Benefiting from Being Alike: Interindividual Skill Differences Predict Collective Benefit in Joint Object Control

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Abstract

When two individuals perform a task together, they combine their individual skills to achieve a joint goal. Previous research has shown that interindividual skill differences predict a group's collective benefit in joint perceptual decision-making. In the present study, we tested whether this relationship also holds for other task domains, using a dynamic object control task in which two participants each controlled either the vertical or horizontal movement direction of an object. Our findings demonstrate that the difference in individuals' skill levels was highly predictive of the dyad's collective benefit. Differences in individuals' subjective ratings of task difficulty reflected skill differences and thus also turned out to be a predictor of collective benefit. Generally, collective benefit was modulated by spatial task demands. Overall, the present study shows that previous findings in joint decision-making can be extended to dynamic motor tasks such as joint object control.

Keywords: collective benefit; joint action; coordination; collaboration; task distribution; social cognition.

Introduction

In our modern world, controlling man-made objects has become an essential part of human everyday life. Human-object interactions range from simple tasks such as carrying a table (Sebanz, Bekkering, & Knoblich, 2006) to complex ones such as flying an airplane (Hutchins, 1995). Humans often do not perform these tasks alone but collaboratively in teams by distributing the task among team members to facilitate performance. For instance, when carrying a table up the stairs, the stronger person may hold the lower, heavier end of the table, or when flying an airplane, pilot and co-pilot efficiently distribute responsibilities.

While collaboration has obvious benefits, coordinating individual actions (in relation to external objects) also gives rise to costs such as the need to predict and integrate another person's action into one's own action plan. Whether benefits or costs prevail depends on a variety of aspects such as the type of control task, the information exchange between individuals, as well as individual skill levels. A study by Knoblich and Jordan (2003) tested whether groups could learn an anticipatory control strategy to jointly track a moving object. Results showed that groups managed to reach the level of individual performance *only if* given extensive training and external feedback about each group member's actions. In another task, individuals outperformed groups in a virtual object lifting task (Bosga & Meulenbroek, 2007). Yet, Masumoto and Inui (2012) provide evidence that in a joint force production task, a dyad's joint action is more successful than individual performance, provided the dyad receives external action feedback. Joint forces were also produced in a different study (van der Wel, Knoblich, & Sebanz, 2011) where participants had to control a pendulum-like object. But here, group and individual performance levels closely resembled each other. When two participants jointly controlled a ball in a virtual labyrinth game, they did not exceed the individual performance level either (Rigoli et al., 2015).

These differing findings across studies may be partly attributed to the use of different types of control tasks. Despite these task differences, it is notable that a collective benefit was only reached when coordinating individuals received some form of feedback about each other's actions. Another factor that has been shown to affect whether a group will outperform an individual or vice versa is the magnitude of the difference in individual skill levels. Previous research has demonstrated that such differences can reliably predict whether a dyad outperforms its more skilled member in a collaborative perceptual decision-making task (Bahrami et al., 2010). In particular, a dyad's collective benefit was higher the more similar the perceptual sensitivities of the two dyad members were. Importantly, the members' opportunity to verbally negotiate the joint decision was crucial for joint success.

Considering that the specific type of task as well as the flow of information between co-actors seem to substantially affect whether joint performance is beneficial, we aimed to test whether Bahrami et al.'s finding that interindividual skill differences predict collective benefit generalizes to a *non-communicative motor* task. Specifically, in contrast to discrete decision-making where two participants first make individual decisions and subsequently communicate to reach a joint decision, we used a dynamic object control task in which participants' interaction was continuous and verbal communication was prohibited.

A further objective was to test two predictions about joint performance: We predicted that joint success should depend on the specific type of spatial control required because action distribution may be more suitable for certain types of control than for others. For instance, flying an airplane in undisturbed midair demands a more coarse control than carefully landing the plane on a small airfield. We further predicted that assigning task contributions in accordance with co-actors' individual skills should facilitate joint performance.

To summarize, it is yet unclear whether and how interindividual skill differences, spatial task demands, and unequal task contributions influence collective benefit in a dynamic task in which communicative exchange is prohibited. Hence in the present study, we used a joint object control task to examine 1) whether the correlation between interindividual skill differences and collective benefit holds not only for perceptual decision-making (Bahrami et al., 2010) but also for dynamic object manipulation, 2) whether spatial task demands modulate the group's collective benefit, and 3) whether assigning task contributions in accordance with individuals' skills facilitates joint performance. We hypothesized that:

H1 Interindividual skill differences between dyad members will be negatively correlated with the dyad's collective benefit.
H2 A dyad's collective benefit will be additionally modulated by the type of spatial task demand (i.e., coarse vs. precise control).
H3 Assigning the higher task contribution to the more skillful dyad member will facilitate joint performance while assigning the lower task contribution to the more skillful member has a detrimental effect (relative to an equal assignment of task contributions).

