Two heads are better than one: both complementary and synchronous strategies facilitate joint action

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Masumoto J, Inui N. Two heads are better than one: both complementary and synchronous strategies facilitate joint action. J Neurophysiol 109: 1307–1314, 2013. First published December 5, 2012; doi:10.1152/jn.00776.2012.—If two people lift and carry an object, they not only produce complementary forces on the object but also walk in synchrony. Previous studies have not examined how two types of coordination strategy are adopted simultaneously. The present study thus tested the hypothesis that complementary and synchronous strategies simultaneously facilitate the action coordination performed by two people. Ten pairs of participants produced periodic isometric forces such that the sum of forces they produced was the target force cycling between 5% and 10% of maximum voluntary contraction with an interval of 1,000 ms (joint action), while individuals alone produced the same target forces with the right hand (individual action). The correlation between forces produced by two participants was highly negative when the total force was visible, indicating that the two participants produced complementary forces. When the image of the total or partner force was presented, the coherence between force-time series produced by two participants was highest at 1 Hz. The relative phase angles were also distributed at the 0–20° phase region. These innovative findings indicate that two participants simultaneously adopted both complementary and temporal synchronous strategies exclusively when the total force was visible. With the vision of total force, surprisingly, while the joint action exhibited a less variable force than the individual action, the joint action exhibited a smaller absolute error of forces than the individual action. These new findings indicated that the joint action controlled force more accurately than the individual action.

DAILY LIFE, as well as sports and art, sometimes requires coordination of movements performed by two persons. For example, two people can lift and carry a table in real life, while two pianists can synchronize their performance to each other’s timing with asynchronies of 30 ms (Keller et al. 2007). Such group action coordination has recently been studied using the term “joint action,” which is defined as a social interaction whereby two or more individuals coordinate their actions in space and time to bring about a change in the environment (Sebanz et al. 2006). However, the behavioral and neural processes underlying such joint action are still poorly understood.

Previous studies have identified two key mechanisms subserving temporal coordination. First, some studies from the dynamical systems perspective (Haken et al. 1985) have shown that when two people perform a rhythmic action while they can see each other, in many cases they fall into the same rhythm, known as entrainment (Richardson et al. 2007; Schmidt et al. 1990). Such studies have also indicated that intrapersonal coordination scales up to the interpersonal case (Marsh et al. 2009). However, because such coordination can occur spontaneously between individuals who have no plan to perform actions together, the dynamical systems approach cannot explain how individuals adjust the timing of their actions to others to achieve a common outcome (Knoblich et al. 2011). Second, previous studies on joint action have provided some information on how individuals adjust their actions to those of another person in time and space (Sebanz et al. 2006; Sebanz and Knoblich 2009). Some studies on joint action have revealed how individuals incorporate others’ actions into their own action planning (Ishenower et al. 2005) and how temporal feedback about others’ actions is used in anticipatory action control (Knoblich and Jordan 2003). Most of the previous studies on entrainment and joint action employed continuous rhythmic tasks in which coordination between two people occurred based on visual (Richardson et al. 2007), haptic (van der Wel et al. 2011), or auditory (Keller et al. 2007; Konvalinka et al. 2010) information.

Recently, behavioral (van Schie et al. 2008) and brain imaging (Newman-Norlund et al. 2007) studies on joint action have investigated differences between imitative and complementary actions. As an example of an imitative action, Brass et al. (2001) asked participants to observe a video of either a lifting movement or a tapping movement on the computer. The participants’ reaction times in performing the lifting or tapping movements were faster after observation of the lifting or tapping movements. Many studies on observation of an action have found that a corresponding representation in the observer’s action system is activated in the premotor and parietal cortices pertaining to the “mirror neuron system” (Rizzolatti and Craighero 2004). In a complementary action, Knoblich and Jordan (2003) asked individuals and pairs to perform a motor task keeping a tracker on a target. The target was moved horizontally across a computer monitor by pressing right and left keys that incremented the tracker’s velocity to the right or left, respectively. Although the pairs had a larger error between the target and tracker than the individuals in the initial practice, there was no difference between the pairs and the individuals in error in the final practice. Bosga and Meulenbroek (2007) asked pairs of participants to perform a virtual lifting task using isometric force with two or four hands. The forces produced by two participants were negatively correlated when visual feedback of their forces was available, indicating the use of complementary forces to control a virtual bar. Neuroimaging studies in humans found that activities in the mirror neuron system
areas were greater during complementary action than during imitative action (Newman-Norlund et al. 2007). The areas were also more active in the joint condition than in the solo condition during the same virtual bar lifting task (Newman-Norlund et al. 2008).

