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The sense of agency during skill learning in individuals and dyads

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ABSTRACT

The sense of agency has received much attention in the context of individual action but not in the context of joint action. We investigated how the sense of agency developed during individual and dyadic performance while people learned a haptic coordination task. The sense of agency increased with better performance in all groups. Individuals and dyads showed a differential sense of agency after initial task learning, with dyads showing a minimal increase. The sense of agency depended on the context in which the task was first learnt, as transfer from joint to individual performance resulted in an illusory boost in the sense of agency. Whereas the quality of performance related to the sense of agency, the generated forces to achieve the task did not. Our findings are consistent with a predictive model account at the perceptual level, such that the sense of agency relies most strongly on sharable perceptual information.

1. Introduction

People perform an immense variety of actions together with others. For example, they carry heavy objects, play music and team sports, and build houses together. Much research has recently investigated how people plan and coordinate such joint actions. In this article, rather than focusing on the processes that may support successful joint actions, we focus on the experiences actors have when engaging in joint actions. We ask how the experience of being in control (i.e., the sense of agency) develops when people learn a new task alone versus together, and whether the sense of agency differs for individual actions versus joint actions. In addition, we examine how developing a sense of agency individually transfers to sensing agency over joint actions, and vice versa.

The sense of agency has often been studied in tasks that vary along two dimensions; an actor (a) objectively either causes (or is subjected to) or does not cause (or is not subjected to) the action (Haggard & Tsakiris, 2009; Metcalfe & Greene, 2007) while (b) an alternative cause for the action is either present or absent (e.g., Sato, 2009; Sato & Yasuda, 2005). A central question in this approach is under what conditions people experience agency over actions they do not produce themselves, or fail to experience agency over actions they do in fact cause. Additional studies have studied the sense of agency in relation to whether movements are actively or passively generated, and in relation to the timing of the feedback accompanying these movements (e.g., Tsakiris, Longo, & Haggard, 2010).

But how do people experience agency over actions they intentionally produce together with somebody else? Before we delve into this question, it is useful to first consider potential differences between individual and joint actions in terms of requirements on action planning and control. We will then outline the major theoretical frameworks concerning the sense of agency, and extract predictions from them for the sense of agency for joint actions.

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2. Individual actions and joint actions

Successfully performing a joint action requires several processes for action planning and action coordination. Some of these processes are not specific to joint action, but also operate when people perform actions by themselves. For example, regardless of whether people act alone or together, they may form predictions about the expected consequences of their actions. In addition, feedback about the action is available from different modalities in both cases. Processes involved in comparing the expected consequences to the actual consequences could operate for both individual and joint action as well (Pacherie, 2011).

Despite these similarities, there are also clear differences between individual and joint actions. At a relatively abstract level, joint actions pose additional planning requirements that people do not face when acting alone. In particular, it is thought that the people involved in the action need to take each other's intentions into account and form shared intentions (Tomasello, 2009). They then need to form some representation of the particular actions and the role they themselves as well as the other people involved play to accomplish the goal (Knoblich, Butterfill, & Sebanz, 2011). One of the most prominent accounts, by philosopher Bratman (1992, 2009a, 2009b), holds that this could be accomplished through the interlocking of intentions and by the formation of sub-plans for the involved actors that could mesh together, allowing for them to be co-realizable.

There are also other, less abstract differences between individual actions and joint actions. At lower perceptual and motor levels, people do not have full information available about the joint action as a whole. Instead, they have information about their own contribution but can only estimate the contribution of a co-actor. The predicted consequences of their own actions as well as of the co-actor's actions then need to be integrated to monitor and adjust performance with respect to the joint goal. Several mechanisms may support the prediction and integration of a co-actor's actions with an actor's own actions. One of these is the overlap in functional (e.g. Jeannerod, 1999, 2003; Prinz, 1997) and neural (e.g. Rizzolatti & Craighero, 2004; Rizzolatti & Sinigaglia, 2010) mechanisms for action production and action observation. Due to this overlap, people may represent their own and others' actions in a commensurable format. Another functional mechanism is task co-representation, the ability of actors to form a representation of their co-actor's task that specifies which events require the co-actor to act (e.g., Sebanz, Knoblich, & Prinz, 2003, 2005; Wenke et al., 2011). Thus, people do have several mechanisms in place that support joint actions. Some of these mechanisms are not necessarily required or not at all required to operate during individual actions. Finally, joint actions differ from individual actions in the ease with which people can keep track of their own contribution during action production. That is, as joint actions inherently are ambiguous with regard to who caused what, individual actions do not have this feature (or at least not to the same extent).

3. Theories addressing the sense of agency

What are the implications of these differences between individual and joint actions for the sense of agency people experience over these actions? Several theoretical accounts provide a foundation for making predictions about the sense of agency for joint actions (see van der Wel and Knoblich (in press) for a review). These accounts are reminiscent of the historical debate between William James and Wilhelm Wundt on the contributions of central and peripheral sources to the conscious experience of actions (see Jeannerod (2006) for a review). A first account is Wegner's theory of apparent mental causation (Wegner, 2002; Wegner, Sparrow, & Winerman, 2004; Wegner & Wheatley, 1999). According to this theory, the extent to which people experience agency over an action depends on three factors; whether a thought corresponding to the action precedes the action (priority), whether the action is consistent with the intended action (consistency), and whether an alternative cause for the action is present or not (exclusivity). It is important to note that this account of agency is postdictive, in the sense that agency is established after the action has been completed. Supporting evidence comes from studies demonstrating that people experience authorship for actions they never performed, as long as priority, consistency, and exclusivity are preserved (Wegner, Sparrow, & Winerman, 2004; Wegner & Wheatley, 1999), as well as from studies showing that people experience their actions to be influenced by others when these provide a potential alternative cause (Wegner, Fuller, & Sparrow, 2003).

