RESEARCH ARTICLE

Force asymmetry deteriorates complementary force production during joint action

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Abstract

The present study aimed to determine the effects of force asymmetry on interpersonal force production. This study consisted of an individual task executed by one participant at a time in a pair, and three joint tasks executed by two participants simultaneously under conditions of 1:1, 1:0.75, and 1:0.5. Two individuals produced discrete forces at the same time so that the sum of forces they produced was the target force in the joint task. Under the 1:1 condition, the target force was the sum of the maximum voluntary contraction (MVC) produced by the index finger of each participant $\times 0.1$ (10% MVC). Under the 1:0.75 condition, the investigators manipulated the force produced by only one of the pair, for example, B, but not A. The feedback was also scaled as a result. The target force was the MVC of participant A + the MVC of participant $B \times 0.75 \times 0.1$. Similarly, the target force under the 1:0.5 condition was the MVC of participant A + the MVC of participant $B \times 0.5 \times 0.1$. The present study found that forces produced by pairs were negatively correlated and the correlation value was higher under the 1:1 condition than the 1:0.75 and 1:0.5 conditions. The absolute error was smaller under the 1:1 condition than the 1:0.5 condition. Complementary force production was attenuated and the error increased as differences between forces produced by two participants increased. Thus, asymmetry of forces produced by pairs deteriorated complementary force production and interpersonal performance.

Introduction

Everyday life and games include many motor tasks that are undertaken by more than one person at the same time. For example, if two people carry a table held at opposite ends, control can be distributed via complementary actions. Alternately, if several people simultaneously pull a rope in the same direction, control might be distributed in a redundant manner by executing the same actions. Many studies have examined whether dyads can outperform individuals in tasks when control is either distributed or redundant (see Wahn et al. 2018 for a review). Individuals tend to outperform

dyads or attain similar performance levels under distributed control (Bosga and Meulenbroek 2007; Knoblich and Jordan 2003; van der Wel et al. 2011). In contrast, dyads outperform individuals under redundant control (Ganesh et al. 2014; Masumoto and Inui 2013, 2014b, 2015, 2019; Reed et al. 2006). Wahn et al. (2018) described that the opportunity to freely distribute control is a crucial factor as to whether or not dyads can outperform individuals. A series of studies by Masumoto and Inui (2013, 2015, 2019) involved participants who controlled periodic force production while cycling between two target forces at a prescribed interval. When movement speed was constrained to synchronize interpersonal force outputs, the participants had the option to freely distribute force control in accordance with their coordination strategies and individual capabilities. As a result, joint action controlled force more accurately than individual action.

On the other hand, joint action can be balanced or unbalanced (Clark 1996). Although two participants play equal roles under balanced joint action, the roles differ under unbalanced joint action. Joint action in most previous studies has been taken as when two individuals lift and carry

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an object. However, these studies have rarely assumed that an adult and a child lifting and carrying an object represent unbalanced joint action.

In a study of unbalanced joint action by Konvalinka et al. (2010), pairs of participants maintained a given beat while synchronizing tapping movements to an audible signal. The individuals in pairs were given different instructions and different amounts of shared auditory information under unidirectional conditions (one-way interaction), in which a follow-the-leader strategy emerged. Under the bidirectional conditions (two-way interaction), each individual followed the other. The two individual systems became coupled as a result of interaction, suggesting the emergence of an interactive unit of two "hyper-followers". Noy et al. (2011) examined improvised joint action using a theater exercise called the mirror game, which they adapted using a custom device to measure motion in one dimension. Two participants faced each other while holding handles that can move along 55-cm long parallel tracks. The participants were told that it was a collaborative game in which the purpose was to have fun creating synchronized and interesting motions together. Under leader–follower conditions with one participant leading and the other following, performances were more variable among the followers than the leaders. By contrast, the participants who moved simultaneously under joint improvisation conditions without a designated leader could synchronize novel complex motions.