In two people lift and carry an object in real-life situations, they not only produce complementary forces on the object but also walk in synchrony. However, previous studies separately examined complementary (Bosga and Meulenbroek 2007; Knoblich and Jordan 2003) and synchronous (Keller et al. 2007; Konvalinka et al. 2010) strategies in joint actions. The present study thus tested the hypothesis that two coordination strategies simultaneously facilitate the action coordination performed by two people. The present study examined the complementary strategy in a joint action using a periodic isometric force production such that the sum of the forces produced by two participants was the target force. A periodic motor task with a prescribed movement interval also allows us to analyze the synchronous strategy in the joint action. While Brass et al. (2001) gave participants visual information on the other’s movement, Bosga and Meulenbroek (2007) gave them information on the sum of forces produced by two participants. Presumably, such different types of visual information have different influences on coordination strategy in a joint action. The present study used a motor task such that the sum of the forces produced by two participants was the target force. It is thus anticipated that a joint action is facilitated by visual information on the sum of forces rather than by information on each participant’s force output. To examine the effects of different types of visual information on complementary and synchronous strategies in a joint action, the present study set four conditions of visual information.

MATERIALS AND METHODS

Participants

This study was performed with 20 healthy male participants without any apparent neurological disorders [mean age = 22.6 yr, standard deviation (SD) = 1.9 yr]. Handedness was tested with the Edinburgh Handedness Inventory (Oldfield 1971). Because all 20 participants were right hand dominant, the mean of laterality quotient scores was +100 (SD = 0). All participants gave informed consent, and the local committee approved the procedures. The work conformed to the principles of the Declaration of Helsinki.

Procedure

This study consisted of the individual condition performed by one participant and the total-force, both-forces, partner-force, and no-feedback conditions performed by two participants paired randomly. The individual condition was conducted with half of the setup shown in Fig. 1A (also see Fig. 1 in Masumoto and Inui 2010). In the individual condition, 20 participants were seated facing the load cell and their palms rested on a support surface 6 cm above the table (see Fig. 1A). In this posture, the participants made periodic isometric pressing movements with the right index finger at the metacarpophalangeal joint with a target peak force of 10% maximum voluntary contraction (MVC), a target valley force of 5% MVC, and a target peak-to-peak (PPI) or valley-to-valley (VVI) interval of 1,000 ms. The force output of the load cell was displayed on a monitor screen so that the participants could see the difference between the actual force and the target force, both of which were indicated on the screen by two horizontal lines.

In the total-force, both-forces, partner-force, and no-feedback conditions, the participants were seated on chairs at opposite ends of a table facing the load cell and monitor (Fig. 1A). They produced the target force such that the sum of the forces produced by the right index fingers of the two participants was a target peak force of 10% MVC or a target valley force of 5% MVC (Fig. 1B) under four conditions (Fig. 1C): 1) The total-force condition displayed the target forces for the pair and a sum of the forces produced by the two participants on a monitor. 2) The both-forces condition displayed the force outputs produced by the two participants separately and the personal targets, which represent 5% and 10% MVC for each participant, on a monitor. While the force output produced by a participant was presented at the top of a monitor, the output produced by his partner was presented at the bottom. 3) The partner-force condition displayed only a partner’s force output and his target on a monitor. 4) The no-feedback condition removed any visual information from the monitor. Under these conditions, the participants were instructed to synchronize their force with their partner’s force. While the participants could not see the other’s action because of the two monitors between them, they were instructed not to verbally communicate to each other.