Another account for the sense of agency is based on the forward model account of action control. This account states that the sense of agency arises from the quality of the match between the predicted sensory consequences that are based on the motor commands issued to execute an action and the actual sensory consequences arising from that action (Blakemore & Frith, 2003; Frith, Blakemore, & Wolpert, 2000). The better the fit, the stronger the sense of agency people will experience. It is important to note here that the sense of agency in this account is established during action execution (or perhaps even earlier, see Fotopoulou et al., 2008) rather than postdictively, and that it depends on input from all available sensory modalities.

Evidence consistent with the forward model account for agency comes from studies showing that gradually disrupting the consequences of actions by for example introducing temporal delays or spatial inconsistencies gradually reduces the sense of agency (e.g., Fourneret & Jeannerod, 1998; Knoblich & Kircher, 2004; Sato, 2009; Sato & Yasuda, 2005). A fundamental issue in evaluating the adequacy of the forward model account for agency however is whether the comparison of estimated actual state against predicted consequences for establishing a sense of agency over an action resides at the perceptual or at the sensorimotor level (Gallagher, 2007; Knoblich & Repp, 2009; Pacherie, 2008, 2011; Repp & Knoblich, 2007).

Whereas the forward model account focuses on the use of sensorimotor information, there are several reasons to believe that establishing a sense of agency may arise predominantly at the perceptual level. For one, there are theoretical reasons to suppose that actions are planned in terms of their perceptual effects rather than in terms of the movements to achieve them (Hommel, Muesseler, Aschersleben, & Prinz, 2001; Prinz, 1997). One theoretical advantage is that this reduces the deep gap between perception and action that dominates more traditional accounts of action perception and action planning. Second, with respect to the sense of agency it has been shown that people can be led to apply sizeable corrections to their movements without noticing it as long as the perceptual consequences of their movements are consistent with the goal they want to achieve (de Fourneret & Jeannerod, 1998; de Vignemont & Fourneret, 2004). Under these circumstances, proprioceptive information related to the implementation of motor commands and the positioning of the limbs is effectively ignored. Finally, it is known from several patient populations that people may have difficulties with sensing agency (e.g., Fletcher & Frith, 2009) even though they do not show impairments in for example error correction during action execution. Taken together then, people may not be as sensitive to sensorimotor cues for sensing agency as the forward model account would suggest.

For understanding the sense of agency for joint action, the use of predictive internal models still provides a useful vehicle if we consider the match between predicted and actual consequences of actions at the perceptual level. Moreover, moving from the sensorimotor level to the perceptual level here would allow people to use similar mechanisms for predicting their own actions and the actions of their coactor, making their integration easier. In terms of perceptual consequences, if the performance on a task (i.e., the perceptual consequences of their own and the co-actor's actions) closely matches what is expected, then making predictions about performance should work just as well for joint actions as it would for individual actions. This raises the question whether the accompanying sense of agency for individual and joint actions would be different at all.

4. Sense of agency during individual and joint performance of the same task

Before explicating the predictions for joint action that follow from prior accounts of agency, we first discuss what a useful task for studying the sense of agency in individual and joint action would look like. To study agency in individual versus joint actions, a useful situation would be one in which the subjective sense of agency could be studied while the objective performance on a task is similar for individuals and dyads. The reason for this is that it would allow one to make inferences about differences in the experiential nature of performing actions alone versus together without having to consider to what extent these differences are due to differences in the objective quality of performance. In addition, it would be desirable for the task under examination to be novel for individuals and dyads, as otherwise this may introduce differences in the sense of agency due to differential amounts of prior experience with the task. Thus, a useful setting to study the sense of agency in individuals and dyads would include a novel task that individuals and dyads learn at approximately the same rate.

A priori, one may suspect that developing a task that people learn equally while performing individually and jointly is not easy because individuals have and dyads do not have internal information about the whole task. Indeed, the previous literature on joint action coordination tasks that rely exclusively on visual information generally shows that dyads learn new tasks at a slower rate than individuals do (e.g., Bosga & Meulenbroek, 2007; Knoblich & Jordan, 2003; Newman-Norlund, Bosga, Meulenbroek, & Bekkering, 2008). However, in a recent experiment we found that providing dyads with a haptic linkage (in addition to visual information sharing) allowed dyads to learn a new coordination task just as quickly as individuals performing the same task bimanually (van der Wel, Knoblich, & Sebanz, 2011). In this task, we asked participants to rotate a pole that moved around a fixed axis (i.e., a modified pendulum) back and forth between two targets. They did so by pulling on cords attached to the base of the pole, one on each side (Fig. 1). By measuring the pole angle during performance we could extract the pole's reversal points relative to the specified target areas, as well as the speed of performance. These measures allowed us to determine how quickly and successfully individuals and dyads learned this new coordination task. The results indicated that individuals and dyads were indistinguishable with respect to their rate of learning as well as the quality of learning the task.

Because the rate of learning for our coordination task (van der Wel et al., 2011) was similar for individuals and dyads, this task provides a useful vehicle for studying how the sense of agency develops while individuals or dyads learn a new skill. In particular, as the perceptual consequences of actions are approximately the same when the task is performed individually or jointly it can be determined whether the match between expected and actual perceptual consequences of action impacts the sense of agency similarly or differentially for individuals versus dyads.

