Different Stable Patterns between Intra- and Inter-personal Systems: Experimental Study on Inter-limb Tapping Coordination

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Abstract

To reveal the differences between intra- and inter-personal systems in terms of the perceptual effect on the stability of inter-limb coordination, the present study conducted a finger-tapping experiment in in-phase and anti-phase mode. We investigated a between-subjects factor (the intra-/inter-personal condition), and a within-subject factor (the phase mode). In the intra-personal condition, participants bimanually tapped their index fingers, paced by a metronome, with the frequency gradually increasing from 1 Hz to 3 Hz. In the inter-personal condition, pairs of participants were asked to perform the same task, but to use their right or left index finger, while sitting side-by-side and looking at each other's fingers moving. Analysis showed that the average number of phase transitions, average time-to-transition and standard deviation of the relative phase differed between the intra-personal system and inter-personal system. Some results do not agree with the predictions of theoretical model proposed in previous studies on inter-limb coordination.

Keywords: Inter-limb coordination; Finger Tapping Task; Perceptual Effect; Dynamical Systems Approach

Introduction

To reveal the differences between intra- and inter-personal coordination systems, a finger-tapping experiment was conducted in which two phase modes (in-phase and anti-phase) were manipulated as a factor. The present study had two objectives. One objective was to reveal the role of perceptual information in inter-limb coordination. For this, we conducted a finger-tapping experiment, comparing the intra-personal condition with the inter-personal condition. Because the tapping task required participants to utilize visual, auditory, and haptic information (e.g., looking at a moving finger, listening to auditory metronome stimuli as well as the sounds of tapping, and touching the surface of the desk), the effect of multi-modal perceptual information could be examined (Kodama and Furuyama, 2010). We investigated not only the intra-personal system, which involves neural and mechanical coupling between limbs, but also the inter-personal system, which involves visual coupling through watching the other's movements. We could thus focus on the perceptual effect on inter-limb coordination. The other objective was to see how generally the existing model on human inter-limb coordination, called the Haken-Kelso-Bunz (HKB) model, could be applied to human inter-limb coordination in the intra-personal system and in the inter-personal system.

The first application of self-organization theory to human inter-limb coordination was attempted by Scott Kelso (Kelso, 1984) and his colleagues (Haken et al., 1985). Since then, research on this topic has developed tremendously. In this approach, called *the dynamical systems approach*, the general findings are that bimanual coordination is more stable in the in-phase mode than in the anti-phase mode; one of the most important observations is that phase transitions take place unidirectionally from the anti-phase mode to the in-phase mode when the required oscillation frequency reaches or exceeds a critical point. These findings led to the proposal of a theoretical model, called the Haken-Kelso-Bunz (HKB) model (Haken et al., 1985).

The above findings have been confirmed for inter-personal coordinated movement (e.g., swinging of pendulums or legs) (Schmidt et al., 1990, 1998). Phase transitions in inter-personal systems indicate that visual information involves coordinated movement because inter-personal systems do not involve mechanical or neural couplings between limbs, unlike intra-personal systems. Schmidt et al. (1998) suggested that the self-organization principle of intra-personal systems governs inter-personal systems as well but that the coupling strength between limbs is stronger in intra-personal systems.

However, most studies on coordinated movement have dealt with either intra- or inter-personal coordination of a pair of oscillators (fingers, legs, pendulums, etc.) wiggling or swaying in the air; that is, these studies did not address the effect of haptic information in terms of contact on a surface of an environment.

On the other hand, in finger tapping studies, Mechsner et al. (2001) conducted an intra-personal four-finger tapping experiment in which the perceptual bias on bimanual coordination was investigated in terms of symmetry defined in visual, perceptual space. Although they found a perceptual bias on bimanual finger tapping, they did not reflect upon the implications of their findings on the HKB model. Some researchers (e.g., Takenaka and Ueda, 2003) conducted tapping experiments both in intra- and inter-personal conditions. These studies, however, did not compare the in-phase and anti-phase modes and did not investigate the frequency effect on the stability of movement.

As far as we can tell from a survey of the literature, no studies have compared intra-personal and inter-personal coordination in finger tapping from the perspective of dynamical systems as regards the in-phase mode and anti-phase mode and none has investigated the frequency effect as *a control parameter*. Therefore, we conducted a finger-tapping experiment to reveal the differences between intra-personal system and inter-personal system in terms of how multi-modal perceptual information affects the stability of tapping movements.

