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RESEARCH ARTICLE

Interpersonal Fitts' law: when two perform as one

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Abstract Intra- and interpersonal coordination was investigated using a bimanual Fitts' law task. Participants tapped rhythmically between pairs of targets. Tapping was performed with one hand (unimanual), two hands (intrapersonal coordination), and one hand together with another participant (interpersonal coordination). The sizes and distances of targets in a pair were manipulated independently for each hand. When target difficulty was unequal across hands, movement times were similar in the coordination conditions, in violation of Fitts' law. Processing speed (measured by index of performance) increased for more difficult tasks, suggesting increased attention, even for dyads. These findings suggest that similar processes, not captured by centralized control, guide coordination for both individuals and dyads. Measures of coordination, though, still showed stronger coordination tendencies for intrapersonal coordination, indicating a possible role for centralized mechanisms.

Keywords Coordination · Motor control · Fitts' law · Joint-action

Introduction

Many situations require an *individual* to produce coordinated movements such as walking, performing gymnastics, or playing the piano. Coordinated behavior is not restricted to an individual, though; many other situations require *groups* or *teams* to produce coordinated interpersonal movements such as dancing, team-lifting a heavy object, or passing a soccer ball. The coordination of one person's limbs is often considered to be the responsibility of the central nervous system or planner (e.g., Schmidt 1975, 2003). The observation that pairs of individuals can spontaneously produce synchronized interpersonal movements suggests that there are other non-centralized—perhaps dynamical—processes underlying coordination (Richardson et al. 2005, 2007; Schmidt et al. 1990; Schmidt and O'Brien 1997; Schmidt and Turvey 1994). The current experiment examined and compared intra- and interpersonal coordination in a rhythmic Fitts' law tapping task.

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Fitts' law

In aimed movements such as pointing or tapping, speed is traded for accuracy as the difficulty of targets increase. Paul Fitts (1954) established a formal relationship between movement amplitude, target width, and movement time in rapidly aimed movements—it is known ubiquitously as Fitts' law. This mathematical description is based on the information-processing framework of behavior (specifically, the processing capacity of the human motor system), adapted from Shannon's (1949) theorem 17 (information theory). Fitts' law ($\mathrm{MT} = a + b \log_2 (2A/W)$) accounts for changes in movement time (MT) to a target based on a movement's difficulty, captured by the amplitude (A) and target width (W) (Fitts 1954; Fitts and Peterson 1964). These parameters are used to quantify the associated difficulty (in bits) of a movement to a target [index of difficulty ($\mathrm{ID} = \log_2 (2A/W)$; Fitts 1954)]. This formulation is also used to calculate a measure of performance (in bits/s), which depicts how quickly information is processed (index of performance ($\mathrm{IP} = \mathrm{ID}/\mathrm{MT} = \mathrm{bit/s}$); Fitts 1954)).

Ever since Fitts's (1954) original findings, a number of studies have demonstrated the generality of the principle for unimanual tasks (e.g., Bainbridge and Sanders 1972; Guiard and Beaudouin-Lafon 2004; Soukoreff and MacKenzie 2004). Fitts' law has also been extended to several motor tasks, such as aimed wrist movements (Meyer et al. 1988), rotary handle turning (Jagacinski et al. 1980), moving a target and pointer across a dyad (Mottet et al. 2001), and foot movements (Langolf et al. 1976). The consistent outcome is MT scales to increases and decreases in ID. Due to the persistent capacity of Fitts' laws to describe various forms of human movement, findings that violate this lawful relationship are of significance. Recent studies have revealed instances of violations of Fitts' law for one-handed movements (Fischer et al. 2007; Pratt et al. 2007). When irrelevant targets are presented simultaneously in an array of targets, these violations occur for movements toward the farthest target (Adam et al. 2006; Fischer et al. 2007; Pratt et al. 2007).

Bimanual Fitts' law

Another violation of Fitts' law occurs during the performance of discrete *bimanual* tapping (Fowler et al. 1991; Kelso et al. 1979; Marteniuk et al. 1984). Kelso et al. (1979) had participants make rapid tapping movements toward pairs of targets of equal and unequal ID. In the case of unequal ID, Fitts' law predicts that the hand aimed at an easy target would have a faster MT than the hand directed at a hard target. Analysis revealed, however, that MT of the hands was approximately equal when directed at targets of unequal ID (Kelso et al. 1979). More specifically, MT for the hand moving to an easy target was lengthened compared to the unimanual case in order to match MT for the hand moving to a hard target. Kelso et al.'s (1979) interpretation of Fitts' law's failure in the bimanual case was that the brain does not program motor units individually—a necessary assumption for applying Fitts' law (Keele 1968). They suggested instead that the muscles are organized into functional groupings. Accordingly, collectives of muscles should be considered a unitary, synergistic unit whereby muscle synergies are constrained to perform in a complementary manner due to anatomical coupling (Bernstein 1967; Kelso et al. 1979).

Using a similar bimanual Fitts' law task, both Marteniuk et al. (1984) and Fowler et al. (1991) found results that differed from those of Kelso et al. (1979). Specifically, both studies found significant differences between the hands performing movements of unequal difficulty, which called into question the finding of virtual simultaneity reported by Kelso et al. (1979). Importantly, however, despite these differences, both Marteniuk et al. (1984) and Fowler et al. (1991) observed similar violations of Fitts' law, associated primarily with a lengthening of the MT for the hand moving to an easier target. Findings of virtual simultaneity between limbs are not a necessary requirement for coordinative structures; in fact, research has shown that both similarities and differences in the timing across hands (e.g., Byblow et al. 1998; Peper et al. 1995) can be captured by dynamical models of interlimb coordination. Taken together, then, the results of multiple experiments using a bimanual Fitts' law task suggest that the limbs are not controlled individually but, rather, as a coupled pair.