Konvalinka et al. (2010) and Noy et al. (2011) gave different instructions and different amounts of shared auditory information to two participants. In contrast, Masumoto and Inui (2014a) gave the same instructions and visual information to two participants in a task of redundant discrete isometric force production such that the sum of the forces they produced was the target force. They manipulated the participants' level of experience and found that stronger and earlier forces were always produced by those with low, rather than high force variability. Whereas pairs that included one experienced participant initially produced more complementary force than a pair of novices, the latter achieved similar performance levels after practicing. The unintentional leader–follower strategy based on force variability is better for force compensation during joint action. Although the instructions and amounts of shared information given to both members of the pair differed among Konvalinka et al. (2010), Noy et al. (2011), and Masumoto and Inui (2014a), none of these studies examined the effects of force asymmetry on joint action. Thus, the present study examined the effects of force asymmetry on interpersonal force production. The anticipation of one partner's movements by another based on reciprocal observation by each is involved in their complementary force output. Each partner's movements are anticipated by simulating their own movement based on anticipation of the other's movement; this is referred to as

"action simulation" (Sebanz and Knoblich 2009; Wolpert et al. 2003). Action simulation by two individuals under conditions of force symmetry allows prediction of a partner's actions based on internal predictive models within personal motor systems (Wolpert et al. 2003). In contrast, joint action simulation by two individuals under conditions of force asymmetry has to be achieved via different motor programs. Because both members of a pair would experience difficulty anticipating the other's motor programs, force asymmetry appears to deteriorate complementary force production during joint action.

Methods

Participants

Healthy males without any apparent neurological disorders [$n = 24$; mean age = 19.5 years, standard deviation (SD) = 2.5 years] were recruited for the present study. Handedness was tested using the Edinburgh Handedness Inventory (Oldfield 1971). Because all participants were right-hand dominant, the mean laterality quotient score was + 94.9 (SD = 8.6). All recruits provided written informed consent to participate, and the ethics committee of Hiroshima Bunka Gakuen University approved the procedures. The study protocol conformed to the ethical principles enshrined in the Declaration of Helsinki.

Procedure

This study consisted of one task performed by one individual (individual task) and three joint tasks performed by randomly paired participants (joint task). The individual task proceeded using half of the setup shown in Fig. 1a. For the individual task, the participants sat facing a load cell with their palms resting on a support surface 6 cm above a table (Fig. 1a). In this posture, the participants made discrete isometric pressing movements with the right index finger at the metacarpophalangeal joint with a target peak force of 10% maximum voluntary contraction (MVC). 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, which was indicated on a screen by a horizontal line.

The joint task consisted of 1:1, 1:0.75, and 1:0.5 force ratios as follows. For the 1:1 condition, the participants sat on chairs at opposite ends of a table facing the load cell and monitor (Fig. 1a). The target force comprised the sum of the MVC produced by the right index finger of each participant × 0.1 (10% MVC). The target force was standardized by having it represented as %MVC during all conditions because force variability increases as force production
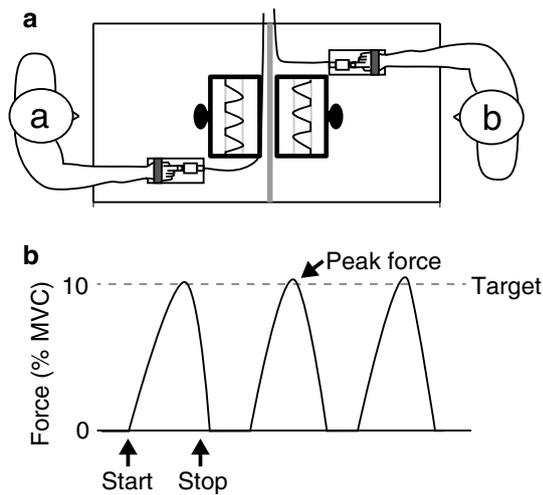
Fig. 1 Experimental setup (**a**) and definition and measurement of the dependent variable (**b**). **a** The individual condition used half of the setup; three joint conditions were executed by two individuals using the entire setup. **b** The start and stop of force production were indicated by audible metronome. Participants started and stopped producing force immediately after hearing a high and a low tone, respectively. The interval between high and low tones was 1 s, and the interval between high tones was 2 s. *MVC* maximum voluntary contraction

