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The phenomenology of controlling a moving object with another person

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ABSTRACT

The phenomenology of controlling what one perceives is influenced by a combination of sensory predictions and inferential processes. While it is known that external perturbations can reduce the sense of control over action effects, there have been few studies investigating the impact of intentional co-actors on the sense of control. In three experiments, we investigated how individuals' judgments of control (JoC) over a moving object were influenced by sharing control with a second person. Participants used joysticks to keep a cursor centered on a moving target either alone or with a co-actor. When both participants' actions had similar perceptual consequences, JoC ratings were highest when self-generated movements were the only influence on the cursor, while the appearance of sharing control with a second person decreased JoC ratings. By contrast, when participants performed complementary actions with perceptually distinctive consequences, JoC ratings were highest when both participants were able to influence the cursor. The phenomenology of control during joint action is influenced by low-level visuomotor correlations, the presence of competing causal influences, and group-level performance.

1. Introduction

To control something is to act in order to bring it to a pre-specified condition, possibly in the face of external forces or changes in the environment that tend to alter it (Powers, 1978). This broad definition encompasses most purposeful human behavior, as voluntary actions are usually performed with the intent of producing a particular change in the environment that can be perceived as a sensory outcome of performance (henceforth "action effects").

The question of what processes contribute to the phenomenology of controlling what one perceives has motivated much research. The emerging consensus is that the sense of control is not a unitary phenomenon, but rather depends on a combination of efferent motor signals, sensory predictions and higher level cognitive processes (Haggard & Tsakiris, 2009; Pacherie, 2008; Synofzik, Vosgerau, & Newen, 2008). The sense of control over body movements is thought to depend on a system of sensorimotor comparators which detects discrepancies between sensory predictions triggered by efferent motor signals, and actually executed movements (Blakemore, Wolpert, & Frith, 1998; Frith, 2012; Tsakiris, Haggard, Franck, Mainy, & Sirigu, 2005). Sensory predictions also influence the sense of control over distal events outside the body. For example, auditory stimuli triggered by keystrokes are more likely to be attributed to external sources when the timing or frequency is different from what was expected (Knoblich & Repp, 2009; Sato & Yasuda, 2005).

The sense of control can also be influenced by inferential processes. For example, priming unintended action effects has been shown to increase feelings of authorship,

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which suggests one's own causal role may be inferred post hoc from the match between a prior mental state and a subsequent action effect (Aarts, Custers, & Wegner, 2005; Moore, Wegner, & Haggard, 2009; Sato, 2009; Wegner & Wheatley, 1999). The sense of control may be further modulated by the fluency of action selection (Haggard & Chambon, 2012), and by the magnitude and valence of action effects (Aarts, Wegner, & Dijksterhuis, 2006; Kawabe, 2013).

Although there has been progress in understanding the mechanisms which contribute to a sense of control, the types of task environments that have been studied are limited in scope. Many investigators have focused on the phenomenology of causal initiation, i.e. the sense of agency. In these experiments, participants are typically asked to rate their agreement that a brief event such as a tone (e.g. Engbert, Wohlschlõger, & Haggard, 2008; Sato & Yasuda, 2005), the sudden appearance of a visual stimulus (e.g. Linser & Goschke, 2007; Sato, 2009), or the sudden stopping of a previously moving stimulus (e.g. Aarts et al., 2005; Jones, de-Wit, Fernyhough, & Meins, 2007; Wegner & Wheatley, 1999) was caused by their own prior action. Although interesting in its own right, causal initiation does not guarantee that an entire action will be experienced as controlled (Pacherie, 2007). One may initiate an event, but lose control as it unfolds over time, as for example when one loses control of an automobile while driving. Yet there have been relatively few studies investigating the sense of control for events lasting longer than a few milliseconds (but see Dewey, Seiffert, & Carr, 2010; Metcalfe & Greene, 2007).

Another limitation of research in this area has been the focus on individuals performing tasks in isolation. In everyday life people often act in a social context, performing joint actions with others. Joint action can be defined as a social interaction where individuals coordinate their actions to bring about a change in the environment (Sebanz, Bekkering, & Knoblich, 2006). There are some studies which have investigated the sense of agency and related processes in social contexts (e.g. Desantis, Weiss, Schütz-Bosbach, & Waszak, 2012; Dewey & Carr, 2013; Obhi & Hall, 2011a,b; Wegner & Wheatley, 1999). Typically, participants perform a task either with or without a partner, but only one agent actually controls the stimulus at any given time. By contrast, we were interested in situations in which two actors share control. For example, consider white water rafting with a group. In this scenario, the motion of the raft is jointly determined by several people working together with a more or less common purpose, plus some unpredictable perturbations caused by the water currents. In a situation like this, what are the implications for the individual's sense of control? Can people distinguish their own contributions from the contributions of their co-actors? Are the contributions of co-actors perceived as perturbations that reduce the individual's sense of control? Or do the contributions of co-actors increase the individual's sense of control by facilitating attainment of shared goals? To begin addressing these questions, in the present study we investigated the phenomenology of control during a cooperative joint action lasting several seconds.