Method

Participants

A total of 30 healthy right-handed participants (15 males and 15 females) took part in the experiment, with 10 participants in the intra-personal condition and 10 pairs of participants (i.e., 20 participants) in the inter-personal condition. All participants were between 21 and 47 years of age (average age=26.9). The procedure was approved by the ethics committee at the National Institute of Informatics, where the experiment was conducted.

Apparatus

A computer-generated metronome produced beeps, each lasting 85 msec. The metronome frequency was increased gradually from 1 Hz to 3 Hz over a 30-s trial after an initial 3-s period at 1 Hz. The metronome was run on a personal computer (Apple MacBook2130/13.3), and the beep sounds were conveyed to the participants through headphones (Sony MDR-NC600D) at a comfortable volume adjusted for each participant. A camcorder (TK-C1380; Victor), as part of the motion analyzer system DKH Frame-DIAS II, videotaped the movements of the participants' index fingers at 60 fields per second through the two-dimensional motion capture function of the Frame-DIAS II. The tapping movements and auditory stimuli were recorded on a hard disk drive (HDD) (Sony HVR-DR-60).

Experimental Design and Procedure

The experiment was designed as a 2 × 2 factorial with one between-subjects variable, i.e., the intra-/inter-personal condition (Figure 1), and one within-subject variables, i.e., the phase mode (in-phase and anti-phase) (Figure 2).

Participants were each seated at a desk in front of the camcorder. The task was to tap either in in-phase mode (two fingers tapping in synchronization) or anti-phase mode (two fingers tapping alternatively) at a pace dictated by the auditory metronome. The participants were instructed to keep their eyes open and watch their tapping movements during a trial, and to complete one full movement cycle, an extension-and-flexion cycle, for each beat of the metronome. They were also instructed to maintain the initial mode of coordination as much as possible, but not at the expense of losing pace with the metronome, and not to resist if they felt a change in the coordination pattern as a result of the increased tapping frequency. In the anti-phase mode, they tapped alternatively: the left finger was tapped in synchronization with the metronome beat while the right finger was in syncopation. Each condition was repeated four times, and the order of the trials was arranged randomly.

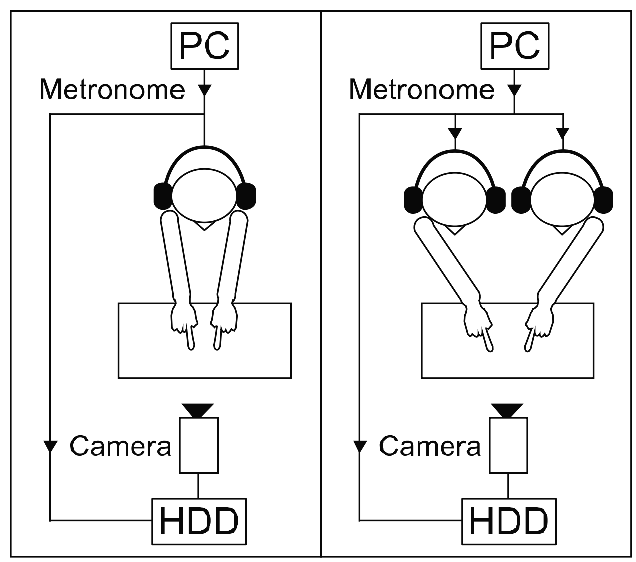

Figure 1: Experimental situation.
(left; intra-, right; inter-personal condition)

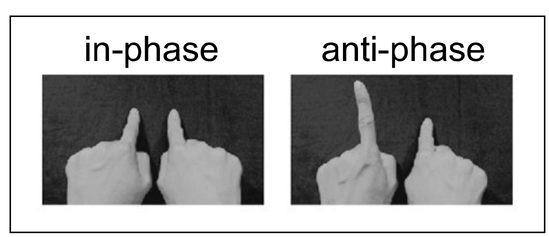

Figure 2: Phase mode.
(left; in-phase mode, right; anti-phase mode)

Data Analysis

In order to assess the stability of the tapping movement, we had previously analyzed the average number of phase transitions and average time-to-transition (Kodama and Furuyama, 2011). These indices, however, revealed only the total stability across a trial, i.e., *how many times* or *when* a phase transition occurred. In the present study, besides these two indices, we conducted a quantitative analysis of relative phase through a trial, to assess how progressively and how much fluctuation of movement increased or decreased. Relative phase is considered as an *order parameter* or, in other words, a *collective variable*, which represents the stability of a system. Thus, the phase transition should be described as a change in the relative phase from the perspective of the dynamical systems approach. In the present study, to assess the effect of frequency on performance, the relative phase was calculated and the standard deviation of the relative phase was obtained with respect to six 5-sec intervals.