Dynamics and interpersonal coordination

Dynamical explanations (e.g., Amazeen et al. 1998; Kelso 1995, 2002; Schmidt and Richardson 2008; Turvey 1990) offer an interpretation of bimanual coordination—including bimanual Fitts' law—as emerging from the coupling (either anatomical or perceptual, see Amazeen et al. 2008) that exists across moving components (Kelso et al. 1988). This coupling produces patterns of behavior that are captured by the order parameters of coordination; control of movement occurs at the level of these patterns, not the individual motor units.

Schmidt et al. (1990) investigated interpersonal coordination in a task that allowed them to make comparisons to known intrapersonal dynamics. In Schmidt et al. (1990), pairs of individuals coordinated leg swinging while visually attending to the other person. Movements initiated in-phase remained stable with increased frequency. However, movements initiated anti-phase spontaneously shifted to in-phase as frequency increased, as had been shown in intrapersonal bimanual coordination (Kelso 1984). Perceiving the movement of the other limb was sufficient to create coordinated behavior. Similar results have been found using pendulum swinging (Amazeen et al. 1995; Schmidt et al. 1998) and rocking chair movements (Richardson et al. 2007) as well as in situations where there is no explicit intention to coordinate (Issartel et al. 2007; Schmidt and O'brien 1997).

The significance of the studies on interpersonal coordination dynamics is that they provide support for the notion that similar dynamical processes govern both intra- and interpersonal coordination. Stable patterns of coordination arise through the coupling of one person's limbs or the visual interaction of two individuals' limbs. No centralized controller is needed to dictate specific commands to individual limbs, especially when such a controller does not exist between people.

Overview

Research suggests that lawful regularities exist to constrain the coordination of both intra- and interpersonal rhythmic movement. The hypothesis in the present experiment was that coordination (either intra- or interpersonal) emerges equivalently across limbs due to anatomical or visual coupling. Participants performed a rhythmic Fitts' tapping task with targets of varying ID (Fitts 1954; Fitts and Peterson 1964). All individuals performed an intrapersonal (bimanual) and interpersonal (two person) coordination task, as well as a unimanual task. We predicted that the violations of Fitts' law previously demonstrated in bimanual coordination (Fowler et al. 1991; Kelso et al. 1979; Marteniuk et al. 1984) should be evident in the interpersonal conditions, despite the tendencies for two independent and uncoupled limbs to have different preferred frequencies of oscillation. Similar patterns emerging across intra- and interpersonal coordination were taken as evidence in support of non-centralized dynamical processes.

Method

Participants

Sixteen undergraduate students (eleven men, five women) at Arizona State University participated in the experiment for course credit to fulfill an Introductory Psychology class requirement. All participants ranged in age from 18 to 27 years. Individuals having no prior experience of each other signed up to participate in groups of two. Two participants were identified as left-handed and fourteen as right-handed based on self-report.

Design

In all conditions, participants tapped their index fingers between pairs of square targets in the sagittal plane. Movement trajectories of each hand were recorded to measure MT (ms), amplitude (mm), standard deviation (SD) of endpoint (mm), and (in the two-handed conditions) relative phase. Target pairs (see Fig. 1) were classified as either easy (width = 60 mm; amplitude = 80 mm) or hard (width = 20 mm; amplitude = 240 mm).

Each participant completed sets of unimanual, intrapersonal, and interpersonal trials in a randomized order. In the unimanual trials, participants tapped between pairs of targets with their left and right hands separately. The IDs for the unimanual conditions were 1.6 for the easy targets and 4.6 for the hard targets. There were four unimanual conditions defined by two levels each for Index of Difficulty (easy or hard) and Hand (left or right). In the intra- or interpersonal trials, two hands tapped between pairs of targets simultaneously (see Fig. 1). In the intrapersonal trials, one participant tapped with his left and right hands simultaneously; this is a typical bimanual task. In the interpersonal trials, two participants each tapped with one hand; this is a joint-action task. The difficulty associated with each hand was manipulated separately, creating four conditions defined by two levels each for the difficulty associated with the Left Hand (easy or hard) and the difficulty associated with the Right Hand (easy or hard). For those analyses that treat the two limbs together (e.g., the coordination analyses), the combined IDs for these conditions were 3.17 for two easy targets, 6.17 for easy-hard/hard-easy pairings, and 9.17 for two hard targets. Combined IDs were calculated as the sum of each target's individual ID. For example, the ID for an easy-hard pairing (6.17) was the result of summing the IDs of an easy (1.6) and hard (4.6) target.

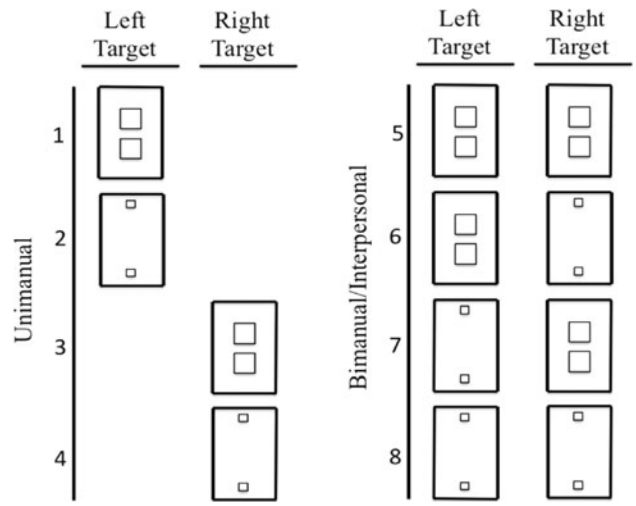

Fig. 1 Target pairings used for unimanual, bimanual, and interpersonal conditions

