COGNITIVE NEUROSCIENCE

Bimanual motor coordination controlled by cooperative interactions in intrinsic and extrinsic coordinates

Takeshi Sakurada,[1,2,*] Koji Ito[2,†] and Hiroaki Gomi[1]
[1]NTT Communication Science Laboratories, Nippon Telegraph and Telephone Corporation, Wakamiya 3-1, Morinosato, Atsugi, Kanagawa, 243-0198, Japan
[2]Department of Computational Intelligence and Systems Science, Tokyo Institute of Technology, Yokohama, Kanagawa, Japan

Abstract

Although strong motor coordination in intrinsic muscle coordinates has frequently been reported for bimanual movements, coordination in extrinsic visual coordinates is also crucial in various bimanual tasks. To explore the bimanual coordination mechanisms in terms of the frame of reference, here we characterized implicit bilateral interactions in visuomotor tasks. Visual perturbations (finger-cursor gain change) were applied while participants performed a rhythmic tracking task with both index fingers under an in-phase or anti-phase relationship in extrinsic coordinates. When they corrected the right finger's amplitude, the left finger's amplitude unintentionally also changed [motor interference (MI)], despite the instruction to keep its amplitude constant. Notably, we observed two specificities: one was large MI and low relative-phase variability (PV) under the intrinsic in-phase condition, and the other was large MI and high PV under the extrinsic in-phase condition. Additionally, using a multiple-interaction model, we successfully decomposed MI into intrinsic components caused by motor correction and extrinsic components caused by visual-cursor mismatch of the right finger's movements. This analysis revealed that the central nervous system facilitates MI by combining intrinsic and extrinsic components in the condition with in-phases in both intrinsic and extrinsic coordinates, and that under-additivity of the effects is explained by the brain's preference for the intrinsic interaction over extrinsic interaction. In contrast, the PV was significantly correlated with the intrinsic component, suggesting that the intrinsic interaction dominantly contributed to bimanual movement stabilization. The inconsistent features of MI and PV suggest that the central nervous system regulates multiple levels of bilateral interactions for various bimanual tasks.

Introduction

We can perform many kinds of skillful motor tasks with the bilateral hands or fingers. To explore the motor coordination mechanisms, the stability evaluated by variability of the relative phase between bimanual movements (Kelso *et al.*, 1986) has often been examined. A number of studies have shown that bimanual movement with simultaneous activations of homologous muscles (i.e. intrinsic in-phase) is more stable than that with reciprocal activations of those muscles (i.e. intrinsic anti-phase) (Kelso, 1984; Carson, 1995; Semjen *et al.*, 1995). Therefore, the relative phase in intrinsic muscle coordinates is a critical factor in bimanual movements.

However, extrinsic visual coordinates are also important for motor coordination (Swinnen, 2002). For instance, Swinnen *et al.* (1997) suggested coordinative constraints in extrinsic visual coordinates representing movement directions as well as in intrinsic muscle coordinates. Isodirectional movements (i.e. extrinsic in-phase) are more stable than non-isodirectional movements (i.e. extrinsic anti-phase) between the hands (Temprado *et al.*, 2003; Salesse *et al.*, 2005; Meesen *et al.*, 2008).

Along with the stability features, intermanual interference during bimanual movements has also been examined as a signature of motor coordination. Even though performers were requested to move their hands with different spatial patterns, bilateral movement amplitudes (Spijkers & Heuer, 1995; Heuer *et al.*, 1998; Heuer, 2006), trajectory patterns (Franz *et al.*, 1991), or directions (Diedrichsen *et al.*, 2004; Heuer, 2006) became assimilated. For instance, Heuer *et al.* (1998) found that the short movements for one hand become longer, whereas long movements for the other hand become shorter. In addition, the movement of the non-dominant hand is assimilated into that of the dominant hand more strongly than that in the opposite direction (Semjen *et al.*, 1995; Byblow *et al.*, 2000).

Correspondence: Hiroaki Gomi, as above.
E-mail: gomi.hiroaki@lab.ntt.co.jp

*Present address: Functional Brain Science Laboratory, Center for Development of Advanced Medical Technology, Jichi Medical University, 3311-1, Yakushiji, Shimotsuke, Tochigi, 329-0498, Japan

†Present address: Tokyo Metropolitan Institute of Medical Science, Motor Disorders Project, 2-1-6, Kamikitazawa, Setagaya-ku, Tokyo, 156-8506, Japan

These previous studies therefore suggested that the temporal and spatial couplings during bilateral movement are governed by intrinsic muscle and extrinsic visual coordinates (Swinnen *et al.*, 1997; Swinnen, 2002; Swinnen & Wenderoth, 2004), which would be formed by various neural interactions between bilateral motor systems (Eliassen *et al.*, 1999; Carson, 2005). However, it is not yet clear how multiple bilateral interactions are regulated in various bimanual motor tasks.

Based on these previous observations, we posed the question of whether an intrinsic interaction synchronizing homologous muscles and an extrinsic interaction synchronizing the movement directions are exclusively switched or additively combined according to bimanual motor tasks. To examine this question, we conducted two experiments using assimilation phenomena in movement amplitude induced by visual perturbations. In experiment 1, we observed different patterns of bimanual coordination characterized by the intermanual interference and coordination stability. In experiment 2, we decomposed the intermanual interference into the intrinsic and extrinsic interaction components using a multiple-interaction model. The model demonstrated a relatively dominant contribution of intrinsic components in stabilizing bimanual movements, although intrinsic and extrinsic components were flexibly regulated according to the task requirements. Inconsistent modulation features of the intermanual interference and coordination stability across the motor tasks suggest that the central nervous system regulates multiple levels of bilateral interactions for various bimanual tasks. A part of the data of experiment 1 was preliminarily analysed and reported elsewhere (Sakurada *et al.*, 2009).

Experiment 1: modulation of intermanual interference and coordination stability in different bimanual motor patterns

Materials and methods

Participants

Seventeen healthy, right-handed people (10 females; mean age 27.5 years, SD 4.9 years) participated in this experiment. All participants gave written informed consent prior to participation. Experimental protocols were carried out in accordance with the Declaration of Helsinki and were approved by the NTT Communication Science Laboratories Research Ethics Committee.