Average number of phase transitions To measure the stability of movement in terms of temporally global stability, the average number of phase transitions was obtained as follows. When the right and left index fingers tapped together within a time window of 67 msec, derived from the video camera's frame rate, the tapping was categorized as being in the in-phase mode. When the time interval between one finger's peak of flexion (tap) and the other finger's peak of extension was within a time window of 67 msec, the tap was considered to be in the anti-phase mode. We considered that a phase transition would take place only if the taps in the opposite phase mode occurred at least five times in a row. The average number of phase transitions was obtained by counting the number of phase transitions in each of the phase mode conditions for each participant and each pair of participants.

Average time-to-transition We calculated the average time-to-transition in order to measure the temporally global stability, following a previous study's method (Riek and Wooley, 2005). The time-to-transition of a trial in which a phase transition occurred was defined as the interval from the start of the trial to the first tap in the opposite phase mode. The time-to-transition of a trial in which no transition occurred was defined as 30 s.

Relative Phase Analysis Besides two temporally global indices, we also calculated the relative phase between taps using standard procedures (e.g., Carson, 1995), in order to measure the temporally local stability of movement. To assess the effect of frequency on performance, each trial was separated into six equal time intervals of 5 s each (Riek and Wooley, 2005). The standard deviation of relative phase (SD ϕ) was calculated in each time interval. SD ϕ reflects the stability of performance.

Results

Average number of phase transitions

Figure 3 shows the average number of phase transitions as a function of the intra-/inter-personal condition and phase modes. In the intra-personal condition, no transition was observed in the in-phase or anti-phase mode conditions; that is, there was no difference in the average number of phase transitions between two phase modes. In the inter-personal condition, no transition was observed in the in-phase mode condition, but it occurred an average of 2.5 times in the anti-phase one; that is, the transition occurred more often in the anti-phase mode than in the in-phase mode. In the anti-phase mode condition, transitions occurred more often in the inter-personal system than in the intra-personal condition.

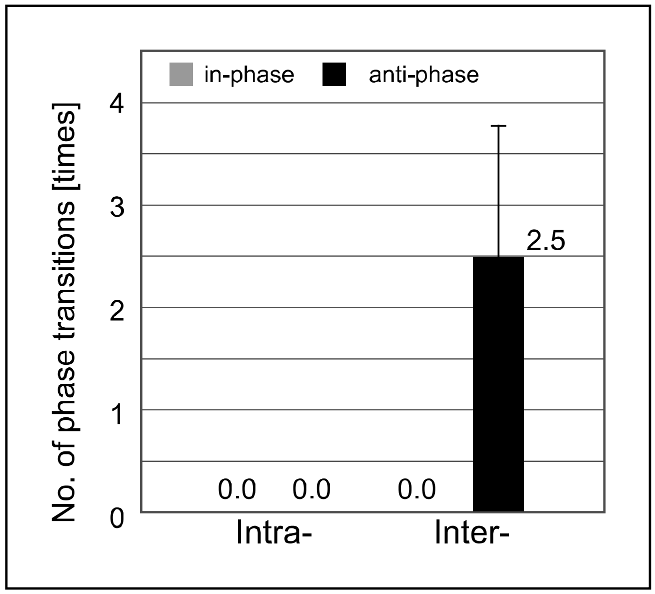

Figure 3: Average number of phase transitions.

Time-to-transition

Figure 4 plots time-to-transition as a function of the intra-/inter-personal condition and phase modes. In the intra-personal condition, the time-to-transition was 30 sec in both modes; that is, the time-to-transition between the two modes had no difference. In the inter-personal condition, the time-to-transition was on average 29.9 s in the in-phase mode and 26.7 s in the anti-phase one; that is, it was shorter in the anti-phase mode than in the in-phase one. In the anti-phase mode condition, the time-to-transition was revealed to be shorter in the inter-personal system than in the intra-personal one.