Method

Participants

Twelve pairs of individuals (16 female, M = 24.83 years, SD = 3.05 years) participated in the study. Data collection was partly conducted at the Central European University in Budapest, Hungary (eight pairs) and partly at the University of Osnabrück in Germany (four pairs). All participants were right-handed and had normal or corrected-to-normal vision. They signed prior informed consent and received monetary compensation. The study was performed in accordance with the Declaration of Helsinki.

Apparatus and stimuli

The experimental setup consisted of two 24" Asus computer screens (resolution 1920 x 1080 pixels, 40.25° x 22.64° visual field, refresh rate 60 Hz) which were placed next to each other. A black cardboard partition (70 x 100 cm) was set up between them (Figure 1). On each screen, the following stimuli were presented (Figure 1): A circle (outlined in black, 0.9 cm = 0.71° diameter) was centrally displayed on a white background. A second, smaller circle (filled in black, 0.5 cm = 0.38° diameter), surrounded by another larger circle (outlined in grey, 4.2 cm = 3.21° diameter) was displayed in one of 16 possible positions. The central circle represented the cursor that participants controlled. The second circle was the target to which the cursor should be moved. The target's periphery was defined as homing-in zone. The target was 12.8 cm away from the start location of the cursor.

The experiment was programmed using the Python library Pygame and the experimental procedure and data collection were controlled by Python 2.7.3. The experiment was run on two Dell Precision computers.

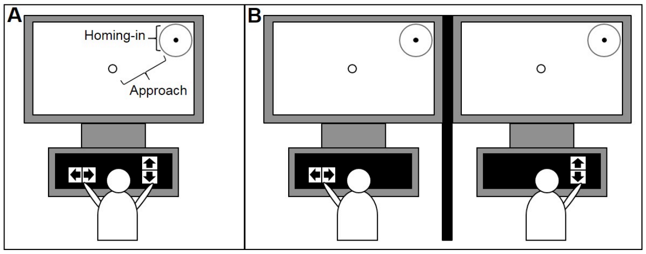

Figure 1: Via key presses, participants controlled the cursor's horizontal movement with the left and its vertical movement with the right hand. In the Individual Condition, participant controlled both dimensions (A); in the Joint Condition (B), control was distributed between participants.

Procedure

Participants were seated next to each other in front of two computer screens (at a distance of 85 cm), separated by a partition (see Figure 1B) such that they could neither see each other nor each other's screens. They were not allowed to talk and wore ear muffs throughout the experiment to shield external noise (e.g. the sound of key presses).

Participants performed the task both individually (Individual Condition) and together as members of a pair (Joint Condition). In the Individual Condition, each participant controlled the cursor displayed on their own computer screen whereas in the Joint Condition, participants jointly controlled one cursor and both screens showed identical displays. Participants first performed five practice trials in both conditions. After the practice, six experimental blocks each consisting of 40 trials followed. Individual and joint blocks alternated, i.e. participants first completed one block in the Individual or Joint Condition and then switched to the other condition in the next block. This way, three blocks in each condition were completed in a counterbalanced order across pairs.

At the start of each trial, the cursor appeared in the center of the screen. After one second, the target appeared in one of 16 possible locations (order of locations was randomized). Relative to the cursor's start location, the target was located in one of five angles (0°, 22.5°, 45°, 67.5°, 90°; see Figure 2). Each angle appeared eight times per block. Participants were instructed to move the cursor to the target as fast as possible and on the most direct path, and to stop the cursor exactly on the target. The target turned green when the cursor came to a halt on it. After the cursor had remained motionless on the target for one second, the trial was completed successfully and the next trial started. Two types of behavior were classified as errors: If the cursor moved into the homing-in zone but then exited it again, and if the cursor moved outside of the screen borders.