Experimental setup

Figure 1 shows the experimental setup. Participants were seated on a height-adjustable chair in front of a desk, and their heads were placed on a chin support to fix the head position. The participants gripped handles attached to the desk with the right and left hands. The distance between the handles was 15 cm. Reflective spheres were attached to the right and left index fingertips for detection of their positions with a motion capture system (ProReflex, Qualisys, Sweden) with sampling frequency of 250 Hz. A monitor showing visual stimuli was placed approximately 23 cm above the hands, and participants could not see their hands while they performed the experimental tasks. As shown in Fig. 1A, the monitor displayed a fixation cross at the centre, two pairs of turning points (open circles) representing the endpoints of the cyclic finger movements, and guide cursors (rectangular shape) for leading the finger movements. In all experimental tasks, the four turning points were located at the same distance from the fixation cross to ensure
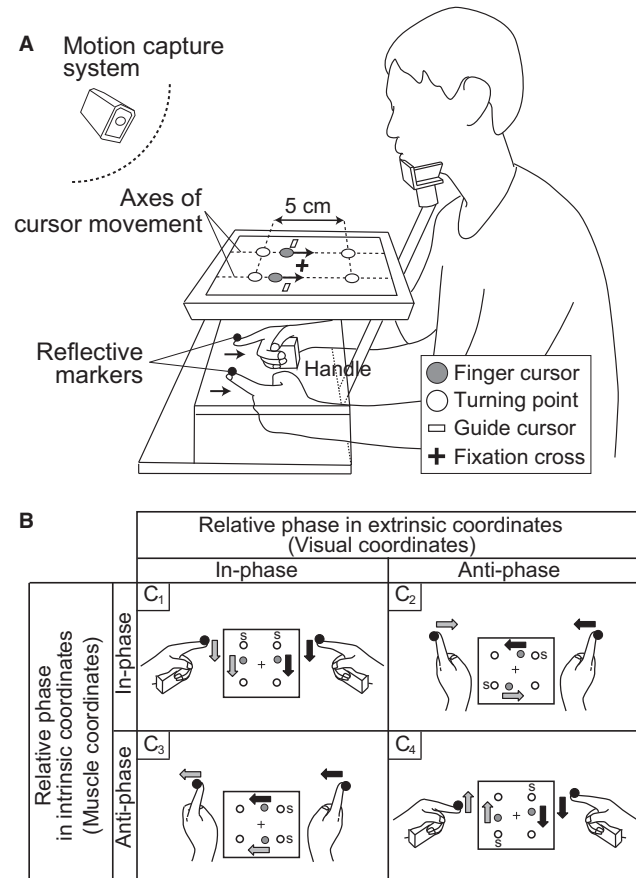

Fig. 1. Experimental setup. (A) The monitor showed real-time visual feedback of the bilateral finger movements. The participant was instructed to match the finger cursor with guide-cursor movement and to keep the left finger amplitude constant throughout a trial. In the post-phase of each trial, the cursor of the left finger was eliminated. (B) Four conditions of bilateral finger movements defined by the relative phases in intrinsic muscle and extrinsic visual coordinates. Orientation of the axis of cursor movement was set along the proximal–distal direction in C_1 and C_4 and along the left–right direction in C_2 and C_3. In C_2 and C_3, finger cursors of the right and left fingertips were displayed at the upper and lower sides of the fixation cross, respectively. In the illustrations depicting the task conditions, 's' indicates the start position of the cursors for the right and left fingers. The origin of the visual task field on the monitor is at the start position of the right finger's cursor.

nearly equal visibility of the turning points. The monitor also displayed two finger cursors representing the positions of the right and left fingertips (gray filled circles) along the direction parallel to the line connecting the two turning points for cyclic finger movements. The distance between the turning points for each finger-cursor movement was 5 cm on the monitor in all experiments. The ratio between the actual finger movements and finger-cursor movements was changed depending on the objective of the experiment; this will be explained in the *Visual cursor gains* section for each experiment.

As shown in Fig. 1B, we used four bimanual motor patterns (i.e. conditions) defined by relative phases in intrinsic and extrinsic coordinates (named as C_1, C_2, C_3 and C_4). The relative phase in intrinsic coordinates represents the synchronization between bilateral homologous muscles, i.e. when the homologous muscles of the two fingers (flexor or extensor) were activated simultaneously or alternately, we describe the bimanual movements as in-phase (C_1 and C_2 in

Fig. 1B) or anti-phase (C_3 and C_4 in Fig. 1B) in intrinsic coordinates. In contrast, with respect to extrinsic coordinates, these four conditions can be categorized differently. The relative phase in extrinsic coordinates represents the directions of bimanual movements, i.e. isodirectional or non-isodirectional finger movements are described as in-phase (C_1 and C_3 in Fig. 1B) or anti-phase (C_2 and C_4 in Fig. 1B) in extrinsic coordinates.

Bimanual visuomotor task

Participants were asked to perform cyclic extension-flexion movements at 0.5 Hz with the right and left index fingers. First, the participants moved the finger cursors to each start position when the finger cursors appeared on the monitor. The start position of the right finger was defined as a finger extension posture in all four conditions and that of the left finger was varied according to the conditions (extension posture in C_1 and C_2; flexion posture in C_3 and C_4). After a delay period (2 s), guide cursors appeared next to the start positions of the corresponding finger cursor and then started to move between the turning points cyclically. Guide-cursor movements were defined by a minimum jerk trajectory (Flash & Hogan, 1985). We instructed participants to continuously move their fingers in order to match the finger-cursor movements to the guide-cursor movements during each trial (eight cycles).

Visual cursor gains

In the visuomotor tasks, we modified the ratio of the actual fingertip movements to finger-cursor movements by altering the visual cursor gain (VG). As intermanual interference during bimanual movement mainly occurs from the dominant hand to the non-dominant hand (Semjen *et al.*, 1995; Byblow *et al.*, 2000), we applied visual perturbation (i.e. VG change) to the right-finger cursor. The VG settings in experiment 1 were as follows.

Visual cursor gain for the right-finger cursor

Pre-phase (from the first to fourth cycles). The finger cursor moved 5 cm on the monitor for the 2.5 cm fingertip movement in the direction parallel to the axis of cursor movement. In this setting, VG was 2.

Post-phase (from the fifth to eighth cycles). Three types of trials were given with different VGs. In the first type of trial ('VG_C' trial), VG of the post-phase was not changed from that of the pre-phase (i.e. VG = 2). In the other two types of trials, VG was suddenly changed (decreased or increased) at the start of the fifth cycle. In the 'VG−' trial, VG was decreased to 1.25 from 2, and then the desired amplitude of the right fingertip became 4 cm. In the 'VG+' trials, by contrast, VG was increased to 5 from 2 and then the desired amplitude of the right fingertip became 1 cm. As a result, the magnitude of desired motor correction in the post-phases was 1.5 cm in both types of trials (4−2.5 cm for VG− trials; 1−2.5 cm for VG+ trials). The participants were asked to adjust the right finger's movement so as to match the finger cursor to the guide cursor as quickly as possible when a visual error (i.e. location mismatch between finger and guide cursors) occurred on the monitor. Note that VG+/− trials were randomized to prevent participants preparing for gain change (see *Experimental protocol* for details), and there was no change in the posture of the right finger at the movement start in all VG trials.

Visual cursor gain for the left-finger cursor

Pre-phase. Along with the right-finger cursor, VG of the left-finger cursor was 2, and the desired amplitude of the left fingertip was 2.5 cm.

Post-phase. The left-finger cursor was eliminated. Without visual feedback of left-finger movements, participants were instructed to keep the amplitude of left-finger cyclic movement constant (i.e. 2.5 cm) in all types of trials.

Experimental protocol

First, the participants completed eight blocks, each of which consisted of five VG_C trials. The conditions, C_1–C_4, were assigned to the first four blocks in random order, and then all four conditions were assigned in reversed order in the last four blocks to reduce the order effect in each participant (e.g. C_2–C_3–C_1–C_4–C_4–C_1–C_3–C_2).

Next, the participants experienced visual-gain-change trials. One block consisted of 10 trials (five VG− trials and five VG+ trials), and the order of these 10 trials was randomized. Therefore, the participants could not predict which visual perturbation (VG− or VG+) was given in each trial. Eight blocks were conducted with the same block-order design as that for the VG_C trials (e.g. C_2–C_3–C_1–C_4–C_4–C_1–C_3–C_2).