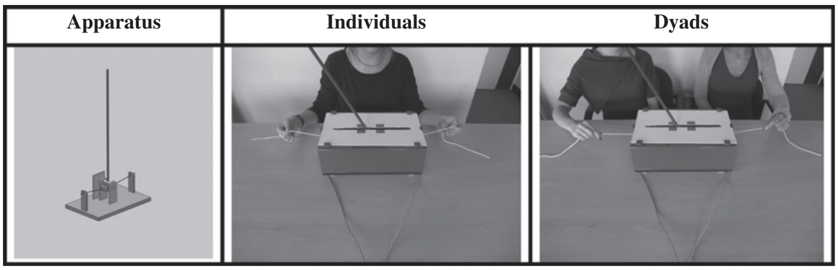

Fig. 1. Overview of the experimental apparatus, and the task for individuals and dyads.

5. Predictions

What are the predictions for joint agency versus individual agency that follow from the different theoretical frameworks outlined earlier? Based on the theory of apparent mental causation, the sense of agency should always be weaker during joint actions compared to individual actions because the criterion for exclusivity is never met during joint actions. That is, because a coactor is always present people can never be sure whether they cause (parts of) an action themselves or not. In addition, Wegner's account suggests that the sense of agency should be stronger for tasks people perform well compared to tasks they do not perform well as the results of people's actions would be more consistent with their expectations.

For the predictive internal model account, we could deduce two sets of predictions, one based on the sensorimotor level and one based on the perceptual level. If people rely on the match between expected and actual consequences of their actions at the sensorimotor level (the sensorimotor account), then the sense of agency should be weaker during joint compared to individual actions. The reason for this is that the mapping between the motor commands that are issued and the consequences of these commands on task performance are not clearly defined during joint action. Rather, they depend on what the coactor does. In addition, the sensorimotor account predicts that the sense of agency increases the better people perform, as the expected sensory consequences of actions would match the predicted sensory consequences more closely in that case.

Whereas the preceding two predictions clearly follow from the sensorimotor account, we also derived a more tentative prediction from this account. This prediction is that the sensorimotor account would suggest that the more an actor contributes to a task (the more force they put into it in this case), the stronger the sense of agency should be. At the sensorimotor level, generating more force implies providing a clearer signal to one's own motor system. That is, the ratio of signal to noise for detecting the expected consequences of one's own motor commands should improve as one applies more force. This prediction is not as strongly specified, however, as it depends in part on the relation between the forces applied on each side of the task. In the dyad case, it may also depend on whether someone is generating more or less force than their partner in the task.

The sensorimotor account makes the same prediction about a reduction in the sense of agency for the joint condition as the theory of apparent mental causation does, although for different reasons. Whereas the theory of apparent mental causation predicts a reduction in the sense of agency for dyads because the criterion for exclusivity is not met, the sensorimotor account predicts such a reduction because the link between issued motor commands and sensory consequences is less clear. Importantly, the two accounts differ in other ways; whereas the sensorimotor account predicts a relationship between the amount of exerted force and the sense of agency, the theory of apparently mental causation does not predict such a relationship.

In contrast to the sensorimotor account, the use of predictive models at the perceptual level (the perceptual account) would predict that the sense of agency for joint actions depends (predominantly) on the match between the expected and actual perceptual consequences of actions. Because predictions at this level are not restricted to actions one performs oneself, this version of the predictive model account would predict that the sense of agency predominantly depends on how well people perform, as the perceptual consequences of actions are easier to predict the better people perform. Thus, both the sensorimotor account and the perceptual account predict that the sense of agency depends on how well people perform, but the sensorimotor account in addition predicts that the sense of agency is reduced during joint action compared to individual action.

A final question we explored is whether the way in which a certain skill was learned (alone or together with another person) affects a person's sense of agency when exerting the learnt skill later on. The question here is how the sense of agency may change when performing a task jointly after having learned it by oneself, or when performing a task individually after having learned the task together with someone else. Little is known about how developing a sense of agency during individual performance subsequently impacts agency during joint performance, and vice versa. For example, one could ask whether a newly licensed driver experiences a heightened sense of agency at first because they do not share control with a driving instructor anymore. Similarly, do musicians who are used to performing solo feel a diminished sense of agency when they first start playing in an orchestra? The answers to these kinds of questions could further shape theoretical models of the sense of agency. To gain a full appreciation of the sense of agency, it would be useful to know to what extent the sense of agency is influenced by the context of previous exposure. To explore this issue, we also included transfer conditions in our experiment. The predictive model accounts and the theory of apparent mental causation do not make specific predictions for the sense of agency with regard to potential transfer effects from individual to joint performance and vice versa. That is, for these theories performing individually versus jointly may induce a differential sense of agency, but these theories do not address whether the sense of agency may differ during individual or joint action depending on the context in which one has learned a task (i.e., performing individually or jointly).

6. Method

6.1. Participants

In total, 105 participants (35 males and 70 females between the ages of 18 and 48) took part in this experiment. Fifteen participants exclusively performed the task individually (Individual-Individual (II) group). Another 15 participants performed the first part of the experiment alone, and were then joined by another participant to perform the second part together (Individual-Joint (IJ) group). Another 15 participants performed the first part of the experiment together with one of 15 other participants, and continued the second part alone (Joint-Individual (JI) group). Finally, 30 participants exclusively performed the task together (Joint-Joint (JJ) group). All participants were right-handed and none reported any neurological deficits. Participants were compensated for their time though course credit. Data from two pairs in the JI-group were removed from the data set due to recording error.

6.2. Apparatus and procedure

Fig. 1 shows the experimental apparatus. For the parts of the experiment that participants completed individually, they controlled the cord on the left with their left hand and the cord on the right with their right hand. For the parts participants completed jointly, they sat next to each other at a distance of approximately 30 cm. The participant on the left controlled the cord on the left with her left hand, and the participant on the right controlled the cord on the right with her right hand.

