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RESEARCH ARTICLE

Bimanual joint action: correlated timing or "bimanual" movements accomplished by two people

Melanie Y. Lam[1] · Jarrod Blinch[2,3] · Elizabeth M. Connors[2] · Jon B. Doan[2] · Claudia L. R. Gonzalez[2]

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Abstract

A crew of two rowing together in perfect synchrony is an example of a task that requires each performer to maintain meticulous timing when coordinating their movements with the other. At the individual level, temporal coordination of the limbs has been observed in bimanual pointing movements even when made to targets of different distance. Timing of the arms is not independent; rather there is a natural temporal coupling. The aim of this experiment was to investigate whether the temporal characteristics of pointing movements can be observed under joint conditions. Sixteen pairs of participants made short and long, unimanual and bimanual pointing movements. In the unimanual and bimanual solo conditions, participants made the movements alone. In the joint condition, each participant contributed one arm to the joint "bimanual" movements. Absolute temporal coupling at movement initiation and termination was measured by the differences in reaction time and total response time. Relative temporal coupling at movement initiation and termination was measured by correlating reaction time and total response time of the left and right limbs. Pointing movements had synchronous movement termination in the bimanual solo conditions and asynchronous termination in the unimanual solo and bimanual joint conditions. The initiation and termination of the arms were not correlated in the unimanual solo condition (initiation $r=0.01$, termination $r=0.03$). Small-to-medium correlations ($r=0.19$, $r=0.24$) were observed in the bimanual joint condition, and they were larger than the unimanual solo condition ($p=0.022$, $p=0.063$). As expected, there were large correlations in the bimanual solo conditions ($r=0.91$, $r=0.81$). Our findings suggest that absolute temporal coupling does not occur between individuals, but there is evidence for relative temporal coupling in the bimanual joint condition.

Keywords Joint action · Bimanual coordination · Temporal coupling

Introduction

Many complex actions benefit from being carried out by more than one person. Rowing solo is feasible, but rowing with another person generates more power to propel the boat forward on the water. However, their efficiency would depend largely on how well they are able to coordinate their movement patterns (see Baudouin and Hawkins 2004; Cuijpers et al. 2015; Williams 1967; Wing and Woodburn 1995). This interpersonal coordination can be characterized by the organization of movements and actions in such a way that they work together both smoothly and effectively. Laboratory tasks have been used to examine both spontaneous interpersonal coordination (e.g., Oullier et al. 2008; Schmidt and; O'Brien 1997; Richardson et al. 2005) and instructed interpersonal coordination (e.g., Newman-Norlund et al. 2008; van Ulzen et al. 2008; Vesper et al. 2009). For example, Oullier et al. (2008) observed spontaneous synchrony as paired participants flexed and extended their right index fingers despite not being given any explicit instruction to do so. This contrasts with the experiment carried out by Newman-Norlund et al. (2008), where the goal of a virtual bar-balancing task was conveyed to paired participants who worked together to achieve it.

What makes interpersonal coordination so fascinating is that two, or more, individuals can coordinate their actions

✉ Melanie Y. Lam
mlam@stfx.ca

1 Department of Human Kinetics, St. Francis Xavier University, PO Box 5000, Antigonish, NS B2G 2W5, Canada

2 Department of Kinesiology and Physical Education, University of Lethbridge, Lethbridge, AB, Canada

3 Department of Kinesiology and Sport Management, Texas Tech University, Lubbock, TX, USA

toward a collective goal despite each neural system working independently. Jung et al. (2011) examined performance in a novel joint action task, a task they described as falling somewhere between spontaneous and instructed interpersonal coordination similar to those that have used the social Simon paradigm (e.g., Atkinson et al. 2014; Atmaca et al. 2008; Fine and Amazeen 2011). The social Simon paradigm was introduced by Sebanz et al. (2003) to better understand how another person's task and actions can influence one's own action planning and execution. What they showed was that when participants performed a go/no-go Simon task alone, a Simon effect was absent. However, when participants performed that same go/no-go Simon task alongside another person doing the same, the so-called 'social' Simon effect was elicited. Jung et al. (2011) put forth that while "coordination between the two participants is not explicitly required...some coordination may be implicitly suggested by the demands of the task..." (p. 472). They chose a bimanual task, where the two arms required to complete it belonged to one participant (intrapersonal) or two different participants (interpersonal). The aim of Jung et al.'s (2011) study was to determine whether performance in a "bimanual" joint setting mirrors that observed when the task is completed in a bimanual solo setting; specifically, that the movements with the left and right arms would begin and end with similar timing. In their first experiment, participants were paired together and instructed to make pointing movements using only one hand to their respective target. These movements were cued at the same time; however, participants were told that the other's task had no bearing on their own performance. The movements were either symmetrical (both pressed the target keys above their respective home keys or the target keys below) or asymmetrical (one pressed the target key above the home key and the other pressed the target key below the home key). The relative temporal coupling of movement initiation and termination was investigated by correlating reaction time and total response time of each hand across a block of trials. These correlations were compared in the bimanual solo conditions, where one participant completed the task with both their arms, and the bimanual joint condition, where two participants completed the task together. Jung et al. found large correlations in the bimanual solo conditions and medium correlations in the bimanual joint condition. They argued that there was weak relative temporal coupling when two participants contributed one arm to the "bimanual" task because the correlations were smaller in the joint condition compared to the solo condition.

What distinguished Jung et al.'s (2011) work from other joint action studies was twofold. First, the bimanual task they used was non-rhythmic in nature. Many studies examining joint action have used rhythmic tasks such as pendulum swinging (Schmidt et al. 1998), rocking in chairs (Richardson et al. 2008), finger tapping (Konvalinka et al. 2010), or leg swinging (Schmidt et al. 1990) to investigate intrapersonal and interpersonal coordination. For example, Richardson et al. (2008) (Experiment 2) used a technique called cross-recurrence quantification analysis (CRQA) to probe behavioural organization over time. CRQA is a means of quantifying "the degree of shared activity between two time series by evaluating how they unfold similarly over time in a multi-dimensional (embedding) space" (Riley et al. 2011, p. 3). Participants completed a task that was made up of two stages. The first was described as intrapersonal coordination and participants were instructed to swing a pendulum from each wrist (left and right). During the second stage a curtain was removed to reveal another participant who was also swinging two pendulums. The goal now was to swing the one pendulum closest to their partner in either an in-phase or anti-phase pattern; this was described as interpersonal coordination. The tempo was initially established with an auditory metronome to control for the frequency of the movement. Their analysis revealed that interpersonal coordination was stable as supported by the high degree to which the two systems visited similar states and the high maxline ($L_{\max}$) which provides an index of attractor strength. The second reason the study by Jung et al. was unique was that the bimanual joint task selected by Jung et al. (2011) was not complementary where participants took turns to respond on each trial. Instead, participants performed their respective pointing movements concurrently.