Data analysis

Task performance

To evaluate the performance of bilateral finger movements, the visual error (VE) between the finger cursor and guide cursor on the monitor at the positional peaks in each cycle was calculated as follows

$$\text{VE}_{\text{side}}^{\text{cycle}} = \text{PK}_{\text{finger}} - \text{PK}_{\text{guide}} \tag{1}$$

Here, $\text{PK}_{\text{finger}}$ and PK_{guide} are positional peaks of the finger cursor and guide cursor on the monitor at each cycle, respectively, and 'side' denotes right or left finger. We also calculated the variance of all $\text{VE}_{\text{side}}^{\text{cycle}}$ of the one to four cycles (pre-phase) in all trials in every condition (C_1–C_4) for each participant (var VE_R^{pre}, var VE_L^{pre}), as a representative index of task difficulty in the corresponding condition because movement variability increased with task difficulty. Note that this index simply represents the variability of the finger movement amplitude as PK_{guide} is constant during the pre-phase. Therefore, if this index is different among the C_1–C_4 conditions, the task difficulty would be different among the conditions.

Amplitude change

Figure 2 shows the typical behavioural results for C_1 in experiment 1 for a particular participant. The movement amplitude of each cycle in a trial was calculated from the difference between positional peaks (proximal/distal or left/right) along the axis of cursor movement (Fig. 2A). In the post-phase, the participant could keep the amplitude of the right finger (VG_C trial shown as a solid line in Fig. 2A) or smoothly modify it (VG− and VG+ trials shown as solid lines in Fig. 2B and C) as required. In contrast, although the participant was asked to keep the amplitude of the left finger constant, the amplitude of the left finger changed unin-
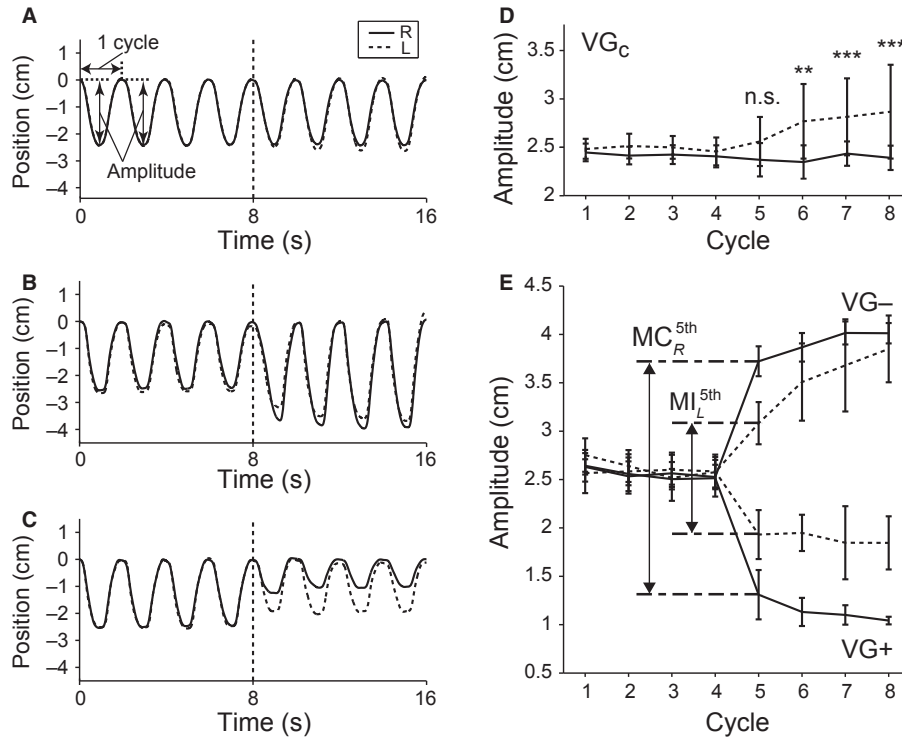
FIG. 2. Typical movement profiles of a particular participant in C_1 of experiment 1. Mean movement profiles of right (solid lines) and left (dotted lines) fingertips in (A) VG_C, (B) VG− and (C) VG+ trials. The amplitude of each cycle was defined by the difference between adjacent positional peaks as indicated in A. Left-finger movement unintentionally changed against the task instruction. (D) Amplitude transitions of the right (solid line) and left (dotted line) fingertips in VG_C trials. Although the participant did not change the amplitude of the right finger voluntarily, the amplitude of the left finger increased gradually in the post-phase. Asterisks indicate significant amplitude increases compared with the mean amplitude in the pre-phase (**$P < 0.01$, ***$P < 0.001$). (E) Amplitude changes for VG− and VG+ trials and indexes of amplitude changes of the finger movements. MC_R^{5th}, amount of voluntary 'motor correction' of the right finger's amplitude at the fifth cycle; MI_L^{5th}, amount of unintentional 'MI' to the left finger's amplitude at the fifth cycle. These values are represented by the sum of absolute changes in VG− and VG+ trials by reference to the mean amplitude during the pre-phase. Error bars represent the SD across trials for this participant.

tentionally in the post-phase (dotted lines in Fig. 2A–C). These voluntary motor corrections of the right finger and unintentional motor interference (MI) to the left finger were also observed in the other participants.

Figure 2D and E shows an example of the amplitude transitions during the VG_C trials and during the VG− and VG+ trials in C_1, respectively. These amplitudes in each cycle were calculated from the temporal profiles of finger movements shown in Fig. 2A–C. To avoid a drift effect in characterizing unintentional MI (for details, see *Amplitude change* in Results section of experiment 1), we analysed the sum of mean amplitude changes of the right and left fingers at the fifth cycle in the VG− and VG+ trials as indexes of voluntary motor correction of the right finger (MC_R^{5th}) and unintentional MI to the left finger movement (MI_L^{5th}), respectively, according to the following equations (Fig. 2E)

$$MC_R^{5th} = \left| \bar{A}_R^{5th}(VG-) - \bar{A}_R^{pre}(VG-) \right| + \left| \bar{A}_R^{5th}(VG+) - \bar{A}_R^{pre}(VG+) \right| \tag{2}$$

$$MI_L^{5th} = \left| \bar{A}_L^{5th}(VG-) - \bar{A}_L^{pre}(VG-) \right| + \left| \bar{A}_L^{5th}(VG+) - \bar{A}_L^{pre}(VG+) \right| \tag{3}$$

Here, $\bar{A}$ denotes the trial mean of movement amplitude A of a corresponding cycle in a particular condition.

Bimanual coordination stability

Using the following equation proposed in a previous study (Kelso *et al.*, 1986), we calculated the relative phase at each moment by taking the difference between the phase angles of cyclic movements of both fingers, which was defined in the intrinsic coordinates

$$\phi = \theta_L - \theta_R = \tan^{-1}\left[\frac{dP_L/dt}{P_L}\right] - \tan^{-1}\left[\frac{dP_R/dt}{P_R}\right] \tag{4}$$

where θ_L and θ_R denote the phase angles of the left and right finger movements, P_L and P_R denote the positions of the left and right fingers after normalization in each cycle, and dP_L/dt and dP_R/dt are the normalized instantaneous velocities of the left and right fingers, respectively. To characterize the difference in bimanual coordination stability among all four conditions, we calculated the variability of the relative phase [phase variability (PV_ϕ^{cycle})] in each condition as follows

$$PV_\phi^{cycle} = \frac{1}{2}\left(\sqrt{\sum_t (\phi_{VG-} - \bar{\phi}_{VG-})^2/t} + \sqrt{\sum_t (\phi_{VG+} - \bar{\phi}_{VG+})^2/t} \right) \tag{5}$$

Here, t denotes the duration over which PV_ϕ^{cycle} is calculated [e.g. t: 8–10 (s) for fifth cycle], and $\bar{\phi}$ denotes the temporal mean of

relative phase for that duration. Note that a low PV_ϕ^{cycle} value denotes a high stability.