increases (Schmidt et al. 1979). This task did not prescribe the onset or contribution by each participant to the target force. The task displayed the target force for the pair and a sum of the forces that they produced on a monitor, but not the force output produced by each participant individually. The individuals in the pairs could not see the action of the other because two monitors were between them, and they were instructed not to speak to each other. In the 1:0.75 condition, the force produced by participant *A* was not manipulated, whereas that produced by participant *B* was manipulated by software (LabChart v7 for Windows, SD Instruments, Dunedin, New Zealand). However, both the participants did not know that the force produced by participant *B* was manipulated. The target force was the MVC of participants $(A + B \times 0.75) \times 0.1$. For example, if each participant produced a force of 5 N, 8.75 N was displayed on the monitor as the sum of the forces produced by two participants. The feedback was also scaled as a result while the force produced by participant *B* was manipulated. Similarly, in the 1:0.5 condition, the target force was the MVC of participants $(A + B \times 0.5) \times 0.1$. Two versions of the 1:0.75 and 1:0.5 conditions were implemented because participants
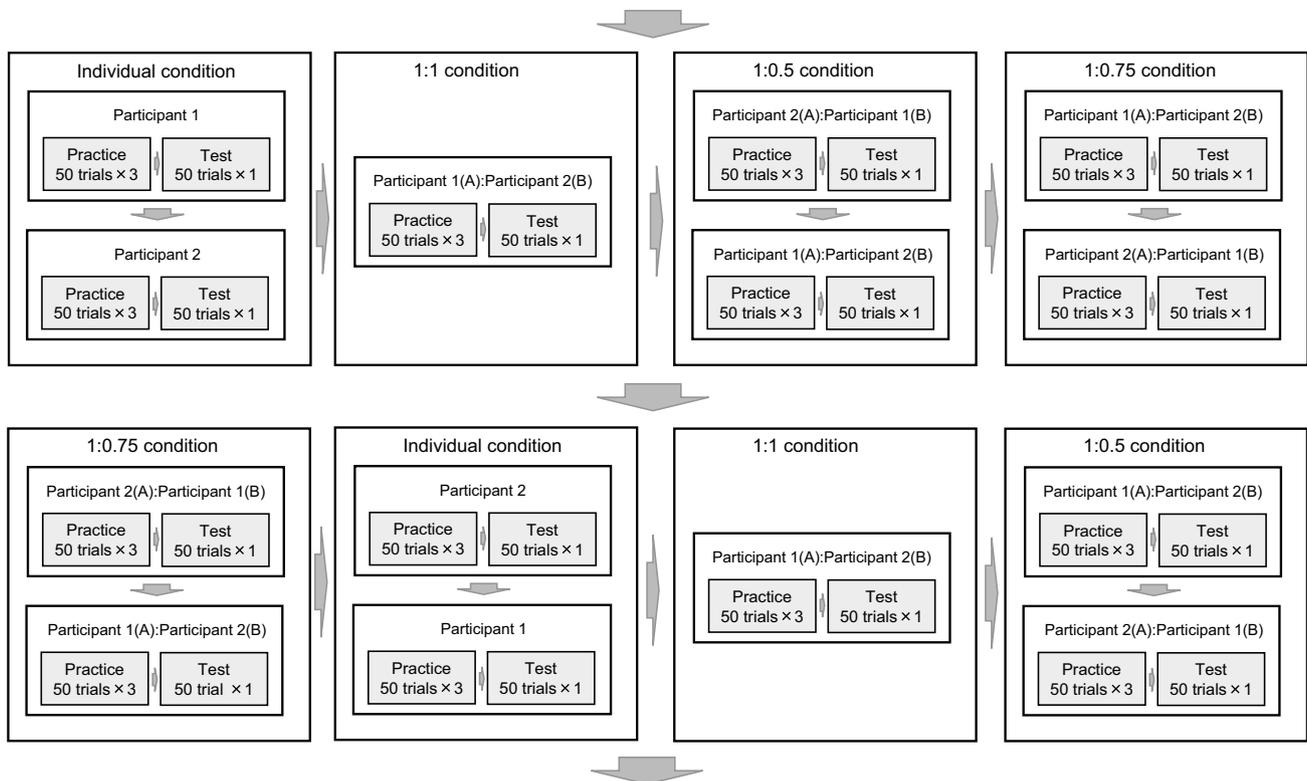