The aim of the present study is to enhance our understanding of interpersonal coordination in a bimanual task. To accomplish this, we made a simple, yet critical change to the type of the asymmetric movement made in a bimanual task. Rather than pointing in opposite directions with the same amplitudes (see Jung et al. 2011), we propose asymmetric movements that involve pointing in the same direction with different amplitudes. Evidence suggests that this modification to the asymmetric movement offers a stronger means of measuring temporal coupling in bimanual movements (see Blinch et al. 2014; Kelso et al. 1979; Marteniuk et al. 1984). In a foundational study, Kelso et al. (1979) used these types of asymmetric movements (same direction, different amplitudes) to examine interlimb coordination. What they found was that when bimanual symmetric movements were executed, they were initiated and terminated at approximately the same time by both hands. Surprisingly, a similar pattern of behaviour was observed when making bimanual asymmetric movements. This finding was not anticipated because according to Fitts' law (1954), long-amplitude movements should take longer than short-amplitude movements. Kelso et al. (1979) argued that these bimanual asymmetric movements exhibit absolute temporal coupling and are "constrained to act as a single unit" to simplify movement preparation and execution (p. 237).

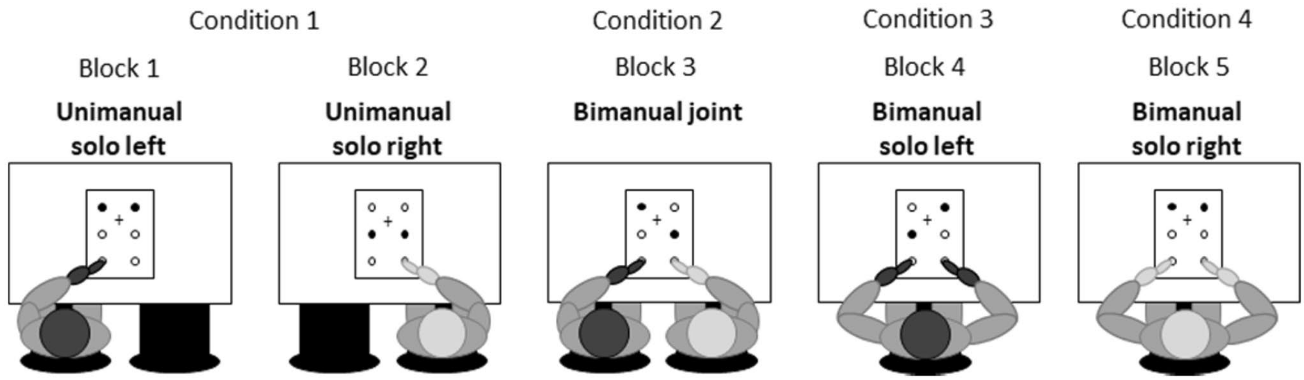


Fig. 1 Depiction of the pair of participants in the four conditions and five blocks of the experiment. Each block shows the go signal and the participant(s) pressing the start button(s) on the button box. The go signals, from left, are long–long, short–short, long–short, short–long, and long–long

The aim of this study was to address whether two people, each contributing a limb to complete a bimanual task, move as a single unit. The question being, would temporal coupling be observed between participants? The temporal coordination of bimanual movements made by one person (bimanual solo) was compared to "bimanual" movements made by two people (bimanual joint) in a discrete, non-rhythmic pointing task. An important distinction from Jung et al.'s (2011) study was that our movement allowed us to measure two types of temporal coupling: absolute and relative. First, we measured absolute temporal coupling of movement initiation and movement termination. This was done by comparing the differences in reaction time and total response time of each arm. Absolute temporal coupling at movement termination is what was measured by Kelso et al. (1979). Second, we measured relative temporal coupling of movement initiation and termination. This was done by correlating reaction times and total response times of each arm, which was the type of temporal coupling measured by Jung et al. (2011). If there is strong interpersonal coordination, then there will likely be absolute and relative temporal coupling in the bimanual joint condition. Alternatively, if the interpersonal coordination is weak, then there will probably be only relative temporal coupling.

Method

Participants

Thirty-two volunteer participants (mean age of 20.0 ± 3.0 years, 6 male) were tested from the university community in exchange for course credit (when applicable). All participants reported they were right-handed and had normal or corrected-to-normal vision. The research ethics board at the University of Lethbridge approved the study, and participants gave informed written consent before participation.

Apparatus

A button box was attached to the surface of a table. On the surface of the button box was a three-row by two-column array of round pushbuttons (12.8 mm diameter). The distance from the middle of one row of buttons to the next row was 10 cm and the distance between columns was 15 cm. The buttons in the closest row to the participants were the start buttons for the left and right hands. The next two rows were the target buttons of pointing movements with the left and right hands. Illuminating an LED inside the button cued the start and target buttons. There was a fixation cross in the middle of the four target buttons (Fig. 1).

Design

Paired participants completed five blocks of trials in total (Fig. 1). The two participants were assigned as either the left or right participant based on which chair they chose to sit in at the start of the experiment. Each participant was tested separately in the first two blocks and they made unimanual pointing movements with their assigned hand (unimanual solo condition). Both participants were tested together in the third block. Joint "bimanual" movements were performed in this block by the left participant pointing to the targets on the left and the right participant pointing to the targets on the right (bimanual joint condition). Each participant was tested separately again in the fourth and fifth blocks. The participants now made bimanual movements on their own by using both their hands (bimanual solo left condition, bimanual solo right condition). The participant who went first in the first and fourth blocks was counterbalanced. In the solo conditions (unimanual and bimanual) the participant that was not being tested waited outside the test room. The bimanual solo conditions were always completed after the bimanual joint condition, while the unimanual solo condition was always completed before the bimanual joint condition. The reason the conditions were not counterbalanced was to prevent the possibility of carryover effects from the bimanual solo conditions to the bimanual joint condition (see Ansorge and Wühr 2004, for a discussion on carryover effects in a Simon task).