At the beginning of the Experiment, participants were instructed to move the pole back and forth between two targets by pulling on each of the two cords. They were also told to do this at a frequency that approximated a sequences of tones played before the onset of each trial (details follow). We did not make any mention about how participants should accomplish this task. Participants then tried out the task for approximately one minute. In the joint groups, dyads were asked not to communicate with each other verbally. Participants were not told beforehand whether another participant would join later (in the IJ-group) or if one of the participants would leave after the first part (JI-group).

During the experimental trials, participants started with the pole resting on the left side, and they could start moving the pole after hearing an isochronous sequence of tones that indicated at which speed the movement should be performed. We used a customized Matlab program to play a sound file that indicated the pace at which the pole should approximately be moved back and forth between the targets. The sounds participants heard consisted of eight alternating 700 and 850 Hz tones (corresponding to four movement cycles) at a target period of 546 ms. Participants listened to these tones, and were told to start moving the pole at approximately the same rate after the tones had played. Thus, the participants did not hear any tones during pole movement.

Participants were told to continue moving the pole back and forth until the experimenter told them to stop. The experimenter did so after participants completed 15 back and forth movements between the targets. None of the participants appeared to have trouble understanding the instructions.

At the end of each trial, participants provided their agency rating for the preceding performance by answering how strongly they had experienced to be in control. They answered this question by providing a rating between 0 (no control at all) and 100 (complete control) by entering their rating on a desktop computer. Participants could not see their ratings on previous trials or the ratings provided by their coactor in the joint groups when they provided a rating.

Participants completed 20 experimental trials per part of the experiment (40 trials in total). We used two amplitudes (4 or 16 cm between the targets) and we counterbalanced their order for individuals and dyads within each experiment part. The reason for including two amplitudes was that this allowed us to explore the generality of task learning. We did not have specific predictions about the effect of this manipulation on the sense of agency. In fact, in a previous study we found that the amplitude condition participant completed was much less related to performance than the number of trials participants had completed in total (van der Wel et al., 2011). Each amplitude condition was completed as a block of 10 repetitions. The experiment lasted about 1 h.

The pole was made from a solid PVC pipe (length = 46.6 cm, diameter = 1.0 cm, mass = 50.7 g), and was affixed to a rotating axis positioned at its base, thus creating a pivot point. A cord was attached at 0.5 cm below the pivot point on each side of the pole. The cords were 65 cm long. Participants always held each cord in the same location, at 30 cm from the pole, between their thumb and index finger. To ensure a fixed relation between the pulling angle and the pole, we ran each cord through a small hole at the same height and 17 cm away from the pivot point of the pole. From rest, the pole required approximately 1.27 N of pulling force to start moving.

Each target region was 3 cm in width and indicated by a colored area. The target regions were drawn on a white piece of cardboard that was placed on a flat platform positioned 4.0 cm above the pivot point of the pole. Different pieces of cardboard were used for the different (4 and 16 cm) amplitude conditions. The target regions on both sides were always equidistant from the balance point of the pole.

A goniometer (Encoder Rotary 360 PPR, Avago Technologies) recorded the pole kinematics and two force sensors (Low profile universal load cell, model LC703-25) positioned between the axis and the cord on each side recorded the exerted forces. The force data were amplified with a strain gage amplifier (INA125P, Texas Instruments). Data were recorded at 200 Hz and outputted to a Hewlett Packard Compaq dc7900 computer through a USB connection. The data were stored on this computer and transferred to another computer for data analysis with customized Matlab programs.

6.3. Data analysis

6.3.1. Performance

Before calculating our performance measure, we first filtered the pole kinematics with a 20-Hz low-pass Butterworth filter to remove noise. From the pole kinematics, we then calculated the amplitude of each pole movement as the distance between direction reversal points of the pole. Our threshold criterion was 20° of movement for the amplitude values to avoid including small corrective movements in measuring performance error. For the movements that satisfied this criterion, we calculated the smallest absolute deviation between the reversal point of the pole and either side of the target areas to quantify mean end point error. The times between successive direction reversals (the same ones we used for the end point error calculation) were used to calculate the movement periods.

To account for the possibility that different participants focused differentially on spatial and temporal criteria of the instruction, we constructed one overall performance score from the mean end point error and movement periods. To accomplish this, we normalized the absolute difference between the produced and the instructed movement periods, such that perfect performance corresponded to a normalized movement period of 1. For the mean end point errors, normalization was less straightforward as normalizing against an error score of zero was not possible. Instead, we normalized the end point error data for each participant (pair) and trial in each group against the grand mean of all our data (all trials in all groups). For the resulting scores, a value of 1 corresponded to the grand mean, whereas values smaller than 1 indicated that the end point error score for a given trial was below the mean (better performance), and a value larger than 1 indicated that the end point error for a given trial was above the mean (worse performance). To construct one integrated score per participant (pair) per trial that reflected the objective quality of performance, we summed up the normalized movement period score and the normalized end point error score for each trial. The lower the resulting value, the better participants performed. We will refer to the resulting performance measure as Combined Error Score.

6.3.2. Force-agency relation

To analyze how the amount of force participants produced related to their sense of agency, we calculated the mean peak force participants exerted averaged over the two sides of the experimental apparatus to determine whether the sheer amount of pulling related to the sense of agency in each group. The reason for including this analysis was to evaluate the extent to which sensorimotor information (approximated by the forces generated through motor commands) related to the sense of agency in each group.

To evaluate whether the sense of agency related to the difference in forces generated on each side (either with each hand in the individual groups, or by each actor in the joint groups), we calculated the correlation between the sense of agency and the difference in mean peak force between the two sides in each trial. For the joint groups, we separately calculated this correlation for agency ratings for the person producing less force and for the person producing more force in a given trial.

