, we tested timing with reduced tactile feedback to explore the role of the tactile sensory motor deficit in the bimanual advantage. When feedback from taps was reduced, no significant bimanual advantage was seen for the crossed or uncrossed postures; however, the bimanual advantage approached significance for uncrossed air tapping ($p = .02$). This finding indicates a more variable bimanual advantage without tactile feedback; when the arms are crossed, feedback specifically related to tactile perception is impaired.

Our findings do not refute the notion of multiple timers; however, they do contest the notion that the bimanual advantage is driven solely by a reduction in clock variance prior to motor implementation. It is likely that crossing the arms confuses systems engaged in motor planning, in addition to perception of feedback. In other words, planning movements with end point goals in the opposite cerebral hemisphere could increase the variance and/or decrease the coupling of internal timers. Therefore, mechanisms of the bimanual advantage might involve accurate representation of the moving effectors in space, accurate representation of timing goals, accurate pairing of sensory feedback to the appropriate effector, and/or accurate and timely detection of temporal errors.

The present results reveal an important addition to understanding the mechanisms associated with the bimanual advantage in continuous interval timing. Crossing the arms generally increased timing variance. Furthermore, crossing the arms reduced the bimanual advantage for tapping with tactile feedback (table), indicating that crossing the arms likely induces some confusion between the somatosensory feedback from the two hands and, possibly, the separate timekeepers for the two hands. The reduced (nonsignificant) bimanual advantage when the arms were crossed supports the role of multisensory integration in the control of timed movement. These results are consistent with a growing body of evidence that suggests the need for adding feedback control processes in models of continuous interval timing (Balasubramaniam, Wing, & Daffertshofer, 2004; Pressing, 1998; Torre & Balasubramaniam, 2009). Future research will need to determine whether the bimanual advantage results from singular or multiple processes involving feedback and cortical representation. It must also be pointed out that the Wing–Kristofferson model on which the original result of bimanual advantage is based (Helmuth & Ivry, 1996) is a two-component model that does not provide room for factors other than clock and motor delay. It is possible that there are other sources of variance, including those related to cognitive, motor planning, and sensory feedback processes, that might need to be integrated to formulate a more comprehensive model of motor timing variability.

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