Each block consisted of 16 practice trials followed by 48 test trials. The go signal involved illuminating a target button on the left and a target on the right. The target buttons that illuminated were one of the following four pairs: long–long (i.e., the long–distance target button on the left-the long-distance target button on the right), short–short, long–short, or short–long. Every block had 16 repetitions of each go signal. The order of these was randomized for each block and participant.

Procedure

The main difference in each condition was whether one or two participants completed the task and whether they used one or two hands. We will first describe the bimanual joint condition and then note the differences for the unimanual solo and bimanual solo conditions. Each trial began with the illumination of the left and right start buttons. This was the cue for the participants to press and hold the start buttons with their index fingers; the left participant pressed the left button with their left index finger and the right participant pressed the right button with their right index finger. When the home buttons were pressed, the lights inside them turned off and a 1–2 s variable foreperiod began. Participants were instructed to focus on the fixation cross during the foreperiod. The go signal involved illuminating a target button on the left and the right. The left participant was instructed to "react and press the left target button as quickly as possible", and the right participant was instructed to "react and press the right target button as quickly as possible". The target lights were turned off when both targets were pressed. The start buttons for the next trial were illuminated 1 s later, at which point the participants could release the target buttons and begin the next trial when ready. We purposely did not give any instructions on how the participants might couple their movements during the bimanual joint condition.

In the unimanual solo condition, one participant was tested at a time and they pressed the buttons on only their assigned side. They were told that the buttons on the other side would illuminate, but they did not need to respond to them. In the bimanual solo conditions, the participants pressed the buttons on both sides using their left and right hands.

Each trial was labelled as "good" or "bad", with bad trials being recycled to the end of the block and excluded from subsequent analyses. Types of bad trials were target errors (pressing an incorrect button), anticipation (reaction time < 100 ms), and inattention (reaction time > 750 or movement time > 500 ms). If it was a bad trial, then the experimenter explained the reason to the participants, but participants were not told these trials were recycled. In total, 8.0% of all the trials were recycled. Most of the recycled trials were caused by inattention with movement time > 500 ms (99.4% of the recycled trials).

Data acquisition and analysis

The state of each button (open or closed) was sampled with a digital input–output device (NI USB-6501, National Instruments). The sampling rate of the device was determined by the performance of the computer it was connected to. The mean and standard deviation of the sampling rate was 168 ± 24.1 Hz. The button states were used to calculate reaction time (from go signal to release of the start button) and total response time (from go signal to pressing the target button) of the left and right hands. Reaction time and movement time in the unimanual solo condition were analysed with 2 Participant (left, right) × 2 Target Button Distance (long, short) × 2 Other Button Distance (long, short) repeated measure ANOVAs. The reaction time of the right hand was subtracted from the left hand to calculate the difference in reaction time. A similar calculation was done to calculate the difference in total response time. These differences were used as a measure of absolute temporal coupling at movement initiation and movement termination. A negative difference value indicated the left hand preceded the right. Difference values in the unimanual solo condition were calculated by pairing the movements in the unimanual left block with the movements in the unimanual right block. For example, the first long–long movement in the left condition was paired with the first long–long movement in the right condition. The differences in reaction time and total response time were analysed with 4 Movement Type (long–long, short–short, long–short, short–long) × 4 Condition (unimanual solo, bimanual joint, bimanual solo left, bimanual solo right) repeated measures ANOVAs.

There might also be relative temporal coupling between the hands, which would not be captured by difference values. The timing of the left hand, for example, might have a linear relationship with the timing of the right hand. We investigated this possibility by correlating the duration values of the left hand with the right hand in the unimanual solo, bimanual joint, and bimanual solo conditions. Correlations on reaction time and total response time were analysed with 4 Movement (long–long, short–short, long–short, short–long) × 4 Condition (unimanual solo, bimanual joint,