Statistical analysis

For VG_C trials, we applied a three-way repeated-measures ANOVA with the relative phase in intrinsic coordinates (in-phase and anti-phase), the relative phase in extrinsic coordinates (in-phase and anti-phase), and movement cycle (five levels: pre-phase, fifth, sixth, seventh and eighth) as within-subject factors to examine the amplitude changes of left and right fingers after the elimination of the left-finger cursor.

Two-way repeated-measures ANOVAS with relative phases in intrinsic coordinates (in/anti) and in extrinsic coordinates (in/anti) as within-subject factors were applied to the task performance (var VE_R^{pre} and var VE_L^{pre}), motor correction of the right finger (MC_R^{5th}), MI to the left finger (MI_L^{5th}) and coordination stability (PV_ϕ^{5th}). Bonferroni post-hoc tests were used to examine pairwise differences. We considered statistical significance to be $P < 0.05$.

Results

Task performance

To examine the task difficulty in C_1–C_4, we evaluated the amplitude variabilities of visual errors (VE_R^{pre} and VE_L^{pre}) over the cycles in the pre-phase of all trials in these four conditions by the two-way repeated-measures ANOVA (see Materials and methods). We did not find any significant main effects of relative phases in the intrinsic coordinates (var VE_R^{pre}: $F_{1,16} = 1.02$, $P = 0.33$; var VE_L^{pre}: $F_{1,16} = 0.06$, $P = 0.81$) and extrinsic coordinates (var VE_R^{pre}: $F_{1,16} = 0.44$, $P = 0.52$; var VE_L^{pre}: $F_{1,16} = 0.10$, $P = 0.76$). Furthermore, the Intrinsic × Extrinsic interaction was not significant (var VE_R^{pre}: $F_{1,16} = 0.84$, $P = 0.37$; var VE_L^{pre}: $F_{1,16} = 1.62$, $P = 0.22$), suggesting that clear differences in task difficulty were not observed among the four conditions.

Amplitude change

In VG_C trials, the participants were required to maintain the movement amplitude of their bilateral fingers. However, the left-finger amplitudes somehow increased gradually in the post-phase as an example of the C_1 condition in Fig. 2D. For right finger movements, no effect reached statistical significance (F-values < 2.50, P-values > 0.13) in the three-way ANOVA. For left-finger movements, by contrast, we found significant main effects of cycle ($F_{4,64} = 180.91$, $P < 0.000001$). In C_1, the mean amplitude in the pre-phase (2.49 cm) was not significantly different from that in the fifth cycle (2.50 cm, $P = 0.99$), but the amplitude from the sixth cycle significantly increased compared with the mean amplitude in the pre-phase (sixth: 2.65 cm, $P < 0.001$; seventh: 2.68 cm, $P < 0.0001$; eighth: 2.72 cm, $P < 0.000001$, Fig. 2D). Similarly, the gradual amplitude increases from the sixth cycles were observed in other conditions (C_2–C_4; sixth–eighth cycles: P-values < 0.0012), whereas they were not in the fifth cycles (P-values > 0.99). Note that statistical significances were also found in the main effect of extrinsic coordinates ($F_{1,16} = 12.96$, $P < 0.01$) and the interactions of Intrinsic × Cycle interaction ($F_{4,64} = 7.95$, $P < 0.0001$), Extrinsic × Cycle interaction ($F_{4,64} = 9.13$, $P < 0.00001$) and Intrinsic × Extrinsic × Cycle ($F_{4,64} = 11.75$, $P < 0.000001$), but we did

not examine these factors further because our focus was on the visual perturbation effects on finger movements.

The above cycle effect in VG_C trials of the left finger suggested that elimination of online visual feedback in the post-phase induced unintentional and gradual amplitude increase of the left finger (i.e. drifting effect). Therefore, during and after the sixth cycle in VG− and VG+ trials (Fig. 2E), the left finger's amplitude was affected not only by the intermanual interference but also by the drifting effect. To focus on the intermanual interference without contamination from the drifting effect, we evaluated the amplitude change in the fifth cycle in VG− and VG+ trials.

For MC_R^{5th} in VG− and VG+ trials, we did not find any significant main effect of Intrinsic ($F_{1,16} = 0.76$, $P = 0.40$) or Extrinsic ($F_{1,16} = 0.47$, $P = 0.53$). The Intrinsic × Extrinsic interaction ($F_{1,16} = 3.47$, $P = 0.08$) was close to significance, but a follow-up analysis by Bonferroni test did not find any significant difference (P-values > 0.26) between each pair of MC_R^{5th} in the four conditions. The results indicate that the participants evenly corrected the amplitude of the right finger according to VG changes regardless of hand postures or relative phases. In contrast, the left-finger amplitude changed unintentionally depending on the task conditions. For MI_L^{5th} in VG− and VG+ trials, we found significant main effects of Intrinsic coordinates ($F_{1,16} = 24.61$, $P < 0.001$) and Extrinsic coordinates ($F_{1,16} = 15.87$, $P < 0.01$). The Intrinsic × Extrinsic interaction was marginally significant ($F_{1,16} = 4.02$, $P = 0.062$). A follow-up analysis by Bonferroni test revealed that MI_L^{5th} in C_4 (0.22 cm) was significantly smaller than those in the other conditions (C_1: 0.89 cm, $P < 0.001$; C_2: 0.78 cm, $P < 0.01$; C_3: 0.65 cm, $P < 0.01$; Fig. 3A). The results indicate that the strength of the MI from the right to left finger would vary depending on the task conditions.

Bimanual coordination stability

For PV_ϕ^{5th} in VG− and VG+ trials, we found significant main effects of Intrinsic coordinates ($F_{1,16} = 19.83$, $P < 0.001$), but a main effect of Extrinsic coordinates ($F_{1,16} = 0.65$, $P = 0.43$) and
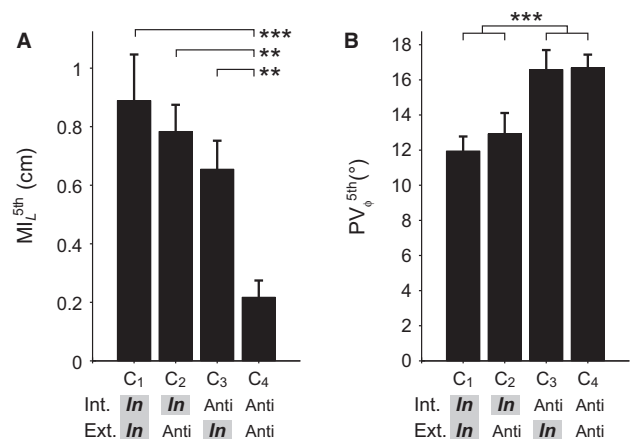

FIG. 3. Bimanual motor coordination characterized by the (A) MI and (B) coordination stability in experiment 1. (A) Although voluntary motor corrections of the right finger (MC_R^{5th}) were not different among the four conditions (data not shown), the unintentional MI to the left finger (MI_L^{5th}) in C_4 was significantly smaller than those in the other conditions. (B) Phase variability (PV_ϕ^{5th}) for each condition was calculated by averaging its values in VG− and VG+ trials. A lower PV_ϕ^{5th} value means stable bimanual movement. Error bars indicate the SE across the participants. **$P < 0.01$, ***$P < 0.001$.