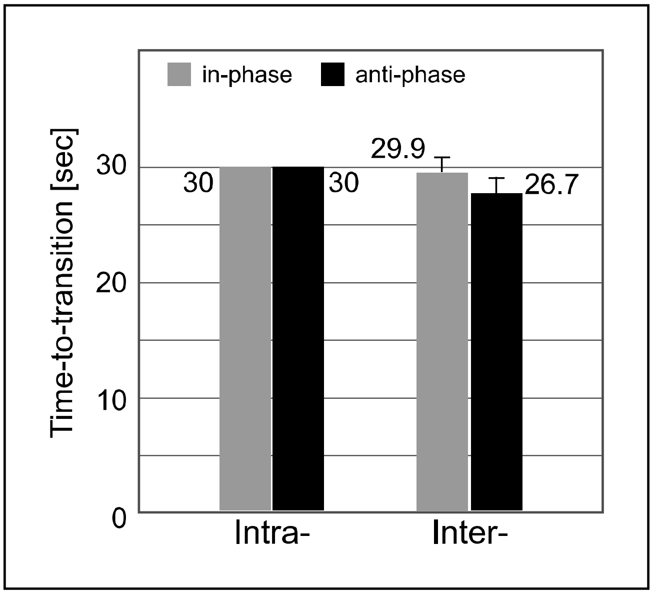

Figure 4: Average time-to-transition.

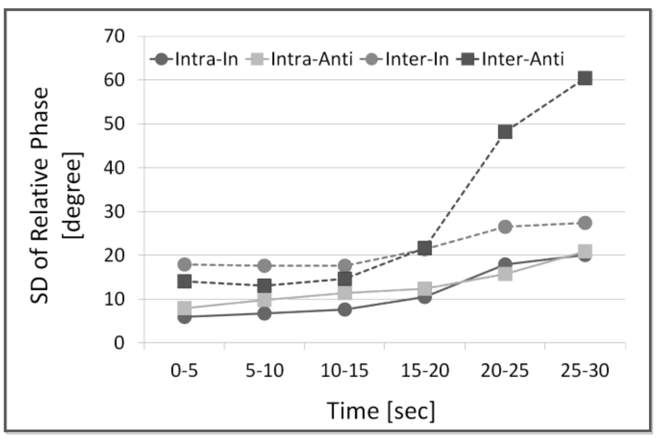

Figure 5: SD of relative phase.

SD ϕ

Figure 5 shows the standard deviation of the relative phase as a function of elapsed time of the trial (grouped into six five-second duration), equivalent to the frequency of movement. A three-way ANOVA (intra-/inter-personal condition (2) x phase mode (2) x frequency (6)) conducted on the SD ϕ confirmed the main effect of the intra-/inter-personal condition ($F(1,9)=48.186$, $p<.001$), phase mode ($F(1,9)=34.097$, $p<.001$), and frequency ($F(1,9)=100.841$, $p<.001$). It also revealed significant interactions: intra-/inter-personal × phase mode ($F=(1,9)=14.338$, $p<.005$), intra-/inter-personal × frequency ($F=(1,9)=16.996$, $p<.001$), phase mode × frequency ($F=(1,9)=19.863$, $p<.001$), and intra-/inter-personal × phase mode × frequency ($F=(1,9)=28.746$, $p<.001$).

The simple main effect test for the intra-/inter-personal × phase mode interaction revealed that there was no significant difference in SD ϕ between in-phase mode and anti-phase mode in the intra-personal condition ($F=(1,9)=2.107$, N.S.)

Discussion

Intra-personal condition

In the intra-personal condition, neither the average number of phase transitions, average time-to-transition nor SD ϕ differed between the in-phase and anti-phase modes. This result did not agree with the prediction of the HKB model (Haken et al., 1985) that the stability of movement is higher in the in-phase mode than in the anti-phase one. It is possible that the range of the metronome frequency did not cover the critical frequency. But this is not the only possibility that contributed the result. We need to consider the contribution of 1) haptic feedback and 2) dynamical relation between inter-limb coordination systems and posture. On the basis of these two possibilities, we suggest two hypotheses to explain why such an unexpected result was obtained.

The first hypothesis concerns perceptual information (e.g., haptic information). Unlike the inter-limb coordination task that many previous studies conducted, e.g., wiggling fingers or swinging pendulums and legs, the participants in this study were required to tap on the surface of a desk, so haptic information was available at the time of the tapping. Kelso et al. (2001) reported that haptic information can stabilize finger extension-and-flexion movement; therefore, we suppose that this kind of haptic information may help to stabilize the anti-phase mode tapping movement.