At the start of the experimental session, the participants produced their maximum force to measure the isometric MVC generated at the fingertip of the right index finger. The participants were instructed to first place the distal pad of the index finger in contact with the load cell, and then to apply as much pressure as possible to the load cells and maintain that force output for 3 s without lifting the hand and forearm. The wrist was fixed to the rest mounted with a load cell by a tape with Velcro, a fastener for clothes consisting of two strips of nylon fabric that adhere when pressed together (Magic Tape, Kuraray, Tokyo, Japan). The MVC (mean = 45.1 N, SD = 2.3 N) was determined by an average of three trials. The order of the conditions performed by the participants was varied randomly. The participants...
practiced each condition separately with the corresponding test trial following immediately after the practice trials. They pressed their fingers against the load cell for 60 cycles in five practice trials for each condition. During practice trials, the pressing rate was prescribed by means of an audible metronome (model SQ100-88, Seiko Holdings, Tokyo, Japan). The participants were instructed to synchronize finger presses on the load cell with the metronome. On the test trial, although they were given the same visual information as the practice trials, they were instructed to produce the interval acquired during the practice trials by means of self-paced movement without the metronome pulse.

**Apparatus and Measurements**

The output of the load cell (model LUB-5KB, Kyowa Electronic Instruments, Tokyo, Japan; rated 5 kg) pressed by participants was amplified (Kyowa model MCC-8A) and recorded by a personal computer (Vostro200, Dell, Round Rock, TX) after the amplified signal was converted from analog to digital (PowerLab/8sp, SD Instruments). The force output was also displayed on a 20-in. computer monitor (1,440 × 900-pixel resolution) located ~60 cm in front of the participant. Data were sampled at a frequency of 1,000 Hz by a 16-bit A/D converter with a low-pass filter for 100 Hz. Figure 2 shows a data sample collected from two participants. Peak force, valley force, PPI, and VVI were measured with software (Emile Soft, Tokushima, Japan) for analysis of force and interval.

**Data Analysis**

In analyses of the test trials, the dependent measures were the average values corresponding to the dependent measures produced. The initial and final five cycles of force-time series were removed from the data to avoid the effects of the initial stabilization period and any premature cessation of force production, and the values were calculated from the middle 50 cycles in each trial.

Complementary strategy, frequency synchrony, phase synchrony, accuracy of force production and interval, and variabilities of force and interval were calculated as follows. 1) To examine the complementary strategy of forces produced by two participants under four conditions, correlation coefficients between the forces they produced were calculated for the peak or valley force. 2) The cross-spectral coherence was calculated to assess the frequency synchrony between movements produced by two participants, which evaluated the correlation of the two force-time series at different frequencies. The coherence was calculated over all force-time series (100 samples/s) with a window length of 500 points (frequency resolution of 0.2 Hz) by using the mscocohere command in Octave Forge v.3.6.1 (John W. Eaton, freeware). Thus the peak coherence over all frequencies was used as an estimate of the frequency synchrony between forces produced by the two participants. 3) The distribution of relative phase angles between the force-time series produced by the two participants was used to quantify the phase synchrony between their force outputs. The continuous relative phase was first computed with the Hilbert transform (Rosenblum and Kurths 1998). The Hilbert transform was calculated by using the Hilbert command in Octave Forge. The distribution of relative phase angles examined the concentration of relative phase angles between forces produced by two participants across nine 20° regions of relative phase (0–20°, 21–40°, 41–60°, 61–80°, 81–100°, 101–120°, 121–140°, 141–160°, 161–180°). The phase synchrony was indicated by a high concentration of relative phase angles near 0°, while an even distribution indicated no phase synchrony. 4) Absolute error (AE) was calculated to assess the accuracy of force production and interval. The AE was calculated by taking the size of each error (the difference between produced and target forces or intervals), regardless of sign, and averaging it over 50 measures. 5) SDs for total force (peak or valley force) and interval (PPI or VVI) were calculated to examine the variability of force and timing.

**Statistical Analysis**

**Analysis of complementary strategy.** Correlation coefficient values were standardized by using a Fisher z transformation for averaging across pairs. A 4 (condition: total-force, both-forces, partner-force vs. no-feedback condition) × 2 (force: peak vs. valley force) analysis of variance (ANOVA) was performed to examine the main effects on the correlation between forces produced by two participants. Masumoto and Inui (2010, 2012) found that the valley force was markedly more variable than the peak force in isometric force productions. The present study showed the same result in the both-forces and individual conditions (see Fig. 6C). The present study thus analyzed peak and valley forces separately.