Intrinsic × Extrinsic interaction ($F_{1,16} = 0.24$, $P = 0.63$) were not significant. A follow-up analysis of the Intrinsic main effect revealed that, in contrast to the results of MI_L^{5th} (i.e. only C_4 represented the small value; Fig. 3A), PV_ϕ^{5th} in C_1 (11.94°) and C_2 (12.93°) were significantly smaller than those in C_3 (16.95°) and C_4 (16.68°) as shown in Fig. 3B.

Although the coordination characterized by the intermanual interferences differed between C_4 and the other conditions, we can separate the four conditions into different categories (C_1 and C_2 vs. C_3 and C_4) based on the phase variability, i.e. these modulation patterns of MI_L^{5th} and PV_ϕ^{5th} depending on the bimanual motor patterns (C_1–C_4) suggest different underlying mechanisms of interactions characterized by intermanual interference and coordination stability.

Experiment 2: decomposition of intermanual interferences by a multiple-interaction model

In experiment 1, we found stronger interferences with high stability in the intrinsic in-phase conditions (C_1 and C_2), and stronger interference with low stability in the extrinsic in-phase and intrinsic anti-phase condition (C_3), i.e. stability and interference were not perfectly correlated with each other. These results lead to the hypothesis that the intermanual interference includes two different types of bilateral interaction components: one contributes to stabilizing bimanual movement and the other does not. To test this hypothesis, we conducted experiment 2 with several VGs. Using a multiple-interaction model, we tried to decompose the intermanual interference into the effects of motor correction and visual error of the dominant hand on the non-dominant hand. The experimental setup and bimanual visuomotor task (except for the VGs) were identical to those of experiment 1. Note that, as in experiment 1, to examine the unintentional MI caused by bilateral interactions, we evaluated several indexes at the fifth cycle (MC_R^{5th}, MI_L^{5th} and PV_ϕ^{5th}).

Materials and methods

Participants

Thirteen healthy, right-handed people (seven females; mean age 28.6 years, SD 6.7 years), who were different from the participants in experiment 1, participated in this experiment. All participants gave written informed consent prior to participation. Experimental protocols were carried out in accordance with the Declaration of Helsinki and were approved by the NTT Communication Science Laboratories Research Ethics Committee.

Visual cursor gains

The participants were instructed to move their fingers with the finger cursors before (pre-phase) and after (post-phases) the visual-cursor gain change, as in experiment 1. Note that the left-finger cursor was eliminated in the post-phase. We used three combinations of VGs (VG_1, VG_2, and VG_3) in the pre-phase and post-phase, as listed in the sixth and seventh column of Table 1. Each combination consisted of VG−/+ (visual gain decrease and increase) trials, and gain values *per se* (VG^{pre}, VG^{post}) were different across the combinations.

The errors just after the VG change can be represented in both visual and motor coordinates. The expected visual error between the guide cursor and the finger cursor of the right finger varied with VG in the pre-phase and post-phase, as listed in the second right-most column of Table 1. These expected visual errors satisfy the relationship $\underline{sVE}_{R1j}^{5th} = \underline{sVE}_{R2j}^{5th} < \underline{sVE}_{R3j}^{5th}$ in all four conditions, as shown in the right-most column of Table 1. Here, the $\underline{sVE}_{Rij}^{5th}$ denotes the sum of amplitudes of expected visual errors at the fifth cycles in the gain decrease and increase trials (VG−, VG_i+) ($i = 1$–3) of the C_j condition ($j = 1$–4).

In contrast, after changing the VG, appropriate motor correction of the right finger was required to reduce the visual error. As the desired amplitudes of the right finger in the pre-phase and post-phase in all VGs were planned as in the second and third columns of Table 1, the sums of required motor corrections in VG_i− and VG_i+ trials for each VG combination ($\underline{MC}_R^{5th}$) can be expected as in the fifth column of Table 1. These sums of required motor corrections ($\underline{MC}_{Rij}^{5th}$) would satisfy the relationship $\underline{MC}_{R1j}^{5th} < \underline{MC}_{R2j}^{5th} = \underline{MC}_{R3j}^{5th}$ in all four conditions. The desired amplitude of the left finger was 3.5 cm for all VGs in all four conditions, and the participants were also asked to keep the left finger's amplitude constant.

Experimental protocol

The participants completed 36 trials (randomized order) with six kinds of different VG (VG_1−, VG_2−, VG_3−, VG_1+, VG_2+ and VG_3+; six times for each VG) in each block. Eight blocks (twice for each of the four conditions, C_1–C_4) were conducted with the

TABLE 1. Combinations of VG (VG_i; $i = 1$–3) in experiment 2. Magnitudes of required motor corrections in VG− and VG+ trials are calculated from the difference between desired amplitudes in the post-phase (DA^{post}) and those in the pre-phase (DA^{pre}), and expected visual errors in VG− and VG+ trials are calculated from $DA^{pre} \cdot (VG^{post} - VG^{pre})$. Values in the fifth and right-most columns indicate the sum of required motor corrections ($\underline{MC}_R^{5th}$) and sum of expected visual errors ($\underline{sVE}_R^{5th}$), respectively

	Desired amplitude of right finger (cm)				Visual cursor gain of right finger			
	DA^{pre}	DA^{post}	Required motor correction (cm)	$\underline{MC}_R^{5th}$ (cm)	VG^{pre}	VG^{post}	Expected visual error (cm)	$\underline{sVE}_R^{5th}$ (cm)
VG_1−	3	4.5	+1.5	3.0	5/3	5/4.5	−1.67	6.67
VG_1+		1.5	−1.5			5/1.5	+5.0	
VG_2−	4	6	+2.0	4.0	5/4	5/6	−1.67	6.67
VG_2+		2	−2.0			5/2	+5.0	
VG_3−	3	5	+2.0	4.0	5/3	5/5	−2.0	12.0
VG_3+		1	−2.0			5/1	+10.0	

same block-order design as that in experiment 1 (e.g. C₂–C₃–C₁–C₄–C₄–C₁–C₃–C₂) to reduce the order effect in each participant.

Data analysis

Variances of visual error (i.e. var VE_R^{pre} and var VE_L^{pre}) were calculated to confirm the task difficulty in all conditions. In addition, to examine the multiple interactions during bimanual movements, we also calculated the amplitude changes (MC_R^{5th} and MI_L^{5th}), sum of visual errors (sVE_R^{5th}), and bilateral coordination stability (PV_ϕ^{5th}). All indexes were calculated by the same methods as in experiment 1.