1.1. The sense of control during joint action

A fundamental question is whether the sense of control during cooperative joint actions engages the same processes which shape the sense of control during individual action, or if it is in some sense a special case. One possibility is that the sense of control is essentially egocentric, depending on the perception of a causal relationship between one's motor inputs and the perceived action effect. In this case the contributions of a co-actor might be experienced as external perturbations if both agents tried to manipulate an object at the same time. On the other hand, if each agent's contribution was perceptually distinctive (for example, the two agents take turns manipulating an object), the egocentric hypothesis predicts that the co-actor's actions would have little impact on the sense of control.

An alternative to the egocentric hypothesis is that the contributions of a cooperative co-actor might increase the sense of control due to the agents' shared intentions. There is evidence that when individuals feel themselves to be part of a group, this can influence action-perception links, including response times (Tsai, Sebanz, & Knoblich, 2011), the perceived timing of actions and their effects (Obhi & Hall, 2011a), and the sensory attenuation of effects generated by another person (Weiss, Herwig, & Schütz-Bosbach, 2011). A catch-all term for these effects of shared intentionality is the "we-mode" (Gallotti & Frith, 2013). Cognition in the we-mode might lead individuals to evaluate control at a group level, e.g. based on the success of the joint action. We will refer to this as the joint control hypothesis. With this background, we considered three non-exclusive ways in which actions performed by agent B might influence agent A's sense of controlling the action effect during a cooperative joint action.

Action effect predictability. When individuals perform tasks alone, the sense of control is influenced by congruence between intended, predicted, and actually perceived action effects. Thus, one way agent B could influence agent A's sense of control is by altering the objective correlation between agent A's motor inputs and the action effect, whether positively or negatively (Fig. 1a). This could be characterized as an impact at the level of egocentric sensory predictions. There could also be an impact of action effect predictability at a perceptual level that does not depend on motor signals. In that case, predictable contributions from agent B might increase agent A's sense of control even if they did not correlate with agent A's motor inputs. The latter possibility would be consistent with the joint control hypothesis.

Performance cues. A second possibility is that agent B's contribution to a joint action could modulate agent A's sense of control by causing the joint action to be more or less successful (Fig. 1a). Positive outcomes can lead to illusions of control, particularly when people are led to believe the outcome is skill dependent (Langer, 1975). For example, acquisition of a goal can influence judgments of control over moving objects, even leading individuals to overlook minor discrepancies between predicted and observed action effects (Dewey et al., 2010; Metcalfe & Greene, 2007). Performance cues can also have a

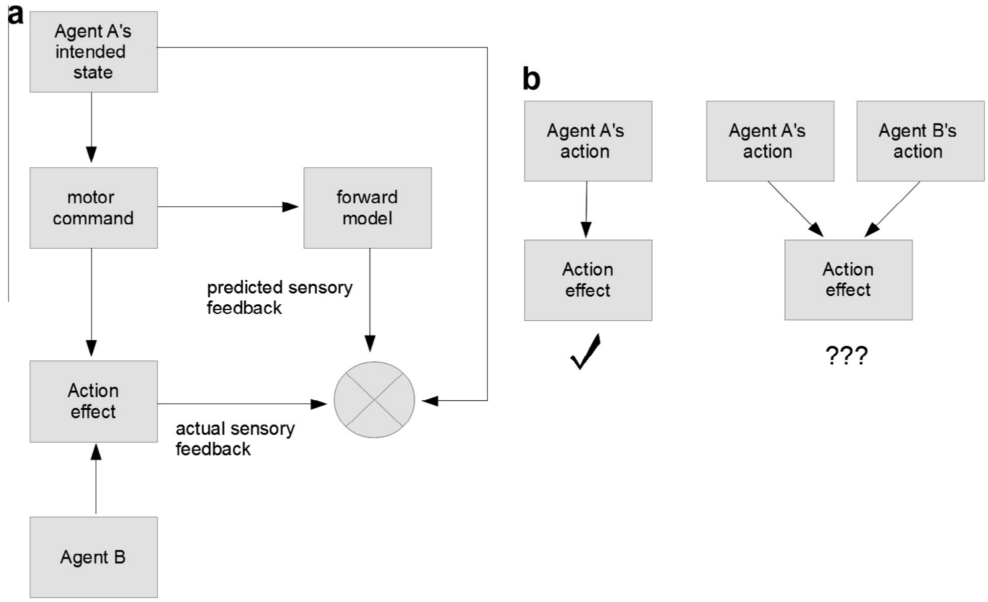

Fig. 1. Potential influences of a co-actor on the sense of control during joint action. (a) Agent B's contribution to the action effect could influence the degree of match between agent A's predicted sensory feedback and actual sensory feedback (action effect predictability), or between agent A's intended state and actual sensory feedback (performance cues). (b) The presence of agent B as a competing causal explanation for the action effect could lead to a reduced sense of control (causal discounting).