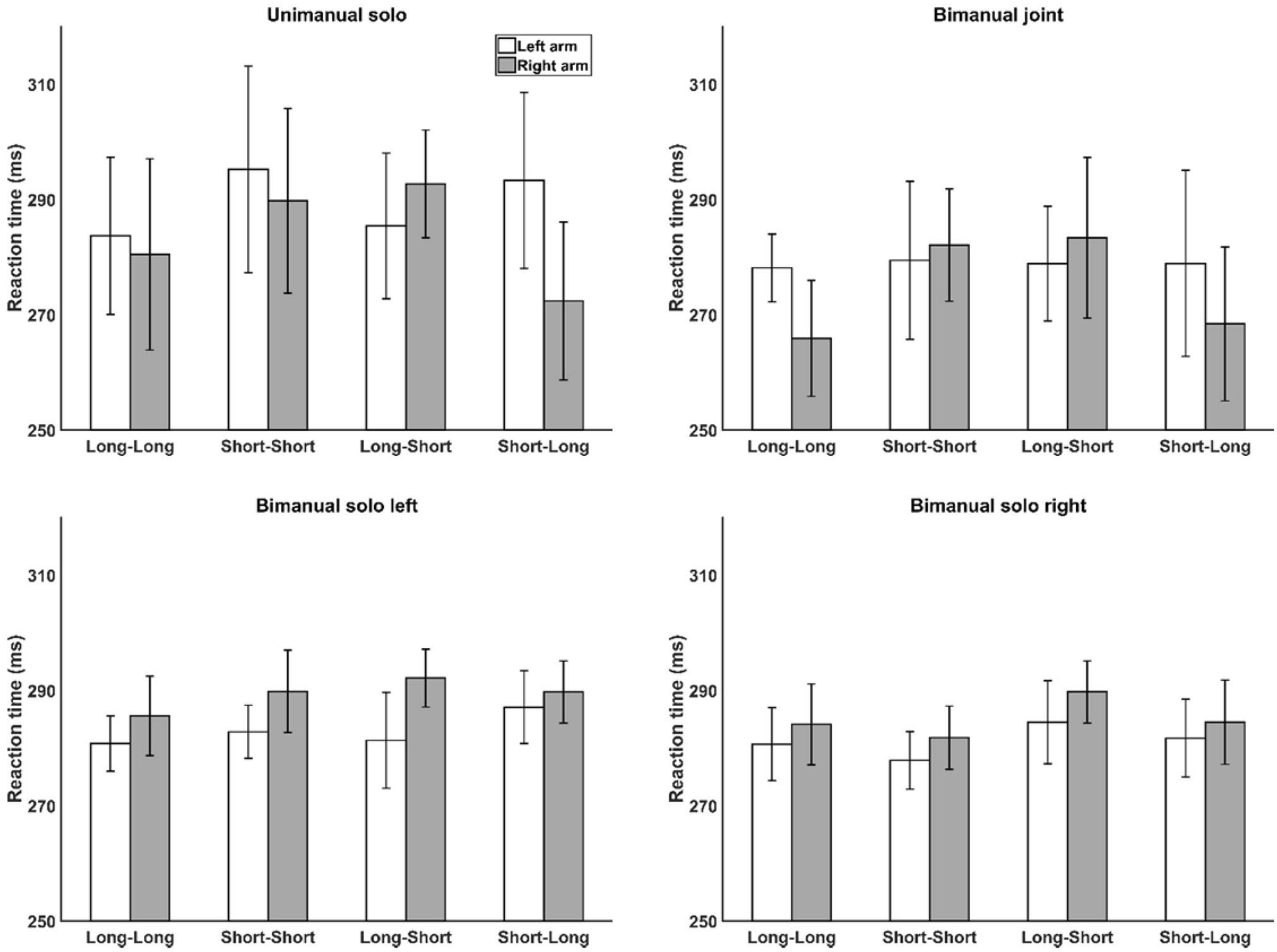


Fig. 2 Reaction time for the four types of movements in the four conditions: unimanual solo (top-left), bimanual joint (top-right), bimanual solo left (bottom-left), and bimanual solo right (bottom-right). Error bars are 95% within-participant confidence intervals (Cousineau 2005; Morey 2008)

bimanual left, bimanual right) repeated measures ANOVAs. The correlations were corrected with Fisher's z-transformation before statistical analysis; the r values were reported.

When local sphericity was violated (as indicated by Mauchly's test, $\alpha < 0.10$), the Huynh–Feldt correction was used when the ε was greater than or equal to 0.75 and the Greenhouse–Geisser correction was used otherwise (Huynh and Feldt 1976). The uncorrected degrees of freedom and the ε values were reported (Huynh–Feldt ε_{HF}, Greenhouse–Geisser ε_{GG}). Significant main effects were analysed with pairwise comparisons and significant interactions were analysed with simple main effects. The familywise error rate was controlled with the Šidák correction. Cohen's d was calculated for post hoc tests with the pooled standard deviation. Reported values, unless otherwise noted, were means and 95% within-participant confidence intervals (Cousineau 2005; Morey 2008). An example of these values is 100, [90, 110], where 100 is the mean and the 95% within-participant confidence interval is 90 to 110.

Results

Absolute temporal coupling at movement initiation was comparable across conditions for each movement type

Reaction time was visibly similar for the four movement types in the five blocks (Fig. 2); the grand mean was 283 ms, [272, 294] (95% between-participant confidence interval). The differences in reaction time between the left and right hands ranged from − 10.8 ms, [− 20.4, − 1.2] to 20.9 ms, [3.0, 38.7]. Recall that negative reaction time differences indicate the left hand preceded the right.

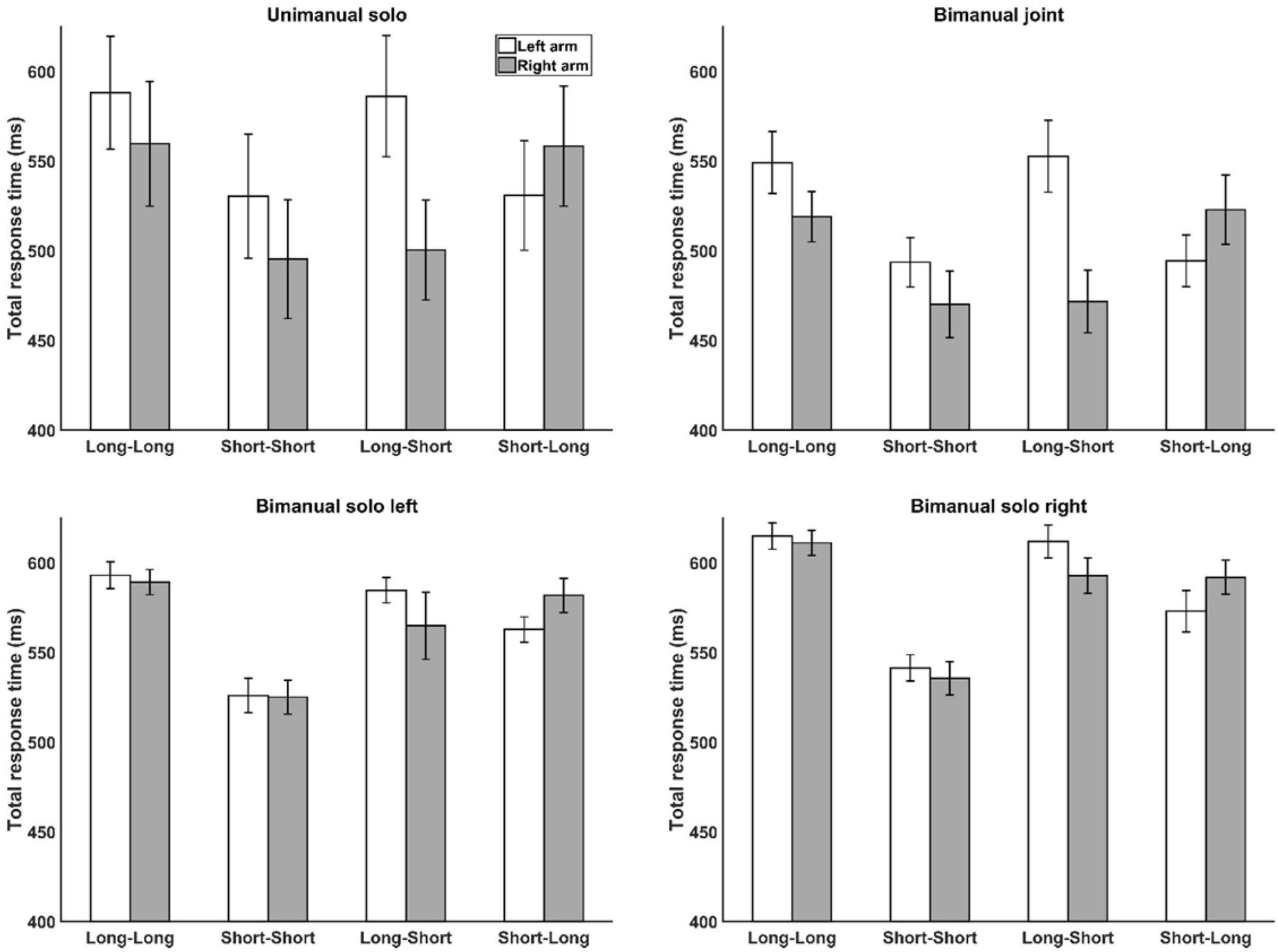


Fig. 3 Total response time for the four types of movements in the four conditions: unimanual solo (top-left), bimanual joint (top-right), bimanual solo left (bottom-left), and bimanual solo right (bottom-right). Bimanual asymmetric movements, particularly the long–short movement, exhibited temporal coupling in the bimanual solo conditions but not in the unimanual solo or bimanual joint conditions. Error bars are 95% within-participant confidence intervals (Cousineau 2005; Morey 2008)