Multiple-interaction model

We here assume that bilateral interaction, which causes an unintentional MI to the left finger movement, is composed of the intrinsic and extrinsic components. According to this assumption, the MI, MI_L^{5th}, can be represented as follows

$$MI_L^{5th} = \alpha_j \cdot MC_R^{5th} + \beta_j \cdot sVE_R^{5th} + \gamma \tag{6}$$

Here, α_j and β_j are the coefficients of the intrinsic and extrinsic components of bilateral interaction, which depend on the conditions (C_j; $j = 1$–4), and γ is a constant term that is assumed to be a common factor over the four conditions. To obtain these coefficients, we used the following equation with a pseudo-inverse method

$$\begin{bmatrix} MI_{L11}^{5th} \\ MI_{L21}^{5th} \\ MI_{L31}^{5th} \\ \vdots \\ MI_{L14}^{5th} \\ MI_{L24}^{5th} \\ MI_{L34}^{5th} \end{bmatrix} = \begin{bmatrix} A_1 & 0 & \cdots & 0 & B \\ 0 & A_2 & \ddots & \vdots & B \\ \vdots & \ddots & A_3 & 0 & B \\ 0 & \cdots & 0 & A_4 & B \end{bmatrix} \cdot \begin{bmatrix} \alpha_1 \\ \beta_1 \\ \vdots \\ \alpha_4 \\ \beta_4 \\ \gamma \end{bmatrix} \tag{7}$$

Here,

$$A_j = \begin{bmatrix} MC_{R1j}^{5th} & sVE_{R1j}^{5th} \\ MC_{R2j}^{5th} & sVE_{R2j}^{5th} \\ MC_{R3j}^{5th} & sVE_{R3j}^{5th} \end{bmatrix}, (j = 1-4), \text{and } B = \begin{bmatrix} 1 & 1 & 1 \end{bmatrix}^T$$

MI_{Lij}^{5th} and MC_{Rij}^{5th} are amplitude changes of the left and right fingers (named MI and motor correction), and sVE_{Rij}^{5th} is the visual error of the right-finger cursor, all quantified in the fifth cycles for the VG_i gain in the C_j condition in experiment 2 (see *Visual cursor gains* of experiment 2).

Statistical analysis

For experiment 2, we analysed the task performance (var VE_R^{pre} and var VE_L^{pre}), bilateral amplitude changes (MC_{Rij}^{5th} and MI_{Lij}^{5th}), coordination stability (PV_ϕ^{5th}), and the estimated coefficients of intrinsic and extrinsic interaction components (α and β). Two-way repeated-measures ANOVAS with the relative phases in intrinsic and extrinsic coordinates as within-subject factors were applied to var VE_R^{pre}, var VE_L^{pre}, α and β. Three-way repeated-measures ANOVAS with relative phases (in/anti) in intrinsic and extrinsic coordinates and of VG_i (three levels: VG_1, VG_2 and VG_3; Table 1) as within-subject factors were applied to MC_{Rij}^{5th}, MI_{Lij}^{5th} and PV_ϕ^{5th}. Bonferroni *post-hoc* tests were used to examine pairwise differences. The Pearson correlation

coefficient was calculated to evaluate the relationship between each interaction component and coordination stability. We considered statistical significance to be $P < 0.05$.

Results

Task performance

To examine the task difficulty in each condition (C_1–C_4), we evaluated the variances of visual error in the pre-phase, as in experiment 1. We did not find any significant main effects of the relative phases (in/anti) in intrinsic coordinates (var VE_R^{pre}: $F_{1,12} = 1.82$, $P = 0.20$; var VE_L^{pre}: $F_{1,12} = 1.92$, $P = 0.14$) and extrinsic coordinates (var VE_R^{pre}: $F_{1,12} = 0.36$, $P = 0.56$; var VE_L^{pre}: $F_{1,12} = 0.21$, $P = 0.65$). The Intrinsic × Extrinsic interaction was not significant for the right finger, but was close to significance for the left finger (var VE_R^{pre}: $F_{1,12} = 0.92$, $P = 0.36$; var VE_L^{pre}: $F_{1,12} = 4.22$, $P = 0.06$), suggesting that the task difficulty of the left finger tended to be affected by the condition.

Multiple interactions associated with intrinsic motor command and extrinsic visual error

Figure 4A and B shows the measured MC_R^{5th} and sVE_R^{5th}, respectively. Regarding MC_R^{5th}, we found a significant main effect of VG_i, but did not find significant main effects of intrinsic and extrinsic coordinates (second column of Table 2). Furthermore, a follow-up analysis for VG_i indicated that MC_{R1j}^{5th} was significantly lower than MC_{R2j}^{5th} and MC_{R3j}^{5th} in all four conditions (Fig. 4A, P-values < 0.00001). Regarding sVE_R^{5th}, we found only a significant main effect of VG_i. A follow-up analysis for VG_i indicated that sVE_{R3j}^{5th} was significantly higher than sVE_{R1j}^{5th} and sVE_{R2j}^{5th} (Fig. 4B, P < 0.00001). These modulation trends of MC_R^{5th} and sVE_R^{5th} are the same as the expected ones shown in Table 1. In contrast, the magnitudes of the MI_L^{5th} observed in experiment 2 strongly depended on the task conditions (Fig. 4C). We should note that this modulation of MI_L^{5th} would not be explained by the variation of task difficulty (var VE_L^{pre}) because of the different trends in these two indexes across four conditions (correlation coefficient $= -0.16$, $P = 0.26$). All main effects were significant, whereas their interactions were not (F-values < 0.54, P-values > 0.59) (fourth column of Table 2).

The estimated coefficients of the intrinsic and extrinsic components of bilateral interaction, α and β in Eqn 7, are shown in Fig. 4D and E. Note that the constant term γ is significantly different from zero (one-sample t-test; $P < 0.001$, $\gamma = 0.45 \pm 0.04$ SE). The fitness of the model, evaluated by the variance-accounted-for value, was $93.9\% \pm 1.90$ SE, indicating that the model sufficiently explains the modulation of MI_L^{5th} across conditions by the interaction components in both the intrinsic and extrinsic coordinates ($\alpha_j \cdot MC_R^{5th}$ and $\beta_j \cdot sVE_R^{5th}$) and the constant term (γ).

As shown in Fig. 4D, α values [the effect of voluntary motor correction of the right finger (MC_R^{5th}) on MI_L^{5th}] in the intrinsic in-phase conditions (C_1 and C_2) were greater than those in the other conditions (C_3 and C_4). Accordingly, α was significantly dependent on the relative phase (in/anti) in intrinsic coordinates (second right-most column of Table 2). Interestingly, α was also significantly modulated by the relative phase in extrinsic coordinates, indicating that the effect of the motor correction was also modulated by the relative phase in extrinsic coordinates.