**Analysis of coherence.** A one-way ANOVA was performed to examine the main effects on the cross-spectral coherence between forces produced by two participants.

**Analysis of distribution of relative phase angles.** A 4 (condition) × 9 (phase region: 0–20°, 21–40°, 41–60°, 61–80°, 81–100°, 101–120°, 121–140°, 141–160°, 161–180°) ANOVA was performed to examine the main effects on phase region.

![Fig. 2. Data samples of the total force (TF) and finger forces of participants A (AF) and B (BF) under the 4 conditions. In the total-force condition, the all-phase difference was 0° and the summed force also matched the target forces nicely.](http://jn.physiology.org/doi/10.1152/jn.00776.2012.supp)
Analysis of accuracy in force and interval. A 5 (condition) × 2 (force or interval; peak vs. valley force or PPI vs. VVI) ANOVA was performed to examine the main effects on the AE of force or interval.

Analysis of force and timing variabilities. A 5 (condition: total-force, both-forces, partner-force, no-feedback vs. individual condition) × 2 (force or interval) ANOVA was performed to examine the main effects on the SD of force and interval.

When significant overall condition effects were found for a dependent measure, post hoc multiple comparisons detected differences between conditions with Tukey’s honestly significant difference test. Statistical significance was defined at the $P < 0.05$ level.

RESULTS

The most important findings of the present study are that the correlation between forces produced by two participants was highly negative and the cross-spectral coherence between force-time series produced by them was highest at 1 Hz under the total-force condition. The phase synchrony between force-time series produced by two participants also depended on ability to see the total or partner force. These novel results indicated that the participants simultaneously adopted both complementary and synchronous strategies with only the total force visible. As far as force distributed over time, a complementary strategy was preferred: if one participant generated maximal force, the partner generated minimal force, and vice versa. On the other hand, as far as changes in force-time series were concerned, a synchronous strategy was preferred: peak and valley forces produced by two people were generated synchronously.

Complementary Strategy

Figure 3 shows data samples of the distribution of the forces produced by two participants under four conditions. Although the correlation between forces produced by two participants was negative under the total-force condition (Fig. 3A), there was no correlation under the both-forces (Fig. 3B), partner-force (Fig. 3C), and no-feedback (Fig. 3D) conditions. Figure 3E shows mean correlations under the four conditions. An analysis of correlation showed a main effect of condition $[F(3,72) = 81.01, P < 0.0001]$, indicating that the total-force condition exhibited a stronger negative correlation than the other three conditions ($P < 0.0001$). Two participants thus adopted a complementary strategy of force so that one person compensated for force errors of the other exclusively with an image of the total force.

Temporal Synchronous Strategy

Analysis of frequency. Figure 4 shows the mean cross-spectral coherence between force-time series produced by two participants under the four conditions to examine the frequency synchrony between their force outputs. The coherence was highest at 1 Hz under the total-force (Fig. 4A), both-forces (Fig. 4B), and partner-force (Fig. 4C) conditions, indicating that a participant synchronized his time-force series with a partner’s at the target interval. In contrast, the no-feedback condition had lower coherence over all frequencies (Fig. 4D). Figure 4E shows the mean peak coherence under the four conditions. An analysis of the peak coherence $[F(3,36) = 20.88, P < 0.001]$ indicated that while the no-feedback condition exhibited a markedly lower peak coherence than the other three conditions ($P < 0.0001$), the total-force condition exhibited a higher peak coherence than the both-forces and partner-force conditions ($P < 0.05$). Thus the analysis of cross-coherence indicated that the temporal synchrony of two participants’ actions depended on ability to see either the total or the partner force.