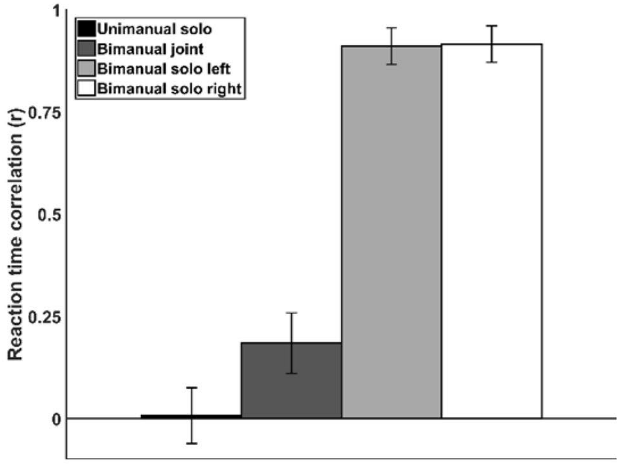
The difference in reaction time between the left and right hands had a significant main effect of Movement and a significant Condition × Movement interaction, $F(3, 45) = 11$, $p < 0.001$, $\eta_p^2 = 0.42$, $F(9, 135) = 2.9$, $\varepsilon_{GG} = 0.55$, $p = 0.019$, $\eta_p^2 = 0.16$. The interaction was analysed with simple main effects on Condition. The differences in reaction time were not significantly different in all conditions for all types of movements, $ps \geq 0.226$, $ds \leq 0.87$. These results suggest the absolute temporal coupling of movement initiation was comparable across conditions for each type of movement. There were, however, small differences in movement initiation for the four movement types.

Unimanual reaction time was determined by the movement amplitude

Reaction time was analysed in the unimanual solo condition (Fig. 2, top-left). A visible trend was that reaction time was shorter for long-amplitude movements (280 ms, [276, 285]) than short-amplitude movements (293 ms, [288, 298]). This was supported by a significant main effect of Target Button Distance, $F(1, 15) = 15$, $p = 0.002$, $\eta_p^2 = 0.50$. Reaction time was unaffected by Participant and Other Target Button. In other words, reaction time in the unimanual solo condition was determined by the movement amplitude.

No absolute temporal coupling of movement termination in the bimanual joint condition

The bimanual solo conditions showed the typical pattern of absolute temporal coupling at movement termination (Fig. 3, bottom-left and bottom-right). Long–long movements had a long total response time and short–short movements had short total response time. Long asymmetric movements (long–short, short–long) had total response time values that were similar to long symmetric movements. Whereas, short



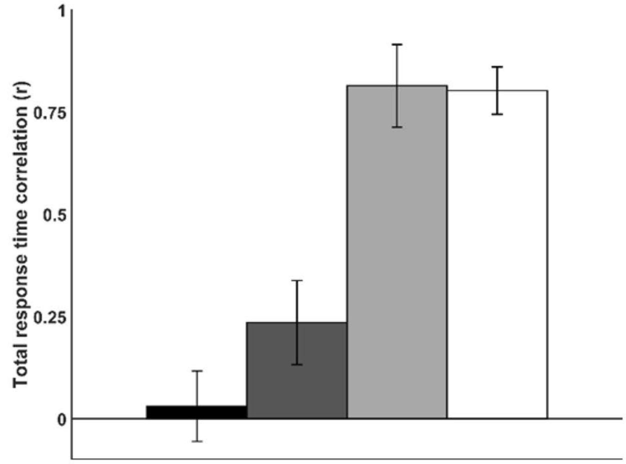


Fig. 4 Reaction time (left) and total response time (right) correlations in the four conditions. In both cases, there were very small correlations in the unimanual solo condition, small-to-medium correlations in the bimanual joint condition, and very large correlations in the bimanual solo conditions. Error bars are 95% within-participant confidence intervals (Cousineau 2005; Morey 2008)

asymmetric movements (long–short, short–long) had total response time values that were longer than their short symmetric counterparts. Critically, absolute temporal coupling at movement termination was not seen in the bimanual joint condition (Fig. 3, top-right). The bimanual joint condition was similar to the unimanual solo conditions in that total response time was determined by the amplitude of the movement.

Absolute temporal coupling at movement termination was investigated by analysing the differences in total response time between the hands. This analysis revealed a significant main effect of Movement and a significant Condition × Movement interaction, $F(3, 45) = 96$, $p < 0.001$, $\eta_p^2 = 87$, $F(9, 135) = 12.0$, $p < 0.001$, $\eta_p^2 = 45$. The interaction was analysed with simple main effects on Condition. The differences in total response time were not significantly different in all conditions for long–long, short–short, and short–long movements, $ps \geq 0.326$, $ds \leq 0.69$. If there was absolute temporal coupling for short–long movements in the bimanual solo conditions, then the differences in total response time in the bimanual solo conditions (− 18.9 ms, [− 41.1, 3.3], − 18.9 ms, [− 43.5, 5.7]) should have been smaller than in the unimanual solo condition (− 27.5 ms, [− 68.3, 13.3]). As this was not the case, short–long movements did not exhibit significant absolute temporal coupling in the bimanual solo conditions.

For long–short movements, the differences in total response time in bimanual solo conditions (19.7 ms, [− 3.8, 43.3], 19.1 ms, [− 2.3, 40.4]) were significantly smaller than in the bimanual joint condition (81.0 ms, [60.7, 101.3]), $ps = 0.005$, $ds \geq 1.35$. The differences in the bimanual joint condition and unimanual solo condition (85.8 ms, [47.4, 124.3]) were not significantly different, $p = 1.000$, $d = 0.06$. These results suggest there was significant absolute temporal coupling for long–short movements in the bimanual solo conditions. The potential absolute temporal coupling of long–short movements in the bimanual joint condition was not significant as it was comparable to the unimanual solo condition.