In contrast, β values [the effect of visual error of the right-finger cursor (sVE_R^{5th}) on MI_L^{5th}], shown in Fig. 4E, were greater in the
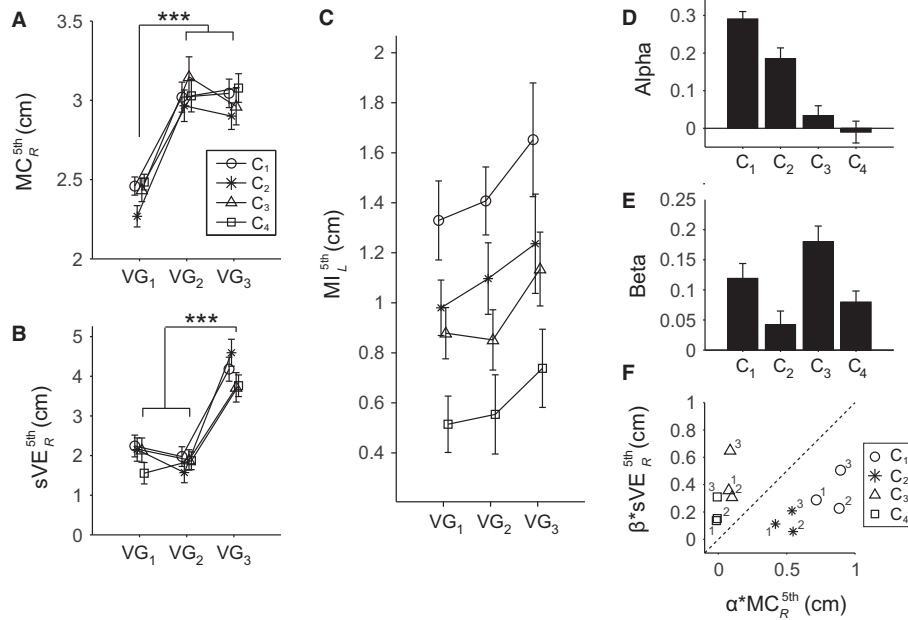
FIG. 4. Amplitude changes of fingers and coefficient values estimated by the multiple-interaction model. (A–C) Magnitude of MC_R^{5th}, sVE_R^{5th} and MI_L^{5th} for each VG_i in each condition (C_1–C_4). In both MC_R^{5th} and sVE_R^{5th}, there is no significant difference among the same VG_i. (D and E) α and β in each condition (C_1–C_4). α became large in intrinsic in-phase conditions (C_1 and C_2), and β became large in extrinsic in-phase conditions (C_1 and C_3). (F) Relationship between intrinsic interaction component ($\alpha \cdot MC_R^{5th}$) and extrinsic interaction component ($\beta \cdot sVE_R^{5th}$) for each VG_i (labelled by numbers 1–3) and condition (C_1, open circles; C_2, asterisks; C_3, open triangles; C_4, open squares). The dotted diagonal line indicates equal magnitudes of the interaction components. In A–E, error bars denote SE across the participants. ***$P < 0.001$.

TABLE 2. *F*-values of the three-way repeated-measures ANOVA for MC_R^{5th}, sVE_R^{5th} and MI_L^{5th} and those of the two-way repeated-measures ANOVA for α and β

Main effect	MC_R^{5th}	sVE_R^{5th}	MI_L^{5th}	α	β
Intrinsic coordinate $F_{1,12}$	4.32	3.68	20.39***	85.80***	4.55
Extrinsic coordinate $F_{1,12}$	1.84	2.00	6.21*	5.37*	14.48**
VG_i $F_{2,24}$	100.68***	65.30***	16.63***	–	–

*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

extrinsic in-phase conditions (C_1 and C_3) than in the extrinsic anti-phase conditions (C_2 and C_4), i.e. β was strongly dependent on the relative phase (in/anti) in extrinsic coordinates (right-most column of Table 2). Additionally, because the effect of the relative phase in intrinsic coordinates on β was marginally significant ($P = 0.054$), the effect of the visual error on MI tended also to be modulated by the relative phase in intrinsic coordinates. The increasing trend of α from C_2 to C_1 (Fig. 4D) and decreasing trend of β from C_3 to C_1 (Fig. 4E) suggest a preference for the intrinsic component in the bilateral interaction.

This preference for the intrinsic component can be clearly characterized when the MI (MI_L^{5th}) is decomposed into an intrinsic component ($\alpha \cdot MC_R^{5th}$) and an extrinsic component ($\beta \cdot sVE_R^{5th}$) by Eqn 6. As shown in Fig. 4F, those components varied with the conditions. All factors of relative phases in extrinsic and intrinsic coordinates and VG were found to be statistically significant by the three-way repeated-measures ANOVA. Specifically, both $\alpha \cdot MC_R^{5th}$ and $\beta \cdot sVE_R^{5th}$ were relatively high in C_1 (open circles in Fig. 4F) but clearly lower than the diagonal line ($\alpha \cdot MC_R^{5th} > \beta \cdot sVE_R^{5th}$ significantly in all VG_i). Additionally, $\alpha \cdot MC_R^{5th}$ components in C_1 were greater than

those in C_3, suggesting that the extrinsic in-phase condition dilated the intrinsic interaction, thereby leading the strongest unintentional MI in C_1, as shown in Fig. 4C.

Relationship between the interaction and stability

To further examine the multiple levels of interaction, we explored the relationship between MI (MI_L^{5th}) and bimanual coordination stability (PV_ϕ^{5th}) quantified in experiment 2. As shown in Fig. 5A, MI_L^{5th} has a significant negative correlation with PV_ϕ^{5th} ($r = -0.63$, $P < 0.05$), indicating that the bimanual coordination stability improved (i.e. variability decreased) with strong MI. Additionally, we found a significant negative correlation between PV_ϕ^{5th} and $\alpha \cdot MC_R^{5th}$ ($r = -0.85$, $P < 0.001$) but not between PV_ϕ^{5th} and $\beta \cdot sVE_R^{5th}$, as shown in Fig. 5B and C. This indicates that the coordination stability was dominantly affected by the strength of motor correction of the right finger.

Discussion

According to previous studies of the bimanual motor coordination mentioned in the Introduction (Semjen *et al.*, 1995; Byblow *et al.*, 2000), the coordination stability of the left finger and unintentional MI to it shown in this study can be ascribed to a bilateral interaction due to a neural connection between hemispheres (Eliassen *et al.*, 1999; Kennerley *et al.*, 2002; Carson, 2005; Sternad *et al.*, 2007). From the functional viewpoint, an additional important question arises as to what kind of functional principle is employed in the interaction for bimanual control. Our results quantitatively demonstrated that the interaction effects are modulated depending on the bimanual motor patterns in which the relative phases (in/anti) in intrinsic and extrinsic coordinates are different. On the basis of our findings, we here discuss the
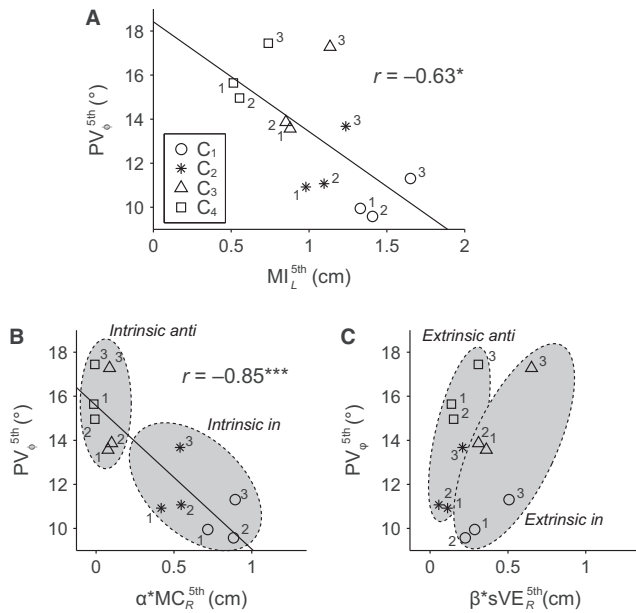
FIG. 5. Relationships between the strength of interaction and coordination stability for all of the VG_i combinations in experiment 2. (A) Each point indicates the mean value across participants, and the VG_i combination is labelled by suffixes 1–3. MI_L^{5th} significantly correlated with PV_ϕ^{5th}. (B and C) PV_ϕ^{5th} has a strong correlation with the decomposed intrinsic interaction component $(\alpha \cdot MC_R^{5th})$ but not with the extrinsic interaction component $(\beta \cdot sVE_R^{5th})$. *$P < 0.05$, ***$P < 0.001$.

bimanual coordination from the viewpoints of stability and multiple levels of interaction.