A different design was used to analyze the coordination data. To assess whether the performance of one hand was being influenced by the task being performed by the other, the data were analyzed with a 2 Index of Difficulty (easy or hard) by 2 Other Hand (easy or hard) design. In this design, Index of Difficulty refers to the task being performed by one of the hands (the one from which the data are recorded) and Other Hand refers to the task being performed by the other hand. So, for the condition labeled 6 in Fig. 1, the data from the left hand (or left participant) would be entered into the condition (Index of Difficulty: easy; Other Hand: hard) whereas the data from the right hand (or right participant) would be entered into the condition (Index of Difficulty: hard; Other Hand: easy). The data were subjected to paired *t*-tests to determine whether the data could be collapsed across the two hands (in order that, for example, the data from the left hand in the condition labeled 6 in Fig. 1 could be combined with the data from the right hand in the condition labeled 7 into the 'Index of Difficulty: easy; Other Hand: hard condition).

Materials

Four poster boards (220 × 280 mm), each with a pair of vertically aligned printed square targets (line width = 0.8 mm) were created. Boards were attached with Velcro to a table (height = 750 mm), centered in front of participant's hands. The movement trajectories of the index fingers were recorded with an Optotrak 3020 motion capture system and First Principles software package (Northern Digital Inc., Waterloo, Canada). The system was positioned in front of the participants (3.00 m) and off of the ground (0.75 m). The cameras recorded the three-dimensional positions (sampling rate = 100 Hz) from infrared light-emitting diodes (IREDs; diameter = 1 mm). Diodes were attached with first aid tape to the distal segment of participants' left and right index fingers.

Procedure

Individuals were recruited in pairs of two for each session. Participants were asked to stand individually or side by side in front of the table and instructed to begin tapping continuously when signaled by the experimenter. For unimanual conditions, participants used their left or right hands; intrapersonal conditions required participants to use both hands; interpersonal conditions required participants to utilize their dominant hands. Participants were allowed to choose the frequency at which they tapped but were asked to tap as quickly and accurately possible. Participants were asked to tap until a maintainable frequency was achieved, upon which they gave a verbal "go" signal and data collection began, lasting for 60 s. One experimenter monitored data collection, while another monitored participants to ensure task performance. Experimental sessions spanning forty trials lasted approximately 1 h; participants were allowed to rest between trials if necessary. The procedures used in this experiment conform to the ethical guidelines of the American Psychological Association and were approved by the Institutional Review Board at Arizona State University.

Results

Unimanual kinematics

Movement time

It is known that Fitts' law typically holds in unimanual tasks; movement time is expected to increase as the target ID increases. Therefore, mean MT was analyzed with a 2 (Index of Difficulty: easy, hard) × 2 (Hand: left, right) repeated-measures ANOVA. As expected, the main effect of Index of Difficulty was significant, $F_{(1,15)} = 89.44$, $P < .05$, $\eta^2 = .856$, where the mean movement time increased from 199 ms for easy targets to 337 ms for hard targets, indicating that unimanual movements for an easy target were performed significantly faster than movements for a hard target. Neither the main effect of Hand nor the interaction of Hand and Index of Difficulty was significant, both $Fs < 1.0$, $P > .05$, both $\eta^2 < .051$.

Index of performance

Index of Performance (quantified as IP = ID/MT = bit/s) was calculated to measure processing speed as a function of ID. Mean IP was analyzed using a 2 (Index of Difficulty) × 2 (Hand) repeated-measures ANOVA. The effect of Index of Difficulty was significant, $F_{(1,15)} = 115.20$, $P < .05$, $\eta^2 = .885$, where the mean IP decreased from .009 bits/s for an easy task to .006 bits/s for a hard task, indicating that processing speed was faster for easy targets. All other effects were non-significant ($P > .05$).

Amplitude and endpoint SD

The means for amplitude (mm) and endpoint SD (mm) indicated that participants were accurately performing the tasks. Data on each measure were analyzed with a 2 (Index of Difficulty: easy, hard) × 2 (Hand: left, right) ANOVA. The main effect of Index of Difficulty on amplitude was, by design, significant, $F_{(1,15)} = 396.80$, $P < .05$, $\eta^2 = .964$. The main effect of Hand and the interaction of Index of Difficulty by Hand were both non-significant, $F < .5$, $P > .05$, $\eta^2 < .05$. More importantly, though, the means (69 mm for the 80 mm condition and 233 mm for the 240 mm condition) were within the target bounds in each condition. None of the effects on endpoint SD were significant, all $Fs < 1.3$, $P > .05$, $\eta^2 < .100$. Again, the more important feature here is that the means (17 mm for the 60 mm width target and 19 mm for the 20 mm width target) were within the target bounds in each condition. Percentages of target misses were estimated using the mean amplitude and endpoint SD. Mean values were 1.21% for easy targets and 4.25% for hard targets; the overall mean was 2.73%.

Intra- and interpersonal kinematics

Movement time

Paired *t*-tests indicated that there were no significant differences ($P > .05$) in MT across the left and right hands.