7. Results

The results are reported in two main sections. In Section 1, we report on the objective performance to evaluate how well individuals and dyads performed, and how well they learned the task over trials. In Section 2, we provide the analyses of the (subjective) agency ratings and their relation to the objective performance and the forces generated during performance.

For each analysis reported here, we applied a Greenhouse-Geisser correction to the degrees of freedom when the assumption of sphericity was violated. For ease of interpretation, we have rounded the reported degrees of freedom and added a *-sign when a correction was applied.

7.1. Performance

To evaluate the quality of performance in each of the experimental groups, we performed a 2 (Experiment Phase) × 2 (Amplitude Part; first or second) × 10 (Trial) repeated measures analysis of variance (ANOVA) on the Combined Error Scores with Group (II, IJ, JI, and JJ) as between-subject factor.

Fig. 2 shows the results. The results indicated three main effects and a two-way interaction. First, there was a main effect for Experiment Phase, $F(1,54) = 12.245$, $p < .01$, partial $\eta^2 = .185$, such that participants performed the task better during the second part compared to the first part of the Experiment. Second, the effect of Amplitude Part on performance reached significance, $F(1,54) = 5.489$, $p < .05$, partial $\eta^2 = .092$, such that participants performed better for the second amplitude they completed compared to the first amplitude they completed. This finding formed a replication of an earlier experiment with the same basic paradigm (van der Wel et al., 2011). Third, the results indicated a main effect of Trial on performance, $F(4,217^*) = 15.789$, $p < .01$, partial $\eta^2 = .226$. Participants performed better for the later trials compared to the earlier trials in each part of the Experiment. Finally, the results revealed a significant interaction between Amplitude Part and Trial, $F(3,9^*) = 3.581$, $p < .05$, partial $\eta^2 = .062$, such that the increase in performance over trials was larger for the first compared to the second amplitude participants completed. The results showed no other significant main effects or interactions, $p > .10$. Most importantly, there was no significant main effect ($F(3,54) = 0.720$, $p = .545$) or interaction effect (all $p > .4$) that involved the Group factor.

To test whether all experimental groups performed similarly during the earliest trials in each part of in the Experiment, we conducted an additional 2 (Experiment Phase) × 5 (Trial) repeated measures ANOVA on the Combined Error Scores with Group (II, IJ, JI, and JJ) as between-subject factor. We performed this analysis on the mean endpoint errors for the first five trials because this corresponded to the first amplitude participants completed (different for different participants, with identical counterbalancing for each of the groups). The results showed a strong main effect for Trial, $F(4,12) = 15.889$, $p < .01$, and

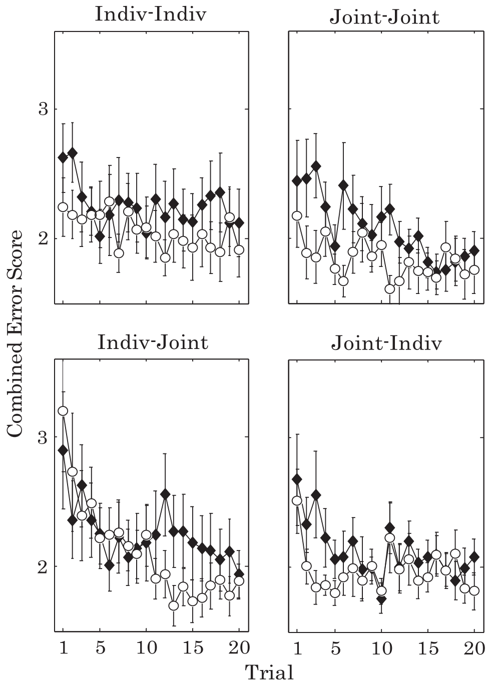

Fig. 2. Mean Combined Error Score (±1 SE) over trials for individuals and dyads in each of the experimental groups. The black diamonds are data from the first Experiment Phase, and the white open circles are data from the second Experiment Phase.

no other significant main effects or interactions. Thus the quality of performance and the rate of learning did not significantly differ between groups (the main effect and all interactions for Group showed $p > .40$).

7.2. Agency ratings

The similarity in the performance measures across the four experimental groups eases the interpretation of how the sense of agency develops when people learn a new task individually versus jointly. In the first part of this section, we address whether participants in our experimental groups developed a similar sense of agency over their actions as they learned our task. We also consider how switching from one coordination mode to another influenced agency. In the second part of this section, we report correlations between objective performance and the sense of agency in each group to determine the extent to which the subjective sense of control scaled with our objective measure of control. The presence of a correlation between performance and the sense of agency would indicate that, regardless of potential differences between groups, participants relied in part on the match between predicted and actual consequences of their actions for establishing a sense of agency.

For each of the analyses on the sense of agency, we only used the agency ratings from the participants who completed both phases of the Experiment. Thus, for the IJ-group and the JI-group we did not consider the ratings for the participants who only performed the joint part.

First, we performed a 2 (Experiment Phase) × 2 (Amplitude Part; first or second) × 10 (Trial) repeated measures analysis of variance (ANOVA) on the agency ratings with Group (II, IJ, JI, and JJ) as between-subject factor. Fig. 3 shows the full results. The results indicated two main effects and two two-way interactions. First, there was a main effect for Experiment Phase, $F(1,54) = 17.230$, $p < .01$, partial $\eta^2 = .242$, such that for all groups taken together participants tended to experience a stronger sense of control for the second part compared to the first part of the Experiment. Importantly, this main effect was qualified by a strong two- way interaction between Experiment Part and Group, $F(3,54) = 4.325$, $p < .01$, partial $\eta^2 = .190$. We will investigate and discuss this interaction in more detail below, as it pertains to the issue of transfer. Second, there was a main effect for Trial on the sense of agency, $F(6,344^*) = 8.699$, $p < .01$, partial $\eta^2 = .139$. This main effect was also qualified by a two-way interaction between Trial and Experiment Phase, $F(7,389^*) = 4.444$, $p < .01$, partial $\eta^2 = .076$, such that the sense of agency increased more strongly over trials during the first part of the Experiment compared to the second part of the Experiment. None of the other main effects or interactions reached significance, $p > .1$.