Fig. 2 Flow chart of the study. The experimental order of conditions varied randomly. Participants separately practiced each condition, and then immediately executed the test session. The first pair sequentially executed tasks under individual, 1:1, 1:0.5, and 1:0.75 conditions. The second pair sequentially executed tasks under 1:0.75, individual, 1:1, and 1:0.5 conditions. The order of condition execution by subsequent pairs was similarly varied

A and B were exchanged to balance the effects of different MVC on complementary force production (Fig. 2).

The participants' wrists were fixed to a rest mounted on the load cell using Velcro (Magic Tape, Kuraray Co. Ltd., Tokyo, Japan) at the start of the study. The participants each produced maximum force to determine the isometric MVC generated by the tip of the right index finger. They first positioned the distal pad of the index finger in contact with the load cell, and then applied as much pressure as possible to the load cell and maintained this force output for 3 s without lifting the hand and forearm. The mean MVC determined by an average of three trials was 29.5 (SD = 1.1) N and the order of the conditions was randomly varied to provide a counterbalance (Fig. 2). The participants separately practiced each condition and the corresponding test session followed immediately thereafter. After producing force 50 times in 3 practice sessions, the participants produced force 50 times during the test session. The start and stop times of the force production were indicated using a Model SQ100-88 audible metronome (Seiko Holdings Corp., Tokyo, Japan). The participants started and stopped producing force immediately after hearing a high and a low tone, respectively. The intervals between high and low tones were 1 s, and those between high tones were 2 s.

Apparatus and measurements

The output of the Model LUB-5 KB load cell rated at 5 kg (Kyowa Electronic Instruments, Co., Tokyo, Japan) pressed by the participants was amplified (Kyowa Model MCC-8A) and recorded using a Vostro200 personal computer (Dell, Round Rock, TX, USA) after the amplified signals were converted from analog to digital using PowerLab/8sp (SD Instruments). The force output was also displayed on a 20-inch computer monitor at 1440×900 pixel resolution located approximately 60 cm in front of each participant. Data were sampled at a frequency of 1000 Hz using a 16 bit A/D converter with a low-pass filter for 100 Hz. Figure 3 shows sample data from the individual and joint tasks. Total peak force produced simultaneously by both participants and the amount of force produced by each individually were assessed using analytical software (Emile Soft Co., Ltd., Tokushima, Japan).