Analysis of phase. To examine the phase synchrony between force-time series produced by two participants, Fig. 5 shows the distribution of relative phase angles. An analysis of the relative phase angles showed a main effect of phase region $[F(8,324) = 135.47, P < 0.0001]$, and an interaction of condition and phase region was significant $[F(24,324) = 10.20, P < 0.0001]$. Separate

Fig. 3. A: distribution of forces produced by 10 pairs under the total-force condition. B: distribution under the both-forces condition. C: distribution under the partner-force condition. D: distribution under the no-feedback condition. In A-D, dashed lines (finger force of participant A + finger force of participant B = 5% or 10% MVC) represent the target force. E: mean correlation coefficient between forces produced by 2 participants under 4 conditions. In E, error bars show the between-participants standard error. Conventions are as in Fig. 1.
analyses on phase region showed that while the percentage of occurrence for the 0–20° phase region $[F(3,36) = 9.51, P < 0.0001]$ was markedly higher in the total-force and both-forces conditions than in the no-feedback condition ($P < 0.005$), the percentage for the 21–40° phase region $[F(3,36) = 10.18, P < 0.0001]$ was markedly lower in the no-feedback condition than in the other three conditions ($P < 0.005$). While the percentages for 61–80° $[F(3,36) = 7.49, P < 0.001], 141–160° [F(3,36) = 5.58, P < 0.005], and 161–180° [F(3,36) = 6.37, P < 0.001]$ phase regions were higher in the no-feedback condition than in the total-force and both-forces conditions ($P < 0.05$), the percentages for 81–100° $[F(3,36) = 8.65, P < 0.0001], 101–120° [F(3,36) = 13.72, P < 0.0001], and 121–140° [F(3,36) = 11.20, P < 0.0001]$ phase regions were higher in the no-feedback condition than in the other three conditions ($P < 0.05$). While the relative phase occurrence in the no-feedback condition was distributed over all nine phase regions, the occurrence increased mainly in the 0–40° phase region under the other three conditions. Thus, although the phase synchrony was observed with the image of the total or partner force, removal of the image did not result in the synchrony.

**Accuracy of Force Production and Movement Interval**

To assess the accuracy of force control and timing, Fig. 6A shows AE of force production, while Fig. 6B shows AE of interval. The analysis on AE of peak and valley forces showed a main effect of condition $[F(4,110) = 19.63, P < 0.0001]$ and an interaction of condition and force $[F(4,110) = 3.59, P < 0.01]$. The post hoc test indicated that the partner-force and no-feedback conditions had a greater AE than the total-force ($P < 0.0001$), both-forces ($P < 0.0001$), and individual ($P < 0.005$) conditions. Importantly, the total-force condition had a smaller magnitude of AE than the individual condition ($P < 0.005$), indicating that the joint action controlled force more accurately than the individual action. Separate analyses on condition showed that although there was no main effect under the total-force, both-forces, and partner-force conditions, the valley force had a greater AE of force than the peak force under the individual condition $[F(1,38) = 6.91, P < 0.05]$. Similarly, the analysis on AE of both intervals showed a main effect of condition $[F(4,110) = 5.45, P < 0.0001]$, indicating that the partner-force and no-feedback conditions had a greater AE of both intervals than the total-force condition ($P < 0.005$).

**Variabilities of Force and Movement Interval**

Variabilities of force and interval were examined under all five conditions. Figure 6C shows the SD of peak and valley forces, while Fig. 6D shows the SD of PPI and VVI. The analysis on SD of both forces showed a main effect of condition $[F(4,110) = 34.26, P < 0.0001]$ and an interaction of condition and force $[F(4,110) = 10.50, P < 0.0001]$. The post hoc test indicated that the partner-force and no-feedback conditions had a greater SD than the total-force, both-forces, and individual conditions ($P < 0.001$). Importantly, the total-force condition had a smaller magnitude of SD of both forces than the individual condition ($P < 0.05$), indicating that the joint action exhibited a less variable force than the individual action. Separate analyses on condition showed that although the valley force had a greater magnitude of SD than the peak force under the both-forces $[F(1,18) = 6.33, P < 0.05]$
and individual $[F(1,38) = 9.10, P < 0.005]$ conditions, the valley force had a smaller magnitude of SD than the peak force under the partner-force $[F(1,18) = 5.96, P < 0.05]$ and no-feedback $[F(1,18) = 11.18, P < 0.005]$ conditions. The analysis on SD of both intervals showed a main effect of condition $[F(4,110) = 4.98, P < 0.001]$. The post hoc test indicated that the SD of both intervals in the no-feedback condition was larger than that in the total-force ($P < 0.001$) and both-forces ($P < 0.05$) conditions.