Participants controlled the cursor by pressing different keys on the keyboard which incremented the cursor's velocity either to the left, to the right, upwards, or downwards (compare Knoblich & Jordan, 2003). The 'left-key' (LK) and 'right-key' (RK) were controlled by the left hand and the 'up-key' and 'down-key' were controlled by the right hand (see Figure 1). If LK was pressed, the cursor started moving to the left. Another LK press accelerated the movement to the left, whereas a RK press decelerated it (by increasing its velocity into the opposite direction). Each key press caused a speed increment/decrement of 0.24°/s. Thus, if a participant had produced leftward movement by pressing LK e.g. four times, she needed to press RK also four times to decrease the cursor's velocity back to zero. If she pressed RK a fifth time, the cursor started moving to the right. In the Individual Condition, participants used both their left and right hand to control all four movement directions whereas in the Joint Condition, task control was distributed between the two members of a dyad such that the participant sitting on the left side controlled only the horizontal dimension (with her left hand) and the participant on the right side controlled only the vertical dimension (with her right hand). Participants were assigned randomly to either the left or the right side. The five different angles determined participants' relative contributions towards task completion in the Joint Condition: For 0° and 90°, only one dyad member controlled the cursor individually, as only horizontal or vertical movement was required. These angles served as baseline measure for individual performance within a joint setting ('baseline angles'). For the other three angles, both members had to contribute to achieve the task goal ('joint contribution angles'). For 45°, both members contributed equally ('50 % contribution'). For 22.5° and 67.5°, one of the members contributed more than the other ('30 % vs. 70 % contribution'); see Figure 2.

Task demands not only differed in terms of the relative contributions across trials but also regarding the two distinct movement phases within a trial, i.e., the Approach and the Homing-in phase (see Figure 1). The Approach was the interval from trial start to the moment the cursor entered the target periphery, where the Homing-in began. The Approach primarily required high movement speed whereas controlled braking and high spatial accuracy was required during the final Homing-in. As we hypothesized that the two movement phases ('Phase') as well as the three contribution angles ('Contribution') could differentially influence joint performance (cf. H2 & H3, respectively), they were included as factors in the analysis.

After task completion, participants were asked to rate (in written form) subjective task difficulty of joint and individual performance on a 7 point scale (1 = very easy, 7 = very difficult). The experiment lasted about 80 minutes.

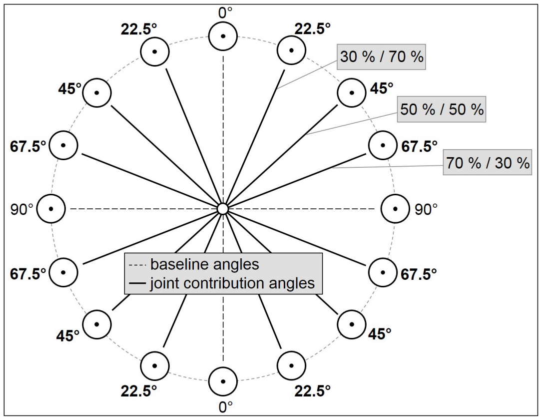

Figure 2: Contribution angles: For 0° only vertical and for 90° only horizontal control by one participant was required. For 45°, both participants contributed equally, and for 22.5° and 67.5°, one participant contributed 40 % more than the other (i.e., contributions were split 30 % / 70 %).

Data preparation and analysis

Prior to analysis, all error trials were removed from the data set (6.7 %). Statistical analyses were done in R (2014).

As performance measures, we derived reaction time (RT) and distance travelled (DIST). RT was the time between cursor appearance and arrival at target. DIST was the absolute path length the cursor traveled from start to target location. Both RT and DIST were also calculated separately for each movement phase. The values for Approach were the time/distance from cursor appearance/start location to crossing the target periphery. The remaining time/distance until arrival at target were the Homing-in values. RT and

DIST served as central measures since participants' goal was to move to the target as fast and as directly as possible.

To evaluate whether performing as a dyad was more efficient than performing alone, we compared each dyad's performance to the performance of the better member of that dyad. Following Bahrami's terminology, a *collective benefit* is achieved if the dyad outperforms the better individual. As lower values of the dependent variables indicate better performance, we calculated the collective benefit by dividing the better member's measurement by the dyad's value. For instance for RT, the faster member's RT (RT min) was divided by the dyad's RT (RT dyad). Values above 1 indicate a collective benefit because dyad RT is lower than the faster member's RT. This measure was calculated separately for the Approach and the Homing-in phase – averaged across all contribution angles as well as separately for each of the three contribution angles (30 %, 50 %, 70 %; defined for the better member's contribution, see Figure 3). We predicted (cf. H3) that the 70 % contribution should result in a higher collective benefit because the better member's contribution dominates joint performance. Conversely, a lower collective benefit should be achieved for the 30% contribution because the weaker member's contribution dominates joint performance.