significant impact on the sense of control during joint action tasks (Van der Wel, Sebanz, & Knoblich, 2012). A caveat to this point is that participants in these studies were simply asked to rate their feelings of control (or agency) without specific instructions as to what that meant. So it unclear whether participants perceived that they contributed more on the more successful trials, or simply felt that having success is part of what it means to be in control. With respect to the question of whether the sense of control is egocentric, an important question is whether individuals' sense of control is influenced when a joint action either succeeds or fails due to the co-actor's contribution.

Causal discounting. Causal discounting is a phenomenon in causal reasoning where the presence of one causal explanation casts doubt on another (Einhorn & Hogarth, 1986; Khemlani & Oppenheimer, 2011). Applying this idea to the phenomenology of voluntary action, Wegner and Wheatley (1999) proposed that perceiving one's own thoughts or actions as the exclusive or most probable cause of an external event is a necessary precondition for the sense of agency. Thus, a third way agent B could influence agent A's sense of control is by leading agent A to *infer* that he or she has less control compared to when agent A performs the task alone (Fig. 1b). If causal discounting had a strong influence on the sense of control during joint action, this would tend to support the hypothesis that the sense of control is egocentric, as it implies that agent B's control comes at the expense of agent A.

1.2. The present study

Broadly, the goal of the present study was to characterize how the sense of control during cooperative joint actions is influenced by contributions (real or imagined) from a co-actor. Of particular interest was the question of whether the sense of control is essentially egocentric, depending on cues which indicate a direct a causal link between one's own motor inputs and the action effect, or alternatively, if the sense of control depends more on performance at the group level.

To disentangle egocentric sensory predictions from group performance, we varied the perceptual distinctiveness of two agents' contribution to a jointly controlled action effect. We considered two scenarios. In the first, agents A and B performed the same action at the same time, which made their respective contributions to the action effect difficult to distinguish. A real-world example would be two people sitting in a boat and paddling in synchrony. In the second scenario, A and B took turns performing complementary but different actions, which made their unique contributions easier to distinguish. A real-world example would be two people sitting on opposite sides of the boat, one side being responsible for making left turns and the other side for right turns.

The reasoning behind this manipulation was that if the sense of control is egocentric, then agent A's sense of control should be modulated by agent B's contributions in the perceptually ambiguous scenario but not in the perceptually distinctive scenario. However, if the sense of control depends on control at the group level, then increasing agent B's control should increase agent A's sense of control if it results in a better outcome, even in the perceptually distinctive scenario. This assumes that both agents' actions are predictable and serve a common goal.

To implement and test the two scenarios just described, we devised a visual tracking task in which participants used joysticks to keep a cursor centered on a moving target. The joysticks could be turned on or off independently, so that neither, one, or both participants had some control over the cursor. To add further variability to performance and the sense of control, random perturbations were added to the cursor during some but not all trials. We hypothesized that individuals' sense of control would be influenced by a combination of action effect predictability, causal discounting, and group performance. We further hypothesized that the relative impacts of egocentric sensory predictions and group performance would depend on the perceptual distinctiveness of each agent's contribution.

In Experiment 1, we tested the scenario in which both agents' contributions to the joint action were perceptually similar. Here, we predicted the agents' actions would overlap and interfere with one another, so individuals' sense of control would be highest when their own joystick was the only influence on the cursor. The causal discounting hypothesis further predicted that the mere appearance of sharing control with another would decrease the sense of control, even if the co-actor had no actual influence on the outcome, because the co-actor would be perceived as a competing causal explanation.

In Experiment 2, we tested the scenario in which agents' contributions were complementary and perceptually distinctive. Here, we predicted that the co-actor's contribution would no longer be perceived as interference, so individuals' sense of control would be highest when both agents' joysticks were able to influence the cursor. In line with the joint control hypothesis, this would demonstrate that the sense of control during joint action can transcend egocentric sensory predictions, in such a way that the sense of control aligns with the performance of the group as a whole. Although it has previously been shown that the sense of control is influenced by performance when control is ambiguous, complementary joint actions represent an interesting case for further study for at least two reasons: (1) the presence of a co-actor may bring causal discounting into play; and (2) it is unclear whether the performance of a co-actor should influence the sense of control when the agents' respective contributions are perceptually unambiguous.