Unimanual total response time was determined by the movement amplitude

Total response time was analysed in the unimanual solo condition (Fig. 3, top-left). A visible trend was that total response time was longer for long-amplitude movements (573 ms, [566, 580]) than short-amplitude movements (514 ms, [508, 521]). This was supported by a significant main effect of Target Button Distance, $F(1, 15) = 179$, $p < 0.001$, $\eta_p^2 = 0.92$. Total response time was unaffected by Participant and Other Target Button. In other words, total response time in the unimanual solo condition was determined by the movement amplitude.

Relative temporal coupling of movement initiation in the bimanual joint condition

Correlations of left- and right-hand reaction time in all conditions are shown in Fig. 4, left. The left and right participants completed the unimanual solo condition separately, and this caused a correlation of 0.01, [− 0.06, 0.08]. The participants completed the bimanual solo conditions on their own with both hands, and this caused large correlations of 0.91, [0.87, 0.96] and 0.92, [0.87, 0.96]. The bimanual joint condition had a small-to-medium correlation of 0.19 [0.11, 0.26], which was visually larger than the unimanual solo condition and smaller than the bimanual solo conditions. These observations were supported by a significant main effect of Condition, $F(3, 45) = 186$, $\varepsilon_{GG} = 0.57$, $p < 0.001$, $\eta_p^2 = 0.93$. The correlations in the bimanual joint condition were significantly larger than the unimanual solo condition, $p = 0.022$, $d = 1.13$, and significantly smaller than the bimanual solo conditions, $ps < 0.001$, $ds \geq 5.00$. These results suggest a relationship between movement initiation of the left and right participants in the bimanual joint condition. This relationship was not as strong as in the bimanual solo conditions, but the participants did show relative temporal coupling of movement initiation in the bimanual joint condition.

Relative temporal coupling of movement termination in the bimanual joint condition

Correlations of left and right hand total response time in all conditions are shown in Fig. 4, right. The pattern of the correlations was similar to the pattern for reaction time. The mean correlation in the unimanual solo condition was 0.03, [− 0.06, 0.12]. There were large correlations of 0.81, [0.71, 0.91] and 0.80, [0.74, 0.86] in the bimanual solo conditions. The bimanual joint condition had a small-to-medium correlation of 0.24 [0.13, 0.34], which was visually larger than the unimanual solo condition and smaller than the bimanual solo conditions. These observations were supported by a significant main effect of Condition, $F(3, 45) = 80$, $\varepsilon_{GG} = 0.64$, $p < 0.001$, $\eta_p^2 = 0.84$. The correlations in the bimanual joint condition were not significantly larger than the unimanual solo condition, $p = 0.063$, $d = 1.03$, but the p value was close to 0.05 and the effect size was large. The correlations in the bimanual joint condition were significantly smaller than the bimanual solo conditions, $ps < 0.001$, $ds \geq 4.15$. These results suggest there might be a relationship between movement termination of the left and right participants in the bimanual joint condition. This relationship was not as strong as in the bimanual solo conditions, but the participants did show relative temporal coupling of movement termination in the bimanual joint condition.

Discussion

The primary purpose of the present study was to further elucidate the nature of interpersonal coordination in a discrete, non-rhythmic task. The novel contributions this study had to offer were the measures of absolute and relative temporal coupling and bimanual asymmetric movements that had different movement amplitudes. The differences in reaction time and total response time measured the absolute temporal coupling of movement initiation and termination. Relative temporal coupling was measured by correlating the timing of the left hand with the timing of the right hand. The left and right hands could be from different participants completing the blocks at different times (unimanual solo), at the same time (bimanual joint), or from the same participant (bimanual solo). Relative temporal coupling was measured for movement initiation and termination. Recall that the bimanual asymmetric movements tested by Jung et al. (2011) involved participants making movements in opposite directions with the same amplitudes. In contrast, the bimanual asymmetric movements in the present experiment involved participants making movements in the same direction but with different movement amplitudes. In a bimanual solo condition, only these latter movements show absolute temporal coupling, with similar timing for each arm (Kelso et al. 1979). This critical manipulation of movement amplitude, rather than direction, allowed us to investigate how the temporal coupling in the bimanual joint condition compared to the bimanual solo and unimanual solo conditions.

As expected, the results from the bimanual solo conditions revealed the typical pattern of absolute temporal coupling at movement termination. When participants completed the pointing movements using their own two limbs, irrespective of whether the movements were asymmetric or symmetric, the left and right arms completed their movements at the same time. This was accomplished for asymmetric movements by increasing the movement time of the short-amplitude movement so that it was similar to the long-amplitude movement. This is in line with Kelso et al. (1979), who noted that "when total response times are considered, any difference in termination between the hands is greatly reduced" (p. 169). There was a much different story for the unimanual solo condition and the bimanual joint condition. It was the movement amplitude (short or long) that dictated the absolute temporal coupling at movement termination. The long–short movements in the unimanual solo and bimanual joint conditions had asynchronous movement termination; specifically, the short-amplitude movement ended well before the long amplitude movement. In both these conditions, participants were contributing only one of their two limbs to complete the task. The only notable difference was that in the joint condition, the task was completed alongside another person. This change in biopsychosocial context did not seem to "unify" the two participants, as there was no absolute temporal coupling at movement termination. There was, however, evidence of relative temporal coupling at movement initiation and termination.

As mentioned earlier, correlating movement initiation and movement termination of the left and right hands assessed the strength of the relative temporal coupling. It was not surprising that there was no relative temporal coupling at movement initiation in the unimanual solo condition as revealed by a very small correlation coefficient (0.01). The participants were on their own using one limb to point to one of two targets which varied in amplitude; there was no opportunity for relative temporal coupling at movement initiation. These results are in stark contrast to those from the bimanual solo conditions, where there were very large correlations between the left and right hands (0.91, 0.92). This implies that the hands were tightly coupled at movement initiation, or, in other words, that there was strong relative temporal coupling at movement initiation. The bimanual joint condition revealed only a small-to-medium correlation (0.19) between the left and right hands; however, there is an important point to be made. The correlation for the bimanual joint condition was significantly larger than the unimanual solo condition but significantly smaller than the bimanual solo conditions. The pattern of relative temporal coupling at movement termination was extremely similar: a very small correlation in the unimanual solo condition (0.03), a small-to-medium correlation in the bimanual joint condition (0.24), and a very large correlation in the bimanual solo conditions (0.81, 0.80). These findings reflect that some degree of relative temporal coupling emerged when performing the task alongside another person that was not exhibited when performing half the task alone (i.e., unimanual solo).