Besides testing whether joint performance would result into an overall collective benefit, we investigated in what way two individuals' performances determine the dyad's joint performance. Based on previous findings (Bahrami et al., 2010), we predicted that the quality of a dyad's performance is determined by the magnitude of the difference between the two individual performances, such that the smaller the individuals' performance difference, the larger their collective benefit during joint performance (cf. H1). To test whether the difference between two individuals' performances is indeed a predictor of their collective benefit, we divided the better individual's performance value by the worse individual's performance value. For instance, the RT ratio was composed of the faster member's RT (RT min) divided by the slower member's RT (RT max). For the resulting skill ratio, a value of 1 indicates that both members perform equally well individually whereas an increasingly lower ratio indicates a larger interindividual performance difference. In our subsequent analysis, we correlated these interindividual skill ratios with the collective benefit for each of the contribution conditions, separately for Approach and Homing-in. We predicted that the collective benefit systematically increases with larger skill ratios, suggesting that dyad members who have increasingly similar individual performance levels benefit more from performing jointly – particularly when both members contribute equally to the joint performance. If however the better individual's dominance compensates for a large interindividual difference (as in the 70% contribution condition), we predicted a reduced correlation relative to the other contribution conditions (cf. H3).

Results

Social facilitation

To exclude the theoretical possibility that differences between individual and joint performance are due to social facilitation (individual performance being affected purely by someone else's nearby presence), we compared RT in the Individual and Joint Condition for the baseline angles in which only one participant controlled the cursor. This comparison was done separately for the Approach and Homing-in phase. We found no significant RT difference for these comparisons (Approach: $t(11) = -0.03$, $p = .979$, Cohen's $d = -0.04$; Homing-in: $t(11) = -0.14$, $p = .894$, Cohen's $d = -0.06$), indicating that participants' performance was not affected by the joint setting. This finding was confirmed by the results for DIST (Approach: $t(11)= -0.92$, $p = .376$, Cohen's $d = -0.27$; Homing-in: $t(11)= -0.28$, $p = .782$, Cohen's $d = -0.08$). For all further analyses, we focused on the joint contribution angles.

Collective benefit

To determine whether joint control was beneficial, we tested whether the collective RT benefit was larger than 1, using one sample t-tests. Results showed that for Approach, dyads did not outperform the better member ($t(11) = -0.88$, $p = .396$, Cohen's $d = -0.26$) whereas a collective benefit was achieved for Homing-in ($t(11) = 2.96$, $p = .013$, Cohen's $d = 0.86$) (Figure 3A). In line with our hypothesis H2, this result suggests that distributing task dimensions is advantageous for precise spatial control over short distances (as during Homing-in) but not for longer distances when speed is prioritized over spatial accuracy (as during Approach).

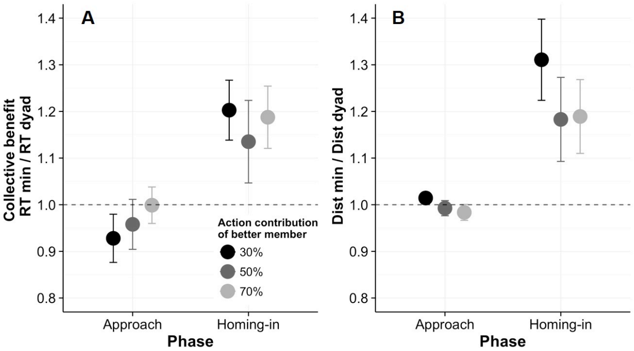

Figure 3: Mean collective benefit for A: RT and B: DIST. Dyads obtained a collective benefit > 1 (see dashed line) for Homing-in only. Error bars reflect Standard Errors.

To test our hypothesis H3 that collective benefit might differ between the three contribution angles, we performed a 2 x 3 repeated measures ANOVA (Phase x Contribution). We found a significant main effect of Phase ($F(1,11) = 20.57$, $p < .001$), indicating that the collective benefit was higher for Homing-in than Approach, as shown by the previous analysis. Neither a significant main effect of Contribution ($F(2,22) = 1.00$, $p = .384$) nor a significant interaction effect between the two factors ($F(2,22) = 1.31$, *p*

= .288) was found, demonstrating that collective benefit did not differ between contribution angles.