As described in the Design section, then, the data were collapsed across Hand. Mean MT for intra- and interpersonal conditions (Fig. 2a, b, respectively) were analyzed with a 2 (Coordination: intra- and interpersonal) × 2 (Index of Difficulty: easy, hard) × 2 (Other Hand: easy, hard) repeated-measures ANOVA. If violations of Fitts' law emerge consistent with those previously demonstrated for bimanual movements (Fowler et al. 1991; Kelso et al. 1979; Marteniuk et al. 1984), then mean MT for a hand aimed at an easy target should increase when the other hand is aimed toward a hard target. The analysis revealed a significant effect of Index of Difficulty, where mean MT increased from 276 ms for the easy task to 332 ms for the hard task, $F_{(1,15)} = 33.04$, $P < .05$, $\eta^2 = .688$. There was also a significant main effect of Other Hand, where mean MT increased from 281 ms when the other hand was performing an easy task to 328 ms when the other hand was performing a hard task, $F_{(1,15)} = 98.03$, $P < .05$, $\eta^2 = .867$. The analysis also revealed that there were significant interactions of Index of Difficulty and Other Hand, $F_{(1,15)} = 17.72$, $P < .05$, $\eta^2 = .542$, and a three-way interaction of Index of Difficulty by Other Hand by Coordination, $F_{(1,15)} = 5.75$, $P < .05$, $\eta^2 = .277$. As can be seen in Fig. 2, the three-way interaction reflects the fact that the Index of Difficulty by Other Hand interaction changed as a function of Coordination. A simple interaction analysis shows that the Index of Difficulty by Other Hand interaction was significant in intrapersonal trials, $F_{(1,15)} = 19.23$, $P < .05$, $\eta^2 = .562$, but not in interpersonal trials, $F_{(1,15)} = 2.86$, $P > .05$, $\eta^2 = .160$. For intrapersonal coordination, the interaction (see Fig. 2a) revealed that when the Other Hand's task was hard, MT did not differ across levels of Index of Difficulty, $F_{(1,30)} = .294$, $P > .05$; however, when the Other Hand's task was easy, MT was different between Indexes of Difficulty, $F_{(1,30)} = 42.73$, $P < .05$. Fitts' law was violated here by showing no difference in MT across ID when the other hand was performing a hard task. Furthermore, these results are similar to past studies (Fowler et al. 1991; Kelso et al. 1979; Marteniuk et al. 1984) showing a lengthening of MT for the hand aimed at an easy target when the other hand is aimed toward a target of greater difficulty.

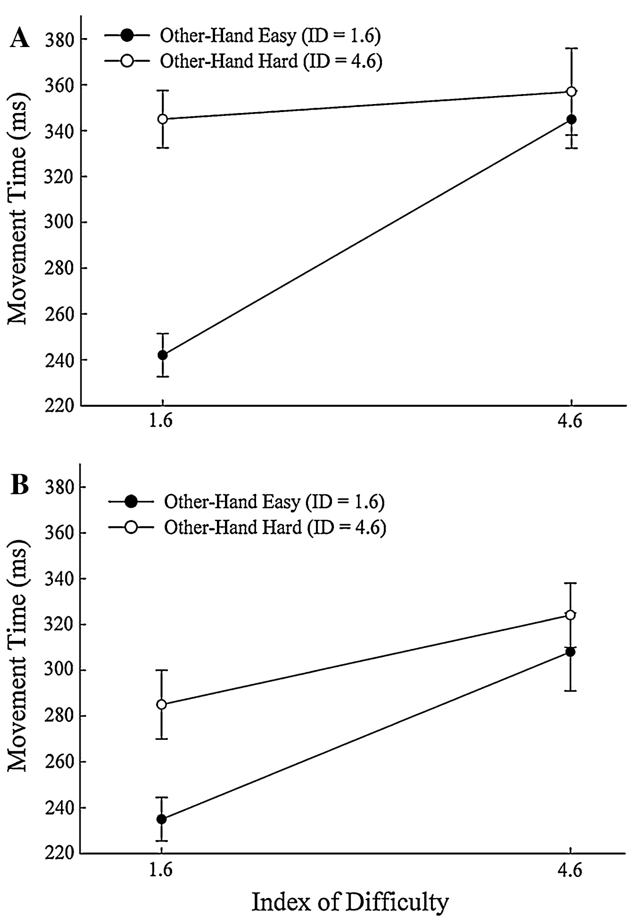

Fig. 2 Mean movement times (ms) as a function of Index of Difficulty and Other Hand. The different conditions are presented in the two panels (**a** intrapersonal; **b** interpersonal)

Index of performance

Index of Performance (quantified as IP = ID/MT = bit/s) was calculated to compare processing speed across intra- and interpersonal conditions. Mean IP (Fig. 3) was analyzed with a 2 (Coordination: intra- and interpersonal) × 3 (Index of Difficulty: easy-easy = 3.17, mixed = 6.17, and hard-hard = 9.17) × 2 (Hand) repeated-measures ANOVA. The analysis revealed significant main effects of Coordination, $F_{(1,7)} = 32.41$, $P < .05$, $\eta^2 = .82$, and Index of Difficulty, $F_{(2,\ 14)} = 82.25$, $P < .05$, $\eta^2 = .93$ (see Fig. 3). Mean IP was overall greater for interpersonal coordination and increased as Index of Difficulty increased. None of the

Fig. 3 Mean index of performance across all levels of combined ID for intra- and interpersonal coordination

other effects on IP were significant, all $Fs < 2.4$, $P > .05$, $\eta^2 < .08$.

Amplitude and endpoint SD

The means of amplitude and endpoint SD reveal that participants were performing the task within an accurate range of the targets. Paired *t*-tests indicated that there were no significant differences ($P > .05$) in either measure across the left and right hands. As described in the Design section, then, the data were collapsed across Hand and these measures were analyzed with a 2 (Coordination: intra- and interpersonal) × 2 (Index of Difficulty: easy, hard) × 2 (Other Hand: easy, hard) ANOVA.