Fig. 4 shows the significant interaction between Experiment Phase and Group that was already reported above. This interaction may indicate that a difference between sensing agency over individual versus joint actions only starts to emerge once a task is performed at a certain level. Alternatively, it may indicate that switching from individual to joint performance and vice versa differentially impacts the sense of agency. Therefore, we further examined this interaction with two separate

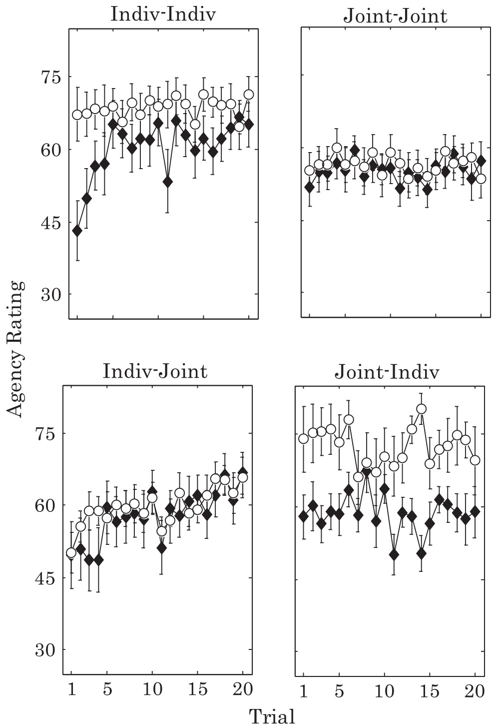

Fig. 3. Mean agency rating (±1 SE) over trials for individuals and dyads in each of the experimental groups. The black diamonds are data from the first Experiment Phase, and the white open circles are data from the second Experiment Phase.

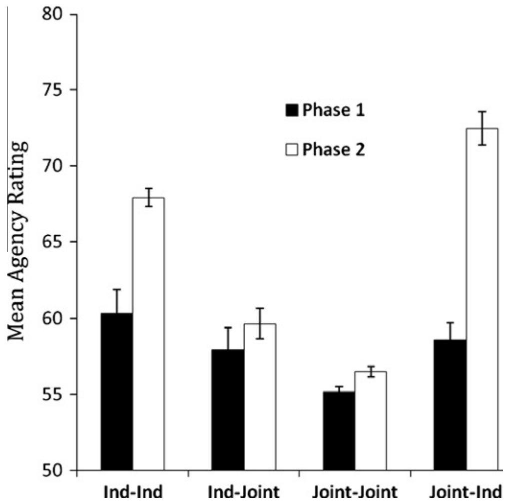

Fig. 4. Mean agency rating (±1 SE) per part of the Experiment for each of the experimental groups.

ANOVAs, one for each Experiment Phase. For the first Experiment Phase, there was a main effect for trial, $F(6,344^{*}) = 10.759$, $p < .01$, partial $\eta^2 = .166$, but not for Group, $F(1,3) = 0.96$, $p = .962$. This result indicates that the sense of agency did not differ significantly for individual versus joint performance when participants start to learn a new task. In contrast, there were marked differences between the groups for the second part of the Experiment. The results indicated a main effect for trial, $F(7,366^{*}) = 2.110$, $p < .05$, partial $\eta^2 = .038$, and most importantly a main effect for Group, $F(1,3) = 5.075$, $p < .01$, partial $\eta^2 = .220$. In particular, whereas the sense of agency did not change much from the first part to the second part of the Experiment in the IJ-group and JJ-group, there was a sizeable increase in the sense of agency for the II-group and the JI-group. Moreover, this increase was larger for the JI-group than for the II-group, indicating that participants experienced a boost in their sense of agency above and beyond the sense of agency they would experience just due to performing individually.

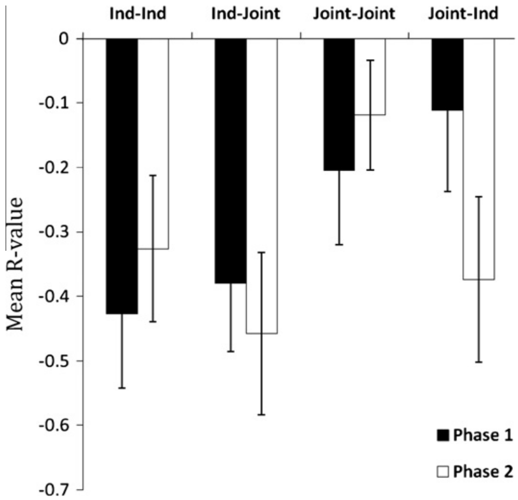

Fig. 5. Mean correlation between Combined Error Scores and agency ratings per part of the Experiment for each of the experimental groups. See text for calculation method.

7.3. Mean agency rating

Another interesting feature of the agency data was that the mean agency rating provided in the joint groups exceeded the value of 50. Thus, on average the two participants performing together claimed more control than was objectively possible.