These findings were corroborated by the analysis of our second performance measure DIST (Figure 3B). As for RT, a collective benefit was present for Homing-in ($t(11) = 3.20$, $p = .008$, Cohen's $d = 0.92$) but not for Approach ($t(11) = -0.24$, $p = .822$, Cohen's $d = -0.07$) and the ANOVA results showed a significant main effect of Phase ($F(1,11) = 12.18$, $p = .005$), but neither a significant main effect of Contribution ($F(2,22) = 2.09$, $p = .147$) nor a significant interaction effect ($F(2,22) = 0.99$, $p = .389$).

Interindividual differences as predictor

Regarding the predicted correlation between interindividual skill ratios and collective benefit measures, results for RT showed that the skill ratio significantly predicts collective benefit for the 30 % and the 50 % contribution angles for Approach (30 % contribution: $r = .90$, $t(10) = 6.46$, $p < .001$; 50 % contribution: $r = .91$, $t(10) = 7.02$, $p < .001$) (Figure 4A). As hypothesized, there was no significant correlation for the 70 % contribution ($r = .48$, $t(10)= 1.75$, $p = .111$). Pairwise comparisons between the correlation value of the 70 % contribution and the values of the two other contribution angles demonstrated a significant difference for both comparisons (70 % vs. 30 %: $z = 2.87$, $p = .004$; 70 % vs. 50 %: $z = 3.01$, $p = .003$) (cf. Steiger, 1980).

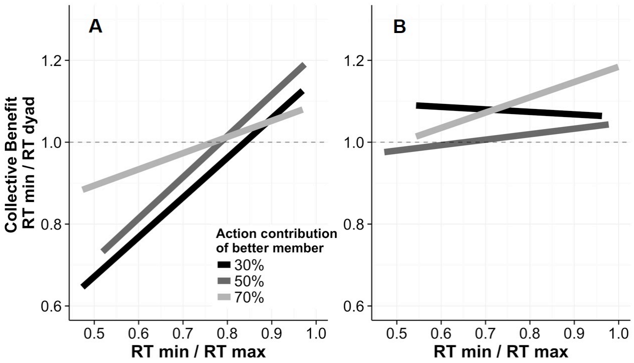

Figure 4: The dyad member's RT ratio predicts the dyad's collective benefit for A: Approach but not B: Homing-in.

In sum, these results indicate that the interindividual RT ratio highly predicts a dyad's collective benefit (cf. H1). Moreover, the predictive power of the RT ratios is significantly reduced when large interindividual differences are compensated for by the better individual's dominant contribution in comparison to the other two contribution angles, suggesting that the collective benefit depends on the individuals' relative action contribution (cf. H3).

For Homing-in (Figure 4B), analyses yielded a significant correlation for the 70 % contribution angle ($r = .58$, $t(10) = 2.27$, $p = .047$) but not for the other two angles (30 % contribution: $r = .38$, $t(10) = 1.32$, $p = .217$; 50 % contribution: $r = .41$, $t(10) = 1.43$, $p = .183$). However, pairwise comparisons showed no significant differences between contribution angles (70 % vs. 30 %: $z = 0.74$, $p = .459$; 70 % vs. 50 %: $z = 0.51$, $p = .614$). Overall, these findings indicate that the interindividual RT ratios predict the collective benefit for Approach but not for Homing-in.

In contrast to the RT results, we did not find significant correlations between interindividual DIST ratios and collective benefit for Approach (30 % contribution: $r = -.23$, $t(10) = -0.73$, $p = .48$; 50 % contribution: $r = -.28$, $t(10) = -0.91$, $p = .39$; 70 % contribution: $r = .09$, $t(10) = 0.29$, $p = .778$). For Homing-in however, interindividual DIST ratios predicted the collective benefit significantly for the 70 % ($r = .62$, $t(10) = 2.51$, $p = .030$) and close-to-significantly for the 30 % contribution angle ($r = .57$, $t(10) = 2.18$, $p = .054$), but not for the 50 % contribution angle ($r = .31$, $t(10) = 1.04$, $p = .183$). The lack of significant correlations for Approach can be explained by participants' overall low variability for DIST in Approach (Approach SD = 0.04 vs. Homing-in SD = 0.15, see Figure 3B).

Subjective difficulty as predictor

Finally, we explored whether differences in individuals' subjective experience might be related to the quality of their joint performance. We hypothesized that participants' introspective access may allow for accurate ratings of perceived task difficulty, thereby effectively providing an indirect measure of one's own performance.