As expected, the main effect of Index of Difficulty on amplitude was significant, $F_{(1,15)} = 1.40$, $P < .05$, $\eta^2 = .989$. Furthermore, the means (95 mm for a 80 mm target and 231 mm for a 240 mm target) were within the boundaries of the targets, indicating that participants were within the target boundaries in the intra- and interpersonal conditions (see Fig. 4). The main effect of Other Hand was also significant, $F_{(1,15)} = 11.48$, $P < .05$, $\eta^2 = .434$, along with the two-way interaction of Index of Difficulty by Other Hand, $F_{(1,15)} = 13.51$, $P < .05$, $\eta^2 = .474$. The three-way interaction of Coordination by Index of Difficulty by Other Hand was also significant, $F_{(1,15)} = 13.97$, $P < .05$, $\eta^2 = .482$. A simple interaction analysis revealed that the interaction of Index of Difficulty by Other Hand was significant for bimanual conditions, $F_{(1,15)} = 74.31$, $P < .05$, $\eta^2 = .832$, but not for interpersonal conditions, $F < 1.4$, $P > .05$, $\eta^2 < .085$. For bimanual tasks, a simple effects analysis revealed that the effect of Other Hand on mean amplitude (84 mm when the Other Hand's task was easy to 114 mm when the Other Hand's task was hard) was significant only when Index of Difficulty was easy, $F_{(1,30)} = 68.37$, $P < .05$. Most likely, this effect is due to the smaller targets (i.e., less room for amplitude to vary) when the Index of Difficulty was hard.

The analysis of endpoint SD revealed a significant main effect of Index of Difficulty, $F_{(1,15)} = 4.87$, $P < .05$, $\eta^2 = .245$, while the effects of Coordination and Other Hand were non-significant, both $Fs < 2.2$, $P > .05$, both $\eta^2 < .128$. The means of Index of Difficulty (23 mm for the 60 mm width target and 18 mm for the 20 mm width target) were within the target bounds in each condition. Also, mean percent of target misses were estimated using the mean amplitude and endpoint SD. For bimanual tasks, the means ranged from 0.51% (easy–easy pairing) to 6.18% (hard–hard pairing); the overall mean was 4.15% across all target pairings. For interpersonal tasks, the means ranged from 0.33% (easy-easy pairing) to 5.54% (hard-hard pairing); the overall mean was 3.63% across all target pairings.

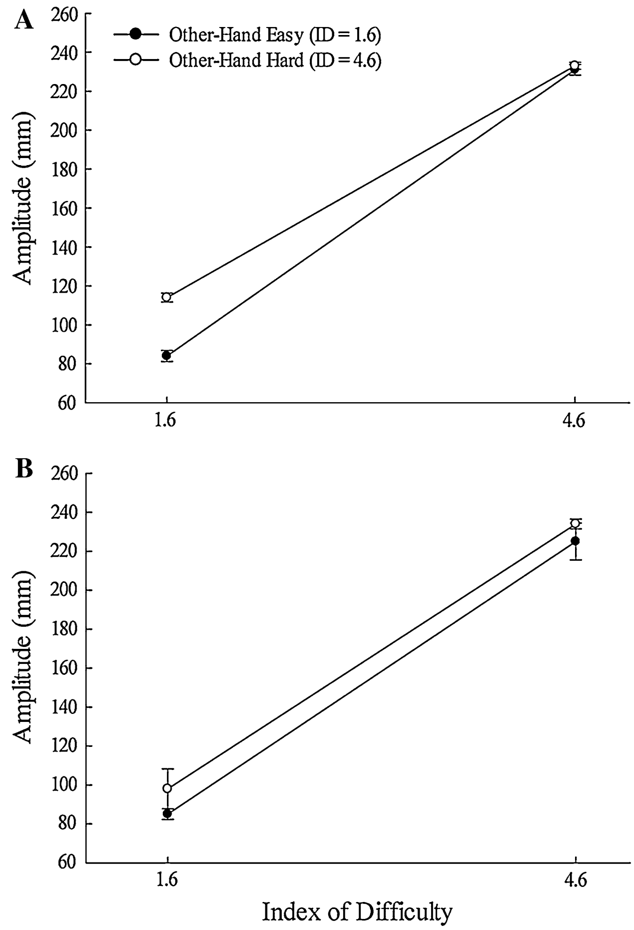

Fig. 4 Mean amplitude (mm) as function of Index of Difficulty and Other Hand. The two conditions are presented in the two panels (**a** intrapersonal; **b** interpersonal)

Coordination

Measures typically used in Fitts' law (i.e., MT) paradigms are necessary for the current study, though such measures do not describe the continuous behavior underlying coordination. MT could distinguish whether movements are, on average, temporally coordinated; alone it provides little information regarding important characteristics of cyclical coordination (i.e., coordination type and strength). Explanations for both partial (Fowler et al. 1991; Marteniuk et al. 1984) and complete (Kelso et al. 1979) bimanual violations of Fitts' law are often based on an interaction or coordination across limbs. Assessing the strength of this coordination, then, may inform the MT results.