7.4. Relation between performance and agency

To evaluate to what extent the sense of agency in each group related to the objective quality of performance, we calculated correlations between the agency ratings and Combined Error Scores for each participant (pair) in each group. To allow for statistical analyses, we then performed a Fisher-*z* transform (Fisher, 1921) on these correlations, and transformed the average *z*-transformed values back into an average correlation for each group. First, we tested each set of correlations against a test value of 0, to determine for which groups and Experiment Phase the correlation between Combined Error Scores and Agency ratings reached significance. Fig. 5 shows the results at the level of group means and Table 1A displays the test statistics and correlations for each group. The results revealed that there was a significant correlation between performance and the sense of agency (or a negative correlation between the Combined Error Score and Agency Rating to be exact) in all parts of the Experiment, except for the first part of the Experiment in the JI-group and the second part of the Experiment in the JJ-group. This finding suggests that participants used the perceptual consequences of their (individual or joint) actions to establish a sense of agency. To specifically evaluate the relationship between the sense of agency and performance during individual versus joint performance, we also performed an independent sample *t*-test on all the data from the II-group and the JJ-group (both Experiment Phases). The results indicated that the correlation was significantly more negative for individuals compared to dyads ($t(70) = -2.126$, $p = .037$). Thus, participants relied more heavily on the quality of performance to establish their sense of agency in the individual group compared to the joint group.

7.5. Relation between exerted forces and agency

To evaluate to what extent the sense of agency in each group related to the forces participants exerted on the cords used to move the pole, we calculated correlations between the agency ratings and the mean peak forces generated in each group. We then *z*-transformed these correlations for significance testing and between-group comparisons.

We tested each set of correlations against a test value of 0, to determine for which groups and Experiment Phase the correlation between Mean Peak Force and Agency ratings reached significance. Fig. 6 shows the average correlation for each group and Table 1B displays the test statistics and correlations. The results indicated no significant correlations between peak forces and agency for any of the groups, (all $p > .1$). Thus, participants did not seem to systematically rely on sensorimotor information to establish a sense of agency in our task.

To evaluate whether the sense of agency related to the difference in forces generated on each side, we ran correlations on the difference in mean peak force and the sense of agency. For the joint groups, we did so separately for the person generating more force and for the person generating less force in a given trial. The results indicated no significant correlations, $p > .10$ (all correlations between $-.10$ and $.10$) for any of the groups. Thus, an asymmetry in task distribution between the hands did not influence agency in a systematic way during individual performance. Asymmetries also did not impact the sense of agency in dyads, irrespective of whether a person generated more or less force than their partner.

Table 1
Mean correlations and test statistics for the relationship between performance and agency (table 1b), and peak force and agency (table 1b).

Group	Agency correlations			
	Table 1A performance		Table 1B force	
	t-Statistic (df)	Correlation	*t*-Statistic (df)	Correlation
II_1	−4.132 (14)*	−.4274	1.164 (14)	.1126
II_2	−3.943 (14)*	−.3262	−0.044 (14)	−.0052
IJ_1	−4.388 (14)*	−.3799	0.334 (14)	.0343
IJ_2	−4.036 (14)*	−.4577	0.287 (14)	.0252
JI_1	−0.589 (12)	−.1111	0.658 (12)	.0571
JI_2	−2.933 (12)*	−.3741	−0.078 (12)	−.0067
JJ_1	−2.459 (29)*	−.2052	−1.691 (29)	−.1562
JJ_2	−1.519 (29)	−.1109	−1.340 (29)	−.0835

Mean *R*-value.
* Correlation significant at $p < .05$.

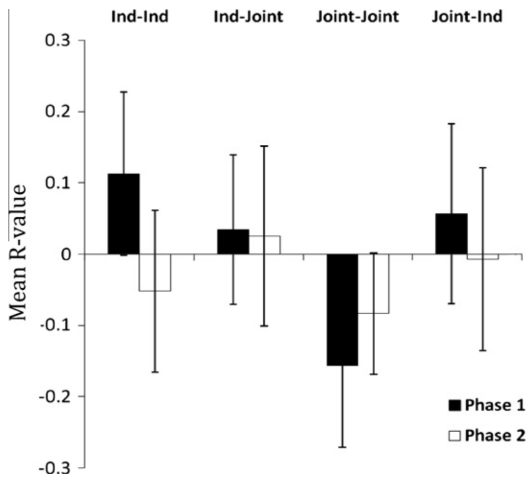

Fig. 6. Mean correlation between Mean Peak Force and agency ratings per part of the Experiment for each of the experimental groups. See text for calculation method.

8. Discussion

Whereas the sense of agency has been studied for individual (unimanual) actions, how people sense agency over joint actions has to our knowledge not been examined experimentally. As people perform many actions together with others, the question of how others' actions affect individual experience during joint action seems to address a basic ingredient of human mental life. The aim of the present study was to examine the sense of agency while people acquired a new skill either individually or jointly. We also investigated how the sense of agency depended on the context in which people first acquired a skill (either individually or jointly). We tested several predictions that follow from two accounts that have been developed in the context of sensing agency over actions people produce by themselves, in particular Wegner's theory of apparent mental causation and two versions of the predictive internal model account (the sensorimotor account and the perceptual account). Wegner's account and the predictive internal model account in principle have been developed as general theories for establishing a sense of agency, but have not been tested for joint actions.

To test the sense of agency in individual and dyads, we chose a task that was novel for both groups and that individuals and dyads would learn equally well. By approximation, both the rate of learning our new task and the absolute quality of performance was similar for each of our experimental groups. This result eases the interpretation of the accompanying agency ratings, because any significant differences in agency ratings between our experimental groups could not be accounted for based on significant differences in the objective quality of performance.