It is not surprising that the correlation in the bimanual joint condition was not as large as that observed in the bimanual solo conditions. When two different individuals complete the task, rather than a set of hands belonging to the same person, one might expect weaker relative temporal coupling at movement initiation and movement termination. This consideration has also been put forth by della Gatta et al. (2017), who examined joint action in a continuous, rhythmic bimanual task in which participants made congruent (e.g., line–line) or incongruent movements (e.g., line–circle). Their findings supported the notion that motoric representations of the collective goals generated in the joint condition influenced motor production such that ovalization (i.e., lines are drawn like narrow ellipses or circles drawn like wide ellipses) emerged. However, the interference effect was attenuated compared to that typically observed in the bimanual solo condition (see Franz et al. 1991). della Gatta et al. (2017) went on to state that, "of course, in joint action, the hands belong to different individuals: this may explain why the interference is stronger in bimanual action than in unimanual joint action" (p. 58). The next logical question is, why is the relative coupling larger in the bimanual joint than in the unimanual solo condition?

The finding that the reaction time and total response time correlations were significantly smaller in the unimanual solo condition than the bimanual joint conditions suggests that something is potentially interfering with unimanual actions. A clear difference between the unimanual solo and bimanual joint conditions is the presence of another person. And not only is this person sitting beside them, but they are making physical responses (i.e., pointing movements) to their own target set. This contrasts with the unimanual solo condition, where one does not receive such visual feedback. It may be that 'visual feedback' facilitates ongoing unimanual processes and in turn induces movement coordination observed in the bimanual joint condition. Being able to observe another person's unimanual actions may have had subtle effects on relative coupling, enough to distinguish the different context in which the task played (i.e., solo vs. joint). The impact that online and offline information may have on merging two people's behaviour in a joint action setting has been explored. For example, both Tsai et al. (2008) and Welsh et al. (2007) set out to determine whether the belief that a co-actor completing the same task in a different room was sufficient to modulate performance on a joint go/no-go task. Oddly, the outcome of these two studies did not match. While Tsai et al. (2008) found a joint go/no-go effect when participants had no visual feedback of the co-actor's action (i.e., co-actor was physically absent), Welsh et al. (2007) reported no effect. A key difference in the methods between these two studies was that participants could communicate with each other via intercom before the task and during breaks in Tsai et al.'s (2008) experiment; this opportunity was not afforded to participants in Welsh et al.'s (2007) experiment. Vlainic et al. (2010) carried out a follow-up study in which they systematically manipulated the amount of online feedback available to participants. In a series of three experiments, they were able to conclude that it was not online action-related feedback that was needed to elicit the joint go/no-go effect but rather prior knowledge that the task was social in nature (i.e., interacting with an intentional partner). To establish the potential influence of visual feedback in the bimanual joint condition, it would be worthwhile to demonstrate how the elimination of online information impacts relative coupling when paired participants are completing the task in separate rooms.

An important question with the present results is whether the block order affected the relative temporal coupling.[1] Our participants completed the unimanual solo blocks, the bimanual joint block, and then the bimanual solo blocks. The strength of relative temporal coupling increased as the experiment progressed; there were very small correlations in the unimanual solo blocks, small-to-medium correlations in the bimanual joint block, and very large correlations in the bimanual solo blocks. Was it simply practice and familiarity with the tasks that caused the increase in strength of the relative temporal coupling and not the differences in interpersonal coordination and tasks? We address this issue by first reiterating the reasons for our block order and then presenting data that suggest familiarity did not affect the strength of the relative temporal coupling.

[1] Our thanks to two anonymous reviewers for raising this issue.

Carryover effects can occur when participants complete a choice reaction time task before a go/no-go reaction time task (Ansorge and Wühr 2004). In different terms, performance on a task with both hands can carry over to a task with one hand. We, therefore, needed to prevent potential carryover effects from the bimanual conditions (either joint or solo) to the unimanual condition. This was ensured by testing the unimanual solo condition first. Carryover effects can also occur between individual and joint tasks (Lam 2013). It is possible that strong absolute and relative temporal coupling in the bimanual solo conditions could carry over to the bimanual joint condition. We prevented these potential carryover effects by testing the bimanual joint condition before the bimanual solo conditions.

We investigated whether familiarity affected the strength of the relative temporal coupling by comparing the strength of the coupling in the first half of each block to the second half across all conditions. Correlations on reaction time and total response time were analysed with 2 Block (first block, second block) × 4 Condition (unimanual solo, bimanual joint, bimanual left, bimanual right) repeated measures ANOVAs. For reaction time correlations, there was a significant main effect of Condition, $F(3, 45) = 144$, $\varepsilon_{GG} = 0.57$, $p < 0.001$, $\eta_p^2 = 0.91$. The main effect of Block and the Block × Condition interaction were not significant, $F(1, 15) < 0.1$, $p = 0.958$, $\eta_p^2 < 0.01$, $F(3, 45) = 0.7$, $p = 0.585$, $\eta_p^2 = 0.04$. These results suggest the strength of relative temporal coupling at movement initiation was consistent from the first half of the block to the second half across conditions. The same pattern of results occurred for total response time correlations. There was a significant main effect of Condition, $F(3, 45) = 61$, $\varepsilon_{GG} = 0.62$, $p < 0.01$, $\eta_p^2 = 0.80$. The main effect of Block and the Block × Condition interaction were not significant, $F(1, 15) = 0.2$, $p = 0.664$, $\eta_p^2 = 0.01$, $F(3, 45) = 1.0$, $p = 0.424$, $\eta_p^2 = 06$. These results suggest the strength of relative temporal coupling at movement termination was also consistent from the first half of the block to the second half across conditions. Therefore, we conclude that the increase in strength of relative temporal coupling throughout our experiment was not likely caused by practice and familiarity with the tasks. Our measures of temporal coupling were also likely free from carryover effects from previous blocks. The change in the strength of relative temporal coupling is most likely caused by the deliberate changes from one condition to the next in social context and unimanual/bimanual responses.

How did our findings line up with those of Jung et al. (2011), who also investigated the influence of social context on the performance of a discrete, non-rhythmic bimanual task? They chose to describe interpersonal coordination on two levels: globally (across-participants correlation) and locally (within-participants [hands] correlation). As we did not measure global coordination, we will only speak to what Jung et al. described as local coordination, which we refer to as relative temporal coupling. In the bimanual solo conditions, we found large correlations for movement initiation and termination, as did Jung et al. (0.983 and 0.993 Experiment 1, respectively). This, however, was not the case for the bimanual joint condition, where we reported small-to-medium correlations for movement initiation and termination; Jung et al. found a medium correlation for movement initiation and termination (0.302, 0.367). A potential explanation for these differences may be attributed to the type of movement made.