**DISCUSSION**

The present study found that the correlation between forces produced by two participants was highly negative when total force was visible, indicating that two participants produced complementary forces. Because the time-force series produced by two participants correlated at a frequency of 1 Hz with the total or partner force visible, their force outputs were synchronized at the target interval. The phase synchrony between two participants’ actions also depended on ability to see the total or partner force. These innovative findings indicated that two participants simultaneously adopted both complementary and synchronous strategies exclusively when total force was visible. Surprisingly, while the total-force condition exhibited a less variable force than the individual condition, the total-force condition exhibited a smaller AEs of forces than the individual condition. These results indicated that the joint action controlled force more accurately than the individual action. The present study is the first study to attempt to examine the hypothesis that two coordination strategies simultaneously facilitate the joint action.

**Complementary Strategy**

Knoblich and Jordan (2003) asked pairs of participants to perform a motor task keeping a tracker on a target and indicated a complementary action. Bosga and Meulenbroek (2007) also asked pairs to perform a virtual lifting task using isometric force, indicating the use of complementary forces to control a virtual bar. In the study of Bosga and Meulenbroek (2007), however, the joint condition produced a more variable bar position than the solo condition. In contrast, in the present study the joint action exhibited a less variable force than the individual action and the joint action exhibited a smaller AE of force than the individual action. Thus, although in the present study the joint action controlled force more accurately than the individual action, the study of Bosga and Meulenbroek (2007), as well as that of Knoblich and Jordan (2003), exhibited the opposite result. The discrepancy between the studies may be affected by the difference between the isometric force tasks. While Bosga and Meulenbroek (2007) performed a self-paced constant force production, the present study asked the participants to control periodic force production cycling between two target forces with a prescribed interval. In the present study, because the movement speed perhaps constrained the participants’ ability to achieve the goal of the task, they had to synchronize the interpersonal finger forces. As a result, in the present study the joint action controlled force more accurately than the individual action compared with the studies of Bosga and Meulenbroek (2007) and Knoblich and Jordan (2003).

In the present study, the force error compensation is consistent with the optimal feedback control theory (Todorov 2004; Todorov and Jordan 2002), which suggests that the central nervous system sets up feedback controllers that continuously convert the state estimate (an internal representation of body and task variable) into subsequent motor outputs in order to overcome feedback delays. Such a feedback controller corrects errors from the average behavior if the errors interfere with the goal of the task; otherwise, they are ignored (the so-called “minimal intervention” principle). The state estimate is updated by integrating sensory inputs and prediction from a forward model. The optimal feedback control theory has been used to explain trial-by-trial variability in a wide range of
motor behaviors, such as obstacle avoidance (Liu and Todorov 2007), object manipulation (Nagengast et al. 2009), and bimanual coordination (Diedrichsen 2007). For the complementary force strategies in the present study, the variance in forces produced by two participants was larger than the variance in the total-force condition. Knoblich (2009) proposed two types of joint action. One is a partner’s movements. Related to this issue, Sebanz and joint actions is unable to explain exclusively the anticipation of the success of free shots by their anticipatory abilities. However, a novice did (Aglioti et al. 2008). Elite athletes use body cues a basket observed on a video earlier and more accurately than the variance in the total-force condition. For example, professional basketball players anticipated the success of free shots at the target interval. Therefore, rather than recalling the target interval. Hence, the two types of action simulation appeared to facilitate the joint action observed in the present study.

Relationships Between Synchronous and Complementary Strategies

In the present study, when the image of the total or partner force was presented, the coherence between force-time series produced by two participants was highest at the target frequency of 1 Hz. The relative phase angles were also distributed in the 0–20° phase region. These results indicated that the frequency and phase synchronies were observed with the image of the total or partner force. In the test trials without auditory information of the target interval, because participants were asked to recall the interval acquired during the practice trials, they tried to recall the target interval. However, when the visual feedback of the partner’s force output disappeared in the no-feedback condition, their frequency and phase synchronies were not observed and the participants were not able to recall the target interval. Therefore, rather than recalling the target interval, the temporal synchrony of two participants’ outputs depended on being able to see the total or partner force. In addition, because all conditions had lower coherence over other frequencies except for the target frequency of 1 Hz, participants performed the joint task as an intentional joint action rather than an unintentional dynamical system.