Data analysis

First, we calculated correlation coefficients between forces produced by each individual in a pair of participants in the test session of three joint conditions to analyze the complementary strategy. Second, we calculated the ratio of the force produced by participant A to the total force (force produced by participants A + B) to determine force asymmetry. If the participants produced a target force according to the task
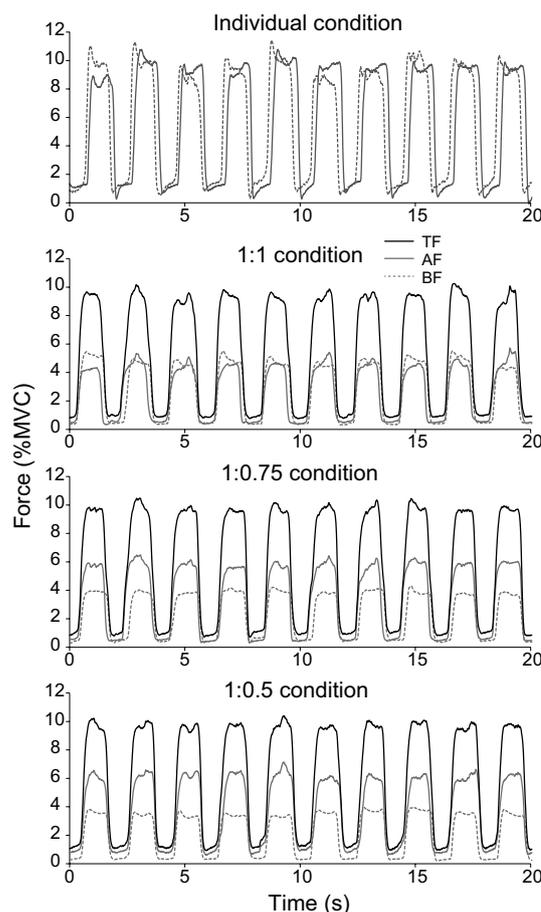

Fig. 3 Data sampled under individual and joint tasks. In the individual condition, the gray solid line represents the force produced by participant *A*, and the gray dashed line represents the force produced by participant *B*. In three joint conditions, the black line represents the total force. The gray solid or dashed line represents the force produced by participant *A* or *B*. *MVC* maximum voluntary contraction

demand, the ratios under the 1:1, 1:0.75, and 1:0.5 conditions were 0.50, 0.57, and 0.67, respectively. Third, we calculated the ratios of the force produced by each participant to the time-to-peak force to examine effects of individual force increase on interpersonal force asymmetry. Fourth, we calculated the absolute error of the total force from 50 discrete force peaks to determine the accuracy of force production in all test sessions under all conditions. The absolute error was determined as the average of errors, regardless of sign, over the total number of repeated force productions. Data were collected from 12 pairs under the 1:1 condition, and from 24 pairs under the 1:0.75 and 1:0.5 conditions because of the 2 versions of each.

Statistical analysis

First, correlation coefficients were standardized using a Fisher z transformation for averaging across complementary

force production generated by pairs. The main effects on the correlation between forces produced by both participants in three joint conditions were determined using one-way analyses of variance (ANOVA). Second, the main effects on the force ratios in three joint conditions were assessed by one-way ANOVA to determine force asymmetry. Because the ANOVA showed no significant main effect, one sample t test for each condition was conducted to examine the ratio against 0.5. Third, the main effects on the ratios of the force produced by each participant to the time-to-peak force in three joint conditions were assessed by one-way ANOVA to examine effects of individual force increase on interpersonal force asymmetry. Fourth, the main effects on the absolute error of force in three joint conditions were assessed by one-way ANOVA to determine accuracy in force because the error did not exert a main effect of tasks under all conditions. When significant overall condition effects were identified for a dependent measure, significant differences were determined using Tukey post hoc honestly significant difference (HSD) tests.

Results

The present study found that the forces produced by two participants were negatively correlated and the correlation value was higher under the 1:1 condition than the 1:0.75 and 1:0.5 conditions. The error was smaller under the 1:1 condition than the 1:0.5 condition. Complementary force production was thus attenuated and the error increased as the difference between forces produced by both participants increased.

Figure 4a shows that correlations between forces produced by both participants differed under three joint conditions ($F(2, 57) = 8.02$, $p < 0.001$). The post hoc test indicated that the correlation was more negative under the 1:1 condition than the 1:0.75 ($p < 0.05$) and 1:0.5 ($p < 0.001$) conditions. An increase in the difference between forces produced by both participants attenuated complementary force production.