The coordination being assessed in the present study was expected to be relative rather than fixed (phase-locked; Schmidt et al. 1990). Thus, assessing the tendencies of limbs to become intermittently coordinated during intra- and interpersonal tasks requires measures that sufficiently probe these emergent patterns (Richardson et al. 2005, 2007; Schmidt and O'Brien 1997). Two measures were calculated to assess the degree to which individuals' hands became entrained. First, to measure the dominant kind of coordination (in-phase or anti-phase), the relative phase angles (degrees) were calculated across a whole time series. The phase angles across nine different phase regions (20° each), ranging from 0° to 180°, were calculated. The standard deviations of relative phase were also calculated to determine the average stability of coordination. Next, the cross-spectral coherence (Gottman 1981; Schmidt and O'Brien 1997) was calculated for each time series to evaluate the correlation between limbs at their dominant frequencies by producing an output ranging from 0 to 1. A value of 1 represents perfect correlation (absolute coordination) while 0 represents no correlation (no coordination). Thus, coherence provides an index of coordination strength in the frequency domain (Richardson et al. 2009).

Relative phase

Relative phase angles were calculated and distributed across the nine phase regions according to percent of occurrence within a trial. Mean relative phase data were collapsed across trials of mixed targets (i.e., easy-hard and hard-easy pairings) due to non-significant *t*-tests (all *ps* > .05). If individuals are coordinated, it is expected that phase angles will be clustered around either 0° (in-phase) or 180° (anti-phase). Mean relative phase was analyzed with a 2 (Coordination: intra- and interpersonal) × 3 (Index of Difficulty: easy-easy = 3.17, mixed = 6.17, and hard-hard = 9.17) × 9 (Phase Region) repeated-measures ANOVA. The analysis yielded a significant main effect for Phase Region, $F_{(8,56)} = 153.37$, $P < .001$, $\eta^2 = .96$, as well as a significant interaction of Coordination and Phase Region, $F_{(8,56)} = 10.54$, $P < .001$, $\eta^2 = .60$. This effect was confirmed by simple comparisons between intra- and interpersonal coordination across the different phase regions. Significant differences were found for the first (0°–20°) and second (21°–40°) regions, both $Fs < 11$, both $ps < .05$, both $\eta^2 < .70$ (all other $ps > .05$). Furthermore, the effect of Index of Difficulty was non-significant ($P > .05$).

Across all target pairings (Fig. 5), intra- and interpersonal conditions revealed a concentration of relative phase angles in the 0° region. The mean relative phase angles (collapsed across targets) for this region went from 99.62% for intrapersonal tasks (other regions < 1%), and 65.42% for interpersonal tasks. The remaining values for interpersonal tasks were distributed between the two neighboring regions (both regions < 18%). The overall concentration of relative phase values in the 0° region demonstrates an attraction to in-phase coordination during intra- and interpersonal coordination.

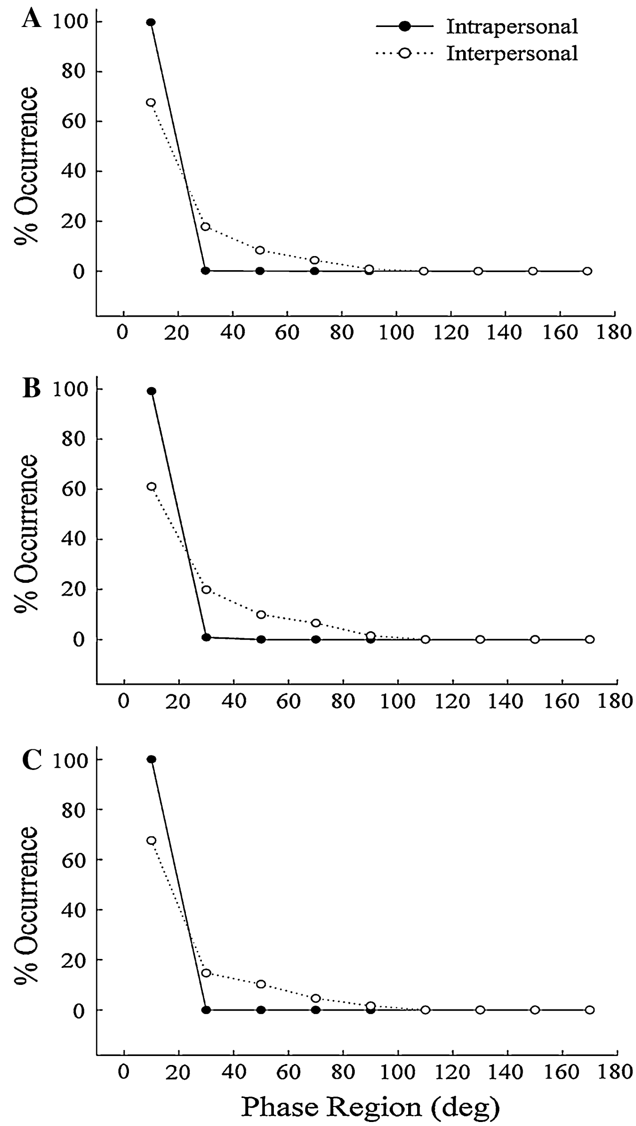

Fig. 5 Percent occurrence of relative phase angles (deg) for intra- and interpersonal coordination. The three levels of target ID are presented in the three panels (**a** easy–easy; **b** easy–hard/hard–easy; **c** hard–hard)

Mean SD of relative phase was analyzed with a 2 (Coordination: intra- and interpersonal) × 3 (Index of Difficulty: easy-easy = 3.17, mixed = 6.17, and hard-hard = 9.17) repeated-measures ANOVA. Analysis revealed a significant main effect of Coordination, $F_{(1,7)} = 17.58$, $P < .05$, $\eta^2 = .72$; SD of relative phase (Fig. 6) were lower for intrapersonal tasks (6°) than for interpersonal tasks (26°). All other effects were non-significant ($P > .05$).