We used participants' ratings of individual task difficulty and subtracted the rating of the faster dyad member from the rating of the slower member. These difference values were then correlated with the collective RT benefit measures (for each of the contribution conditions, separately for Approach and Homing-in). Results showed that for Approach, the difference in difficulty ratings indeed significantly predicted the collective benefit for all contribution angles (30 %: $r = -.73$, $t(10) = -3.33$, $p = .008$; 50 %: $r = -.76$, $t(10) = -3.67$, $p = .004$; 70 %: $r = -.58$, $t(10) = -2.23$, $p = .050$). For Homing-in, we found significant correlations for the 30 % ($r = -.76$, $t(10) = -3.74$, $p = .003$) and 70 % ($r = -.59$, $t(10) = -2.33$, $p = .042$) contribution angles, as well as a trend towards significance for the 50 % contribution angle ($r = -.55$, $t(10) = -2.09$, $p = .063$). These results indicate that the differences in participants' subjective difficulty ratings can be used to predict the collective temporal performance benefit.

The same tests were conducted with the collective DIST benefit measure. Based on the finding that only Homing-in performance is predicted by interindividual DIST ratios, we computed the correlations with the rating differences only for Homing-in. Yet no significant correlations were found (30 %: $r = -0.46$, $t(10) = -1.66$, $p = .128$; 50 %: $r = -0.33$, $t(10) = -1.10$, $p = .296$; 70 %: $r = -0.43$, $t(10) = -1.49$, $p = .167$), suggesting that subjective difficulty ratings cannot be used to predict the collective spatial performance benefit.

Discussion

The aim of the present study was to target a gap in the existing literature by examining group performance in a dynamic object control task. We investigated whether the relationship between interindividual skill differences and collective benefit previously found for perceptual decision-making (Bahrami et al., 2010) also holds in a dynamic motor task (cf. H1). Whereas Bahrami et al. used a discrete perceptual decision-making task in which two participants first took individual decisions and subsequently communicated to reach a joint decision, we used a dynamic task in which participants' interaction was continuous. Two members of a dyad jointly controlled a cursor movement with the shared goal of moving it to a target location, while one member controlled the vertical and the other member the horizontal movement dimension. In contrast to Bahrami et al. (2010), group members were not allowed to verbally communicate. Additionally, the present task tested whether spatial control demands (coarse vs. precise control) affect collective benefit (cf. H2). Finally, we manipulated the dyad members' relative action contributions to test whether assigning the higher task contribution to the more skillful dyad member facilitates joint performance (cf. H3).

Despite using a dynamic instead of a discrete task and not allowing verbal exchange between participants, the present data are in line with Bahrami and colleagues' (2010) finding that a dyad's collective benefit varies according to the interindividual skill differences of its members (cf. H1). Thus our results generalize our current knowledge regarding individuals' skills as predictors of collective benefit to the domain of dynamic object control, demonstrating a systematic relationship between interindividual skill ratios and the quality of joint performance. Adding to Knoblich and Jordan (2003) who highlighted the influence of external action feedback on collective benefit in object tracking, we identify interindividual skill differences as a further predictor for collective benefit in a similar motor task.

When comparing the dyad's performance to the performance of the more skillful dyad member, we found that dyads outperformed the individual in the Homing-in phase of the task while there was no such collective benefit in the Approach phase. This suggests that collective benefit is modulated by spatial task demands such that joint control is advantageous only for precise but not for coarse spatial control (cf. H2). The two phases may have also differed in overall task difficulty – future studies are needed to tease apart the effects of spatial control type and of overall control difficulty. With regard to spatially coarse control, we showed that the influence of individual skill differences on collective benefit can be effectively reduced by assigning contribution percentages in accordance with the individual skill level (cf. H3).

Finally, the present study shows that not only individuals' performance differences but also differences in individuals' subjective experience predict the quality of their joint performance. Relatedly, Bahrami and colleagues' (2010) found that collective benefit was highly dependent on whether participants were allowed to share their confidence ratings when agreeing on a joint decision. Both confidence ratings as well as subjective difficulty ratings require assessing one's own performance level. In Bahrami et al.'s (2010) task though, participants *shared* their confidence before taking a joint decision. In the present study, subjective task difficulty was *privately* assessed after task completion. When assessing task difficulty, participants could rely on introspective access and/or regard their own skill in relation to their task partner's. In any case, participants' ratings provided an indirect performance measure such that interindividual rating differences predict the dyad's collective benefit. Possibly, sharing these ratings online might have further improved a dyad's performance.

Taken together, the present study shows that the collective benefit in a joint object control task depends on interindividual skill differences, as well as on the type of spatial task demand. Future research could investigate whether interindividual skill differences are viable predictors for other types of joint action.

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