Figure 4b shows that the ratio of the force produced by participant A to the total force did not differ under three joint conditions ($F(2, 57) = 1.67$, $p = 0.20$). The target ratio under the 1:1, 1:0.75, or 1:0.5 condition is 0.50, 0.57, or 0.67. The mean ratio under the 1:1, 1:0.75, or 1:0.5 condition was 0.50, 0.60, or 0.64, indicating that participants produced asymmetrical forces according to the task demand under the 1:0.75 and 1:0.5 conditions. One sample t test on the

Fig. 4 Forces produced by two participants under three joint conditions. **a** Correlations between forces produced by two participants. **b** Force ratio between forces produced by two participants (force of participant A/force of participant A + force of participant B). **c** The ratio of the force produced by each participant to the time-to-peak force (force/time-to-peak force). **d** Absolute error (AE) of total force
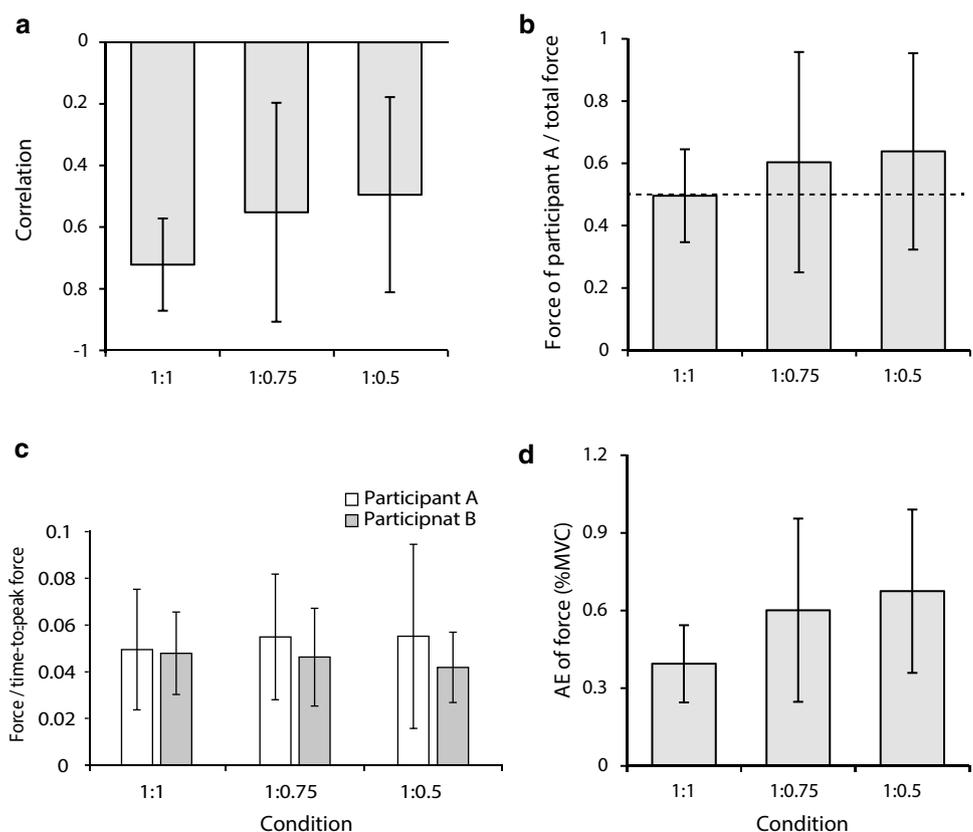
ratio showed that although the ratio did not differ from 0.5 under the 1:1 condition ($t(11) = -0.07$, $p = 0.94$), the ratios significantly differed from 0.5 under the 1:0.75 ($t(23) = 2.29$, $p < 0.05$) and 1:0.5 ($t(23) = 2.87$, $p < 0.01$) conditions. These ratios thus showed that two participants produced asymmetrical forces under both the 1:0.75 and 1:0.5 conditions.