Cross-spectral coherence

Mean coherence data were collapsed across trials of mixed targets (i.e., easy-hard and hard-easy pairings) due to

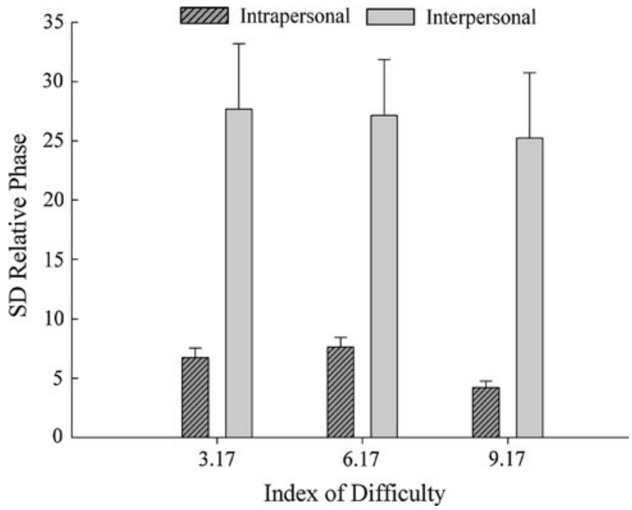

Fig. 6 Mean SD of relative phase (deg) for intra- and interpersonal coordination across all levels of combined ID

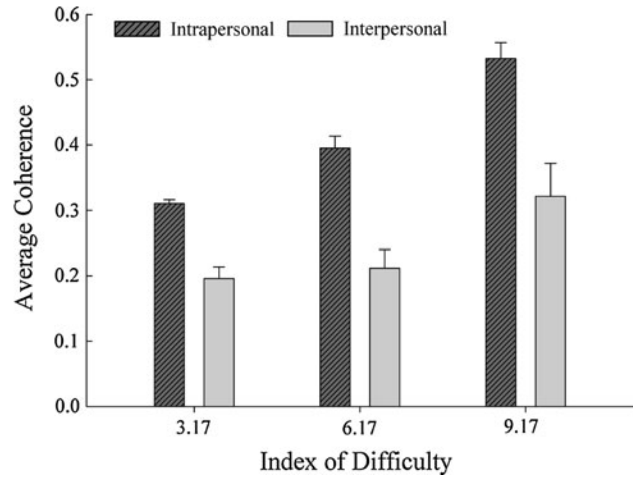

Fig. 7 Mean cross-spectral coherence across all levels of combined ID for both intra- and interpersonal coordination

non-significant *t*-tests (all *ps* > .05). Thus, mean coherence was analyzed with a 2 (Coordination: intra- and interpersonal) × 3 (Index of Difficulty: easy–easy = 3.17, mixed = 6.17, and hard–hard = 9.17) repeated-measures ANOVA. The analysis revealed a significant main effect of Coordination, $F_{(1,7)} = 55.51$, $P < .05$, $\eta^2 = .88$, where the mean coherence went from .41 (intrapersonal) to .25 (interpersonal). The main effect of Index of Difficulty was also significant, $F_{(2,14)} = 38.10$, $P < .05$, $\eta^2 = .85$, where the mean coherence was .25 for easy-easy trials, .31 for mixed targets (easy-hard & hard-easy), and .43 for hard-hard pairs. This main effect suggests that as Index of Difficulty increased the degree of coordination also increased. The analysis also revealed a significant interaction of Coordination by Index of Difficulty, $F_{(2,14)} = 6.58$, $P < .05$, $\eta^2 = .49$. To assess the source of the interaction, *t*-tests were used to determine differences between target pairings within a condition. As is displayed in Fig. 7, the analysis revealed no significant difference between easy-easy and mixed target pairings for interpersonal tasks; values were significantly different between all other pairings.

Discussion

The present study sought violations of Fitts' law during interpersonal rhythmic tapping. Previous studies have shown that there are systematic violations of Fitts' law when participants perform coordinated aiming tasks to targets of unequal difficulty (Fowler et al. 1991; Kelso et al. 1979; Marteniuk et al. 1984); in each of these studies, the MT of hand moving to the easier target was lengthened, making it more similar to the MT of the hand moving to the more difficult target. Participants in the present experiment, then, performed intra- and interpersonal rhythmic tapping between target pairs that varied in difficulty (ID). Fitts' law was similarly violated for the hand aimed at an easy target ID for both intra- and interpersonal conditions with mixed target IDs. Paired limbs demonstrated an emergent tendency to perform cooperatively. Because coordination occurred across a visual medium in the interpersonal conditions—where there is no centralized controller—we will consider the position that coordination emerges from non-centralized processes (Amazeen et al. 1995; Richardson et al. 2005, 2007; Schmidt et al. 1990).

Non-centralized control

In both intrapersonal and interpersonal conditions, the two oscillating limbs coordinated with each other, even when the tasks performed were not identical. It has been suggested that such bimanual violations of Fitts' law result from programming interference or neural crosstalk (Marteniuk et al. 1984; Rosenbaum et al. 1986), which leads to temporal invariance or an assimilation effect between the hands (Schmidt et al. 1979; Schmidt 2003). However, visually coupled dyads lack a shared controller, which eliminates the possibility that centralized programming creates the invariant timing effect.