Our main findings on the sense of agency were the following; first, we observed very little difference in the sense of agency for individual and dyads during initial performance. This finding provides an interesting elaboration on Wegner's account on the sense of agency. In particular, it suggests that during initial learning of a task, the sense of agency mostly depends on the factors priority and consistency, and less so on the factor exclusivity (i.e., being the only possible cause for an action). The reason for this is that the sense of agency for individuals and dyads was initially very similar, even though for dyads the criterion for exclusivity could never be met. With respect to the predictive internal model accounts, the lack of an initial difference in the sense of agency is also surprising based on the sensorimotor account, but not based on a perceptual account. Whereas the sensorimotor account predicts a general reduction in the sense of agency for dyads compared to individuals due to an impoverished match between the issued motor commands and their sensory consequences, the perceptual account does not predict a reduced sense of agency as long as the perceptual consequences of actions (i.e., the quality of performance) are equally predictable.

Second, even though there were no statistically significant differences between individual and joint performance for the second part of the Experiment, the agency ratings did reveal such differences. In contrast to increases in the sense of agency for individual performance, the results indicated that the sense of agency for dyads did not increase from the first to the second part of the Experiment. Thus, only once participants became more acquainted with the task did clear differences in the sense of agency between individuals and dyads emerge. The finding that differences in the sense of agency between individuals and dyads only emerged after some practice on a new task speaks to the dynamic nature of establishing a sense of agency. This finding provides an important elaboration for theories of agency, as none of the existing theories on the sense of agency predicts such experience-dependent changes in the importance of the different factors contributing to the sense of agency.

Third, the results from the transfer conditions indicated that participants did not experience a greater reduction in their sense of agency when they started to perform the task jointly after initially performing the task by themselves compared to participants who had started out jointly. This result is reflected in the observation that the sense of agency during joint performance did not differ for participants who first performed by themselves compared to participants who performed jointly throughout the Experiment. In contrast, participants did experience a heightened sense of agency when they first started performing a task by themselves after initially performing the task jointly. In fact, participants experienced a stronger sense of agency when they performed individually after having performed together with someone else compared to when they performed by themselves throughout the Experiment. This finding indicates that the sense of agency can reflect changes in the action context rather than reflecting performance in the current context only. The boost in the control felt over individual actions following joint performance is noteworthy given that it cannot be explained by differences in objective performance. It seems likely that participants treated their prior experience in the joint action context as a kind of baseline against which they judged their sense of agency during individual performance. Since there was no decrease in the sense of agency for participants who started out individually and then performed jointly, the switch from joint to individual performance may indicate a) that people are more sensitive to increases rather than decreases in control and/or b) that individual control may be felt most strongly when it contrasts with the experience of joint performance. This may have interesting implications for (skill) development, where children often acquire skills through joint action with an adult (Brownell, 2011) and gradually learn to perform the jointly performed actions alone.

Fourth, our results indicated that the sense of agency depended on our objective measure of the quality of performance, as evidenced by significant (negative) correlations between participants' error scores and their agency ratings. With regard to Wegner's theory of apparent mental causation, these correlations confirm the importance of the factor consistency. In particular, as participants performed the task better their expectations about performance likely became more consistent with the actual performance, thus giving rise to a greater sense of control. From the predictive internal model perspective, such correlations would also be expected as they indicate that the sense of agency increases when the match between expected and actual consequences of actions improves.

In contrast to the significant relationship between performance and the sense of agency, our results did not indicate a significant relationship between the amount of force people generated and their sense of agency. From a sensorimotor account, such a relationship may have been predicted under the assumption that generating more force would allow people to distinguish their own contributions to the task more clearly. If people have a clearer signal to determine what they cause in cases when they heavily influence performance due to exerting larger forces, then increases in the amount of force applied may increase the sense of agency. Based on the current data, there is no evidence for this hypothesis.

The lack of a correlation between the amount of generated force and the sense of agency is also interesting in relation to previous findings suggesting a link between effort and the sense of agency. For example, Preston and Wegner (2007) found that exerting physical effort (i.e., squeezing a handgrip) increased the likelihood for participants to think that they generated the solution to a problem (i.e., claimed authorship) later on. Although our experimental task was much different from the task used by Preston and Wegner (2007), one may have intuited that contributing more physical effort (as reflected in the amount of exerted force) would similarly increase the sense of agency in our task. Our results do not support this assertion, however.

Despite the significant correlations between performance and the sense of agency, we also observed that these correlations were relatively weak. A first reason for this observation may be that different participants may have differentially focused on our spatial versus temporal task criterion. This could reduce the correlation between our objective measure of performance and the agency ratings as participants may have based their agency rating on only one of the criteria instead of both. Second, for dyads it may be that we did not observe stronger correlations between performance quality and the sense of agency because being in the joint setting drove participants' rating more strongly than the actual quality of performance. This possibility may particularly explain why participants who performed jointly throughout the Experiment showed a very weak correlation between performance quality and the sense of agency for the second part of the Experiment, when performance stayed relatively constant.

A final point worth mentioning is the observation that the sum of the ratings participants provided after joint performances on average exceeded a value of 100. Thus, participants appeared to have a general bias in the joint task setting to claim more control than they objectively had. We currently do not have a clear theoretical explanation for this finding. Future research could address whether the tendency to overestimate the amount of control at the level of dyads is a general feature of how people sense agency during joint actions.

The present experiment indicates that there are both similarities and differences in how people experience agency for individual versus joint actions. Whereas the match between expected and actual performance feeds into the sense of agency in both cases, people's sense of agency does not reach the same level for joint performance, even if they objectively perform a task just as well as they do on their own. A complete understanding of how people experience joint actions will require explication of the functional processes involved in producing joint actions, as well as how these processes contribute to the sense of agency. Finally, the present results suggest that the sense of agency for individually performed actions may be rooted in and shaped by prior learning experiences involving joint action.

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