The second hypothesis is that the posture may stabilize the finger tapping movement. In the tapping task, participants could support their postures by touching a desk, and cancel their body sway each time they tapped, so both the posture and limb movement might be less affected by each fluctuation. On the other hand, in the wiggling task, they could not cancel the body sway caused by the limb extension-and-flexion movement, and the instability of the posture might cause the phase transition in the anti-phase movement.

Inter-personal condition

In the inter-personal condition, all indices of the average number of phase transitions, average time-to-transition, and SD ϕ showed that the stability of movement was higher in the in-phase mode than in the anti-phase one. This result was in agreement with the results of the previous study (Schmidt et al., 1998); that is, visual information might involve organization and stabilization of coordinated finger tapping movements. Moreover, as in the previous study (Schmidt et al., 1998), one participant in the inter-personal tapping experiment can always perceive the metronome beats as auditory information; that is, "on the beat" situation. On the other hand, the other participant must always tap at the midpoint between the metronome beats; that is "off the beat". The possibility still remains that the "off the beat" participant might couple with not visual information, i.e., the partner's finger's motion, but rather auditory information, i.e., the metronome beats. Further experiments have to be done in order to reveal which kind of perceptual information (e.g., visual or auditory) is involved in organization and stabilization of the inter-personal coordination systems.

Future direction

Recently, some researchers have referred to social coordination or joint-action in the inter-personal coordination paradigm from the cognitive perspective and the behavioral dynamics perspective (Schmidt et al., 2010). The cognitive perspective supposes there is a common coding of perception and action; that is, the same representations are used to perceive and perform an action. Additional evidence for such a common coding comes from discovery of mirror neurons in monkeys (Iacoboni et al., 1999), and mirror system in humans (Calvo-Merino et al., 2005). Although such mirror/common coding systems might be important for forming simple inter-personal coordination or imitating another's behavioral patterns, it is difficult to explain how such a coordination or synchronization occurs *in time*. Even if perception and action coding occurs in mirror systems in the brain, we cannot share those representations directly, because the central nervous systems are not connected to each other. Therefore, we suppose that not only cognitive approaches based on neuroscience but also behavioral dynamics perspectives inspired by the dynamical systems approach are needed to reveal the coordination mechanisms in inter-personal systems. To do this, it will be important to identify which kind of perceptual information is involved in organization and stabilization of inter-personal coordinated movement. Recently, Ulzen et al. (2010) tried to apply the HKB model to inter-personal coordination during a treadmill walking task and confirmed that the dynamical model for rhythmic inter-limb coordination does not readily apply, at least not generically or robustly, to inter-personal coordination when people are walking side-by-side on a treadmill. These results suggested the possibility that the HKB model does not necessarily apply to every system.

As important as identifying the perceptual information available in the inter-personal system, it is also important to compare the intra-personal and inter-personal coordination systems. Coey et al. (2011) attempted to compare these two systems and evaluate the relationship between the stability of intra-personal coordination and the emergence of spontaneous inter-personal coordination. However, against their hypothesis that the stability of the intra-personal coordination patterns would affect the emergence of inter-personal coordination in a pendulum-swinging experiment, the stability of the intra-personal coordination patterns did not affect the emergence of inter-personal coordination, and the emergence of inter-personal coordination did not affect the stability of the intra-personal coordination patterns (Coey et al., 2011). The present study did not clarify whether or not the stability of the intra-personal coordination patterns and the emergence of inter-personal coordination influence each other in the finger-tapping task. In the future, we should evaluate the possibility of such influences by means of analyzing the stabilities of both intra-personal and inter-personal systems.

Conclusions

The present study investigated the differences between intra- and inter-personal systems in terms of the perceptual effect on the stability of inter-limb coordination in a finger-tapping experiment. A between-subjects factor (intra-/inter-personal system) and a within-subject factor (phase mode) were investigated. Standard deviation of relative phase revealed that the stability of the tapping movement differed for each factor and significant interactions among these factors. The stable pattern of the intra-personal system was different from that of the inter-personal system.

These findings require us to reconsider the perceptual effect on inter-limb coordination and its theoretical model. In order to classify complicated factors (e.g., the effect of haptic information on anti-phase tapping movement in the intra-personal system), we should conduct further experiments in the future.

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