Addendums to centralized and information-processing theories have been proposed to explain the spontaneous coordination of a dyad by pointing toward the mirror neuron system (MNS) as a potential physiological grounding for perception and action (Sebanz et al. 2003, 2006). The MNS responds similarly to both self-produced and observed movements. The assumption, then, is that perceiving another individual's movements induces subsequent neural firing in the perceiver. Such neural firing would simulate another actor's movements, thereby creating a common motor coding (i.e., interference) within the dyad. This interference has been demonstrated even when the other actor's movements are incongruous, but only when the other actor is human; these effects disappear when coordinating with a robotic arm (Kilner et al. 2003).

Approaches that rely on neural simulations, however, are not always clear regarding the nature of the neural simulation (Rizzolatti and Craighero 2004; Rizzolatti et al. 2001). These explanations do not specify whether such common coding (or the MNS) serves as a predictive or retrospective function. In fact, researchers still question whether it is better to consider these neural simulations as 1:1 neural mappings or a more general tuning of perceiver–actor interactions (Marsh et al. 2006; Richardson et al. 2009; Turvey 1977). Further, the present results—specifically those for mixed ID tasks—suggest that such simulations are not of the 1:1 variety; otherwise one would expect greater superimposition of movement amplitude (see Schwartz et al. 1995). Alternatives to 1:1 neural mappings generally involve concepts such as a soft assembly of coupled interactions (Amazeen et al. 1997; Schmidt et al. 1993; Scholz and Kelso 1990; Turvey 1990), which imply non-centralized processes. The evidence of interpersonal coordination in the present experiment, then, suggests that coordination emerges from a more general dynamic interactive coupling of the limbs (see also, Richardson et al. 2005; Schmidt et al. 1990). Although these results provide support for a non-centralized approach, no single study can make this distinction. However, with regard to theories of joint-action and neural simulation, these results implicate dynamic informational coupling as a constraint on potential neural correlates or simulations. We would like to suggest, based on the similarities across coordination conditions, that this principle applies to both intra- and interpersonal coordination.

Interpersonal coordination

If the coordination of limbs (each with individual tendencies) is reflective of a coupled oscillator system (Von Holst 1937/1973), then coordinated movements should demonstrate an attraction to stable patterns (Amazeen et al. 1998; Kelso 1984; Schmidt et al. 1990). Specifically, coupling of the limbs should lead to relatively stable patterns of either in-phase or anti-phase (Kelso 1984). The relative phase results support these predictions. The distribution of intrapersonal task phase angles revealed that all values clustered around the 0° region (in-phase). Across all target pairings for interpersonal tasks, the majority of phase angles fell in the 0° region. The remaining angles were distributed across the two neighboring regions. It is worth noting that other studies of interpersonal coordination have found relative phase angles distributed across all regions (0–180°) even when attention was focused on the other participant (Richardson et al. 2005, 2007; Schmidt and O'Brien 1997). However, in the current study only the two regions neighboring 0° were visited.

The coherence results provided a measure of the strength of coordination. Across the intra- and interpersonal conditions, these results showed a stronger coordination tendency within a person. Specifically, coherence was greater in intrapersonal coordination than it was in interpersonal coordination. Similar findings were observed in the mean SD of relative phase; however, the SD of relative phase only measures its stability, not the strength of coordination. Such findings suggest a possible role for centralized control mechanisms. Although it would be tempting also to conclude that this difference suggests a superiority of anatomical over visual coupling (see discussions in Amazeen et al. 2008; Mechsner et al. 2001), the present design does not allow us to make such conclusions. Anatomical coupling was only present in the intrapersonal conditions; visual coupling was potentially available in both intra- and interpersonal conditions. It may be that the addition of anatomical coupling strengthened already present influences of visual coupling. Despite the differences between intra- and interpersonal coordination, though, the coherence values in both increased as a function of ID. This result suggests that increasing task difficulty strengthens coordination. The implications of this finding are more apparent when considered in light of the IP results.

The Index of Performance (IP) results suggest that some of the differences in coordination evident in the coherence data may follow differences in attention. The first and most obvious finding was that IP was greater for interpersonal than intrapersonal coordination. This finding indicates that a system composed of two individuals, with two nervous systems, processed information more quickly than a system composed of one individual with one nervous system. This highlights the proposal that processes underlying coordination are not the programming of individuals, but rather processes that emerge across the coordinated system. The more surprising and potentially informative result was that IP increased with increases in task difficulty. Participants unimanually or in pairs (compared to bimanual tasks) processed information more quickly while performing a more difficult task. This suggests that more resources (for example, attention) were devoted to the more difficult tasks. Other studies have demonstrated that giving one hand a more difficult task leads to a shift in attentional resources and decreases coordination variability (Amazeen et al. 2005, 2008). Although there was no significant decrease in coordination variability (measured by SD of relative phase) in the present study, there was a significant increase in coordination strength (measured by coherence). The more demanding task (as measured by ID), then, may have required more attention, thereby strengthening coordination.

Conclusions

Previous research has shown that Fitts' law is violated during bimanual aiming to targets of unequal difficulty (Fowler et al. 1991; Kelso et al. 1979; Marteniuk et al. 1984). The present study extended these findings by demonstrating that Fitts' law is violated similarly for intra- and interpersonal rhythmic tapping. Bimanual coordination was evident despite differing task demands between hands and, in the interpersonal condition, the lack of a centralized mechanism. Consistent with extant research and suggestions (Richardson et al. 2005; Schmidt et al. 1990), we propose that the dynamical approach offers an explanation appropriate to capture such emergent coordination. The advantage of a non-centralized account is that predictions about future behaviors are attainable through models of physical systems (i.e., coupled oscillators), wherein neural and biomechanical factors facilitate coordination within the boundaries of lawful regularities (Kelso 1995; Schmidt and Richardson 2008).

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