Strong bimanual coordination stability governed by intrinsic motor command

Bimanual coordination stability has been widely examined by analysing the relative phase variability, and many studies demonstrated that intrinsic in-phase movement, which requires synchronization of homologous muscle activities, greatly contributes to the stability of cyclic movements (Kelso, 1984; Semjen *et al.*, 1995; Swinnen *et al.*, 1997, 1998). Isodirectional movements also contribute to decreasing the relative-phase variability, but the effect of extrinsic coordinates would be weak for bimanual coordination, compared with that of intrinsic coordinates (Swinnen *et al.*, 1997; Park *et al.*, 2001; Temprado *et al.*, 2003; Salesse *et al.*, 2005; Meesen *et al.*, 2008).

In experiment 1 of the current study, we found two types of different coordination patterns of strong intermanual interference, one with low phase variability and the other with high phase variability. These results suggest the possibility that the interaction mechanisms characterizing the phase variability and those characterizing the unintentional MI are not identical. Bilateral interaction in the cortical level contributes to the stability of bimanual movement (Maki *et al.*, 2008). However, our findings suggested that the bilateral motor systems have qualitatively different interactions in multiple levels; one is the interaction that occurs during intrinsic in-phase motor patterns and contributes to the stability, and the other is the interaction that occurs during extrinsic in-phase motor patterns and weakly contributes to the stability.

In addition, as shown in experiment 2, the phase variability (PV_ϕ^{5th}) was highly correlated with the intrinsic interaction component ($\alpha \cdot MC_R^{5th}$; Fig. 5B), whose coefficient α was mainly modu-

lated by the relative phase in intrinsic coordinates. Interestingly, the phase variability was evidently higher in the extrinsic in-phase and intrinsic anti-phase condition (C_3) than in the extrinsic anti-phase and intrinsic in-phase condition (C_2), suggesting that bilateral interaction in extrinsic coordinates is weak in keeping low phase variability. These results are consistent with previous observations (Swinnen *et al.*, 1997; Park *et al.*, 2001; Temprado *et al.*, 2003; Salesse *et al.*, 2005; Meesen *et al.*, 2008), and they further suggest that the bimanual coordination stability, indexed by phase variability, proportionally varies with the strength of intrinsic interaction (i.e. the effect of the voluntary motor correction component of the right finger on the unintentional motor change of the left finger) rather than with a simple 'interaction-mode' change between in-phase and anti-phase.

In addition to the effects of multiple coordinates on the bimanual coordination stability, the mirror symmetry of visual feedback could enhance the stability of the relative phase during bimanual movements (Mechsner *et al.*, 2001). The visual symmetry effect, however, would not explain the modulation of coordination stability observed in experiment 1 because a similar amount of relative-phase stability was also observed in the condition with mirror-asymmetric visual feedback (C_2; intrinsic in-phase and extrinsic anti-phase) as in the visual symmetric condition (C_1).

Combination of multiple levels of bilateral interactions in the central nervous system

In addition to the idea that homologous muscle groups define the intrinsic coordinates, it has been suggested that movement directions in extrinsic coordinates are also important constraints for characterizing the bimanual control coordination (Swinnen *et al.*, 1997, 1998; Lee *et al.*, 2002). Our findings of the stronger unintentional MI to the left finger found in C_1 (in-phases in extrinsic and intrinsic coordinates), C_2 (in-phase only in intrinsic coordinates), and C_3 (in-phase only in extrinsic coordinates) in experiment 1 are consistent with those previous observations, i.e. as the multiple coordinates coexist in a bimanual control (Swinnen & Wenderoth, 2004), the interaction would be regulated in different coordinates according to the motor pattern in each condition.

A further question that we would like to pose here is whether the bilateral interactions in intrinsic and extrinsic coordinates are mutually exclusive or additively incorporated. Actually, condition C_1 in experiments 1 and 2 induced under-additive MIs of C_2 and C_3, suggesting an imperfect additivity of the 'in-phase' effects on the MI. To quantitatively understand the MI, we introduced a multiple-interaction model. As shown in the Results, this model succeeded in decomposing MI into intrinsic and extrinsic interaction components and showed that the estimated intrinsic interaction component was mainly modulated by the relative phase in intrinsic coordinates, whereas the extrinsic interaction component was mainly modulated by the relative phase in extrinsic coordinates, i.e. the relative phases in the intrinsic and extrinsic coordinates act as dominant factors in forming bilateral interaction in the tasks, whereas previous observations were limited to suggest a reinforcement of the stability (Swinnen *et al.*, 1997, 1998; Lee *et al.*, 2002).

In addition to those dominant modulation effects, we found that the coefficient of intrinsic motor correction (α) significantly increased in C_1 (the condition with in-phases in both intrinsic and extrinsic coordinates) compared with that in C_2 (the condition with in-phase only in intrinsic coordinates) (Fig. 4D), whereas the coefficient of visual error (β) in C_1 tended to decrease compared with that in C_3 (the condition with in-phase only in extrinsic coordinates)

(Fig.4E). As a result, in the condition with in-phases in both intrinsic and extrinsic coordinates, MI was driven more by the intrinsic component than by the extrinsic component (Fig. 4F), whereas MI was mainly driven by the intrinsic or extrinsic component in the condition with in-phase only in the corresponding coordinates. Therefore, although intrinsic and extrinsic components are additively incorporated in producing the interaction, those effects would not be independently controlled. Instead, they would be cooperatively regulated according to the preference or efficacy of interaction.

Possible neural substrates for multiple levels of bilateral interactions

As in the above discussions, our results suggest that the combination of bilateral interactions would be critical in forming sophisticated and flexible bimanual coordination. What neural substrates could contribute to form the multiple levels of interactions during bimanual movements? Previous studies suggested that bimanual control is governed by a distributed network (Gerloff & Andres, 2002; Pollok et al., 2005; Grefkes et al., 2008). In particular, activations in the supplementary motor area (SMA) (Sadato et al., 1997; Gross et al., 2005) and premotor area (PM) (Debaere et al., 2004) were found to depend on the relative phase between bilateral movements, indicating that these areas play an important role in bimanual coordination. The SMA has transcallosal connections to the contralateral homotopic area (Brinkman, 1984; Rouiller et al., 1994; Kazennikov et al., 1999; Marconi et al., 2003; Boussaoud et al., 2005), and the SMA and PM have strong connections to the primary motor area (M1) (SMA-M1: Donchin et al., 1998, 2001; PM-M1: Mochizuki et al., 2004; Liuzzi et al., 2011).Furthermore, the neurons in M1 have representations of muscle and movement direction (Kakei et al., 1999), and those in the PM mainly have representation of movement direction (Kakei et al., 2001). The distributed neural connections between bilateral hemispheres in the higher (SMA or PM) and lower (M1) motor areas potentially cause the different levels of interactions for achieving various types of bilateral coordination. With reference to these neural representations and hardware constraints, computational mechanisms of bimanual coordination should be further clarified in future studies.

Conflict of interests

The authors declare no competing financial interests.

Acknowledgements

Abbreviations

M1, primary motor area; MI, motor interference; PM, premotor area; SMA, supplementary motor area; VG, visual cursor gain.

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