The anticipation of partners’ movements based on their observation of each other is involved in their temporal synchronous and complementary force output. The partners’ movements are anticipated by simulating their movement based on anticipation of the actors’ own movements, referred to as “action simulation” (Knoblich et al. 2011; Sebanz and Knoblich 2009). Action simulation allows people to predict a partner’s actions based on internal predictive models in their own motor system (Wolpert et al. 2003). For example, professional basketball players anticipated the success of free shots at a basket observed on a video earlier and more accurately than a novice did (Aglioti et al. 2008). Elite athletes use body cues to perform the task successfully, and they anticipated the success of free shots by their anticipatory abilities. However, temporal synchronous and complementary force production for joint actions is unable to explain exclusively the anticipation of a partner’s movements. Related to this issue, Sebanz and Knoblich (2009) proposed two types of joint action. One is simulation of the actors’ own movements as well as those of others to synchronize their own movements with the other’s movements. The simulation also needs to detect the difference between both movements. If pianists were asked to record one part from each of several piano duets, and later to play the complementary part in synchrony with their own or others’ recordings, the pianists were better at synchronizing with recordings of their own performances than with recordings of others (Keller et al. 2007). This result indicated that the anticipation of pianists’ own performance corresponded with recordings of their own performances, producing accurate synchronization between their own performances and recordings. Another type of joint action is prediction of changes in the environment produced by movements performed by two persons (Knoblich and Jordan 2003). In the present study and the study of Bosga and Meulenbroek (2007), because participants simulated and anticipated changes in the total force for the complementary force production, one participant compensated for another’s force errors exclusively with an image of the total force. Hence, the two types of action simulation appeared to facilitate the joint action observed in the present study.

Control of Force and Timing

During bimanual force production such that the sum of the two finger forces was the target force, Masumoto and Inui (2012) exhibited that, with visibility, correlations between the two finger forces changed from negative to positive with force level. This result indicated that the strategy of the bimanual force control changed from force error compensation (Ranganathan and Newell 2008) to force coupling (Kelso et al. 1979). The findings of the present study extended the complementary strategy for force error from the bimanual action to the joint action. Masumoto and Inui (2012) reported that a bimanual task exhibited a less variable interval than a unimanual task irrespective of visibility and change in force, congruent with the results of Helmuth and Ivry (1996). Helmuth and Ivry previously found that within-hand temporal variability was reduced in bimanual tapping compared with unimanual tapping, suggesting that the effect was due to combining the output of two separable timing systems. In the study of Masumoto and Inui (2012), however, although the bimanual task exhibited a less variable force than the unimanual task with visibility, there was no difference between the tasks for force variability without visibility. Similarly, in the present study with an image of the total force, the joint task exhibited a less variable force than the individual task (cf. Vesper et al. 2011). Hence, the new findings of the present study extended information about an important feature of the bimanual action of force to the joint action. Because interhemispheric information processing across the corpus callosum increases with force level in bimanual coordination (Diedrichsen et al. 2003), control centers for each hand are neuroanatomically linked. However, information processing between two participants during the joint action did not depend on neuroanatomical linkages between the control centers but visuomotor linkages between the participants.

Conclusion

In the present study two participants simultaneously adopted both complementary and synchronous strategies when total
force was visible. The joint action controlled force more accurately than the individual action. Thus two coordination strategies simultaneously facilitated the joint action. This suggests that during walking as a periodic movement, if two people lift and carry an object, they can produce complementary forces on the object and walk in synchrony. Presumably, as practice progresses in synchronized swimming, dance, and piano duets, joint actions exhibit larger performance gains than solo actions. In future studies we will examine effects of a call on complementary and synchronous strategies in a joint action using a periodic isometric force production. In addition, we will examine effects of a leader-follower strategy (see Konvalinka et al. 2010; Noy et al. 2011) on a joint action employing novice and experienced participants.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: J.M. and N.I. conception and design of research; J.M. and N.I. performed experiments; J.M. analyzed data; J.M. and N.I. interpreted results of experiments; J.M. prepared figures; J.M. and N.I. drafted manuscript; J.M. and N.I. edited and revised manuscript; J.M. and N.I. approved final version of manuscript.

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