Figure 4c shows that the ratio of the force produced by each participant to the time-to-peak force did not differ under three joint conditions ($F(2, 114) = 0.08$, $p = 0.92$). Although participant *A* seemed to have higher the ratio than participant *B* under the 1:0.75 and 1:0.5 conditions, there was no significant difference for ratio between participants *A* and *B* ($F(1, 114) = 2.41$, $p = 0.12$). Thus, asymmetrical forces produced by two participants under the 1:0.75 and 1:0.5 conditions were unable to be explained by this ratio.

Figure 4d shows that the absolute error of total force differed under three joint conditions ($F(2, 57) = 3.34$, $p < 0.05$). The post hoc test indicated that the error was smaller under the 1:1 condition than the 1:0.5 condition ($p < 0.05$). An increase in the difference between forces produced by two participants increased the error.

Discussion

In the present study, while two participants did not know that the force produced by participant *B* was manipulated under the 1:0.75 and 1:0.5 conditions, they simultaneously produced asymmetrical forces according to the task demand. The present study found that the forces produced by pairs negatively correlated and the correlation value was higher under the 1:1 condition than the 1:0.75 and 1:0.5 conditions. The absolute error was smaller for the 1:1 condition than the 1:0.5 condition. These novel findings indicated that complementary force production was attenuated and that the error increased with an increase in the difference between forces produced by two participants.

Konvalinka et al. (2010) and Noy et al. (2011) provided different instructions and different amounts of shared auditory information to pairs of individuals and identified a leader–follower relationship. Masumoto and Inui (2014a) provided the same instructions and visual information to pairs of individuals and found that a stronger and earlier force was always produced by the one who had lower rather than higher force variability. Their joint action spontaneously produced a leader–follower relationship in which individuals with lower performance followed those with better performance. The spontaneously produced leader–follower strategy is more effective for the force error compensation in the joint action executed by individuals with different levels of performance. In the present study, although pairs did not know that the force produced by participant *B* was manipulated under the 1:0.75

and 1:0.5 conditions, they produced asymmetrical force while they received well-scaling down of the force feedback from participant *B*. Similar to our previous findings (Masumoto and Inui 2013, 2014b, 2015, 2019), however, the correlation between forces produced by two participants was negative under all joint conditions, indicating that they each compensated for force error.

The complementary strategy is based on predictions of both an actor's own actions and a partner's actions rather than separate predictions for their actions because the strategy depends exclusively on visualization of the total force (Masumoto and Inui 2013). Because monitoring the collective output produced by pairs is essential for the error compensation mechanism, this suggests that there is a representation of the shared goal in between two participants. As the complementary force production depends on anticipating changes in the total force, two participants presumably share a collective goal (Loehr et al. 2013; Loehr and Vesper 2016) or a task representation (Sebanz et al. 2006) for a joint action by a comparison between anticipation of changes in the total force and visual feedback information. The representation of a shared goal underlies the negative correlation between forces produced by two people as an indicator of complementary force production.

In the present study, however, because the force produced by participant *B* was manipulated, both the total force and visual feedback were similarly manipulated. Consequently, the manipulation of the force produced by participant *B* caused an inaccurate comparison between anticipation of changes in the total force and visual feedback. The negative correlation between forces produced by two participants as an indicator of complementary force production was attenuated by an increase in the difference between forces produced by the two participants. Therefore, asymmetry of forces produced by pairs and the feedback deteriorated complementary force production.

In addition to a deterioration in complementary force production, an increase in the error under the 1:0.5 condition can be also explained due to the same mechanism as the deterioration. Well-scaling down of the force feedback from participant *B* made his force variations invisible to both participants *A* and *B* in an image of the total force they saw. Again, the manipulation of the force produced by participant *B* caused an inaccurate comparison between anticipation of changes in the total force and visual feedback. This leaded to larger errors in the joint task, as seen in Fig. 4c. Linking with an increase in the error, both participants *A* and *B* were unable to compensate for the force error fully, consequently deteriorating complementary force production in the asymmetrical joint action.

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