Recall that participants made movements in either the same or different directions in Jung et al.'s procedures. In the present study, participants made movements that were either the same or different amplitudes. Jung et al. may have found somewhat larger correlations because equal bimanual movements in opposite directions should have more similar timing than asymmetric movements with different amplitudes but similar directions. For example, while the movement time for forward and backward movements are quite similar, they are very different for short and long movement amplitudes. It is critical, with either type of bimanual asymmetric movement, to compare the size of the correlations in the bimanual joint condition to the unimanual solo condition. By including the unimanual solo condition, we can confirm that the small-to-medium relative temporal coupling in the bimanual joint condition was caused by two people completing the task together. In other words, this comparison is evidence against the possibility that relative temporal coupling existed in the absence of another person. Jung et al. did not include a unimanual solo condition. It is, therefore, not possible to determine whether the medium correlations in their bimanual joint condition were caused by two people completing the task together.

Another point that should be highlighted is that in the bimanual joint condition participants did not know in advance which target distance (short, long) they would be moving to, nor did they know which target distance the other person would be moving to. The targets illuminated after a variable foreperiod and participants were instructed to respond as quickly as possible. Sebanz et al. (2006) argued that effective joint action arises when (1) shared representations are generated, (2) actions can be predicted, and (3) predicted effects of one's own and others' actions are integrated. They identified knowledge of another person's task as a mechanism by which another person's actions can be predicted and, in turn, shared representations are generated. In Sebanz et al.'s (2003) study, participants were aware of each other's stimulus–response assignment, allowing for task co-representation. In the current study, the timeline of trial events did not afford participants the opportunity to make predictions based on prior information. That is to say, participants were not given advance information about the movement amplitude made by the other. It would be worth testing whether larger relative temporal coupling in the bimanual joint condition could be elicited if participants were given valid precues indicating movement amplitude before the go signal. The idea here is that this advance information would allow participants to anticipate the other person's action and form a representation of it. As a result, this might elicit increased amplitude coupling on asymmetrical movement trials, which in turn support a co-representation account. Nevertheless, there was evidence for relative temporal coupling in the bimanual joint condition, albeit a small-to-medium correlation, perhaps indicating the brief offering of information prior to movement initiation was sufficient to form a weak shared representation.

What was not considered in this study that may well have had an influence on the results is the implicit goal structure of the task. In our study, participants were not given any explicit instruction on how to couple their movements during the bimanual joint condition. However, they were instructed to "react and press the left/right target button as quickly as possible". When performing the task alongside another person, participants may have interpreted the need to "react...as quickly as possible" to mean that they needed to achieve shorter reaction times than the other person. A competitive mindset would explain why small-to-medium correlations were observed in the bimanual joint condition. In a competitive situation, it would be beneficial to ignore the other person's actions and focus solely on their own. Joint action studies have already explored how a cooperative or a competitive context can modulate the degree of co-representation. For example, de Bruijn et al. (2008) demonstrated that in a competitive setting, fast responders do not incorporate another person's action into their own motor plan. While Liepelt el al. (2011) showed that in a task requiring participants to cooperate, co-representation was facilitated. As part of future work, we intend to address the roles of cooperation and competition on performance in a joint bimanual coordination task.

Intrapersonal and interpersonal coordination have been investigated extensively in the context of continuous, rhythmic bimanual coordination tasks. For instance, Coey et al. (2011) presented two experiments that examined the influence of spontaneous interpersonal coordination on the stability of intrapersonal coordination. Paired participants sat side-by-side and held a pendulum in each of their left and right hands. They were instructed to swing their pendulums in either an in-phase or anti-phase pattern at a self-selected frequency (intrapersonal) while completing a problem-solving task together (interpersonal). Contrary to what they predicted, the results indicated that intrapersonal and interpersonal coordination were mutually independent of one another. Other studies have demonstrated that the removal of sensory information (e.g., visual feedback) about another person's movements has a modulatory effect on coupling (Schmidt et al. 1997, 1998). When participants were facing each other (visual information available), unintended interpersonal coordination was greater than when they were facing away from each other (visual information unavailable); this was substantiated by differences in coordination variability as indexed by the standard deviation of relative phase. These findings have been extended to a task in which participants were paired and instructed to flex and extend their index finger continuously at a self-selected pace while opening and closing their eyes for 20-s period over the course of a 60-s trial (Oullier et al. 2008). Not only did visual feedback (eyes open segment) of the other's finger result in the spontaneous adoption of an in-phase coordination pattern, but they also showed that performance did not necessarily return to one's own intrinsic frequency once visual feedback (eyes closed segment) was removed. Instead, Oullier et al. (2008) reported what they described as a social memory effect. While the slower partner increased the frequency of their movement to match the other when their eyes were open, they returned to their own frequency when their eyes were closed. In contrast, the faster partner maintained the frequency that they established during the eyes open segment during the eyes closed segment. What these studies demonstrated was the strong influence that visual feedback has on continuous, rhythmic bimanual coordination tasks, a finding that does not align with our results. Even though the current study did not manipulate the availability of visual feedback on interpersonal coordination, the motion arising from the other person's limb did not seem to have a strong enough influence to elicit absolute temporal coupling of movement. However, it may have been sufficient to give rise to the weak relative temporal coupling that was observed in the bimanual joint condition. The only way to determine whether visual processing of another's moving limb influences interpersonal coordination would be to remove this sensory information. One way to accomplish this would be to remove visual information after the targets have been presented at the beginning of the trial; this could be done by having participants wear eye goggles that occluded vision. What this potential difference nicely illustrates is the importance of investigating interpersonal condition when performing discrete, non-rhythmic bimanual coordination movements. Ultimately, these undertakings expand our understanding of the principles of coordination.

In conclusion, our findings indicate that some degree of interpersonal coordination occurs when two people complete a discrete, non-rhythmic bimanual coordination task. While no absolute temporal coupling of movement termination was observed in the bimanual joint condition, there was a relative temporal coupling of movement initiation and movement termination in the bimanual joint condition. Even though the relative temporal coupling was weaker than in the bimanual solo conditions, what was of greater interest was that the coupling was significantly stronger than in the unimanual solo condition.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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