In Experiment 3, we replicated Experiment 2, and also compared judgments of self control to judgments of the co-actor's control. The joint control hypothesis predicted symmetry between the two sets of control ratings, i.e. a shared sense that "we" do or do not have control. An alternative hypothesis would be that individuals show a self-serving bias to take more credit for successful outcomes while attributing less control to the co-actor.

2. Experiment 1

2.1. Methods

Participants. Thirty right-handed participants (22 females and 8 males, mean age 22.43) were recruited from student organizations in the Budapest area in exchange for small monetary payments. Participants were recruited two at a time, with appointments to arrive at the lab at the same day and time. Participants did not know each other prior to the experiment and all participants were naïve to the purpose of the study.

Apparatus and stimuli. All stimuli were presented on Macintosh computers with 21.4 in. displays, with screen resolution set to 1920 × 1080. Participants used Logitech Attack 3 joysticks to manipulate the cursor, and the number keys on a standard keyboard to indicate their judgments of control (JoC). Participants were seated in a position where their eyes were approximately 57 cm from the monitor. During the joint action portion of the task, an occluder was positioned between the participants' arms so neither could observe the other's joystick motions and JoC ratings could be given privately (see Fig. 2). The occluder did not obstruct viewing the monitor in any way, so both participants could see the entire screen.

The experiments were programmed in MATLAB with the Psychophysics toolbox extension (Brainard, 1997). The main stimulus display consisted of a light blue background, a filled red circle (the cursor), and a hollow black circle (the target). The cursor and target each had a diameter of about 1.14 degrees of visual angle. During the moving part of each trial, the target wavered left and right (movement was restricted to the horizontal plane) in a pseudorandom fashion while participants used their joystick(s) to try to keep the cursor centered on the target. The movements of the target were unpredictable but non-jittery wave-like motions. The moving part of each trial consisted of 400 frames (about 6.67 s).

The position of the target T on frame f was calculated prior to each trial by averaging three sine waves:

$$T(f) = (\sin(i+\varphi) + \sin(2i+\varphi) + \sin(4i+\varphi))/3$$

where φ was a random phase offset between 0 and 2π which randomly varied across trials, and i was an index of position on the sine wave $2\pi \times (f/400)$.

The position of the moving cursor C on frame f was determined by the position on the previous frame plus a weighted sum of the current joystick inputs and random perturbations:

$$C(f) = C(f-1) + S(w_1) + O(w_2) + N(w_3)$$

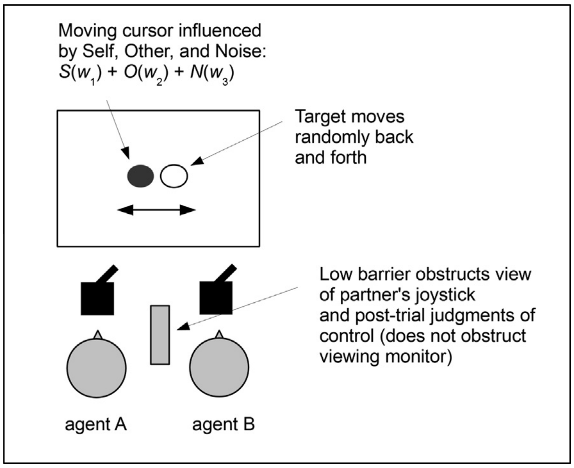

Fig. 2. Apparatus and stimuli. Note that from agent A's perspective, agent A is the "self" and agent B is the "other", and vice versa.

where *S* and *O* represented the inputs from the two human agents (*S* = self and *O* = other) provided through the joysticks and *N* was an array of noisy perturbations generated in the same way as the pseudorandom movements of target *T*, but using different random values. There were three possible states for the joystick inputs: left (−.5), middle (0), or right (+.5). A joystick was considered to be in the leftward or rightward position when its horizontal axis position exceeded an arbitrary threshold. Pushing the joystick further left or right beyond this threshold did not increase the effect. There was a technical reason for this: the joystick axis values communicated to MATLAB were quite variable even while the joysticks were at rest, which resulted in jittery movements when a more gradual left-to-right gradient was used.

The values of the weights (w_1, w_2, w_3) in the equation above were either "on" (8) or "off" (0). Thus the two joysticks canceled each other if both were turned on and pushing in opposite directions, but the effect was doubled if they pushed in the same direction. If all three weights were off, the cursor remained stationary throughout the trial. The moving cursor was not influenced by momentum. Thus if both participants released their joysticks, the cursor would immediately stop moving but for the noisy perturbations. This simple control scheme was decided on following pilot testing which showed that participants were worse at discriminating their degree of control when the cursor maintained momentum.

Design. A within-subjects, repeated measures design was used. The first experiment consisted of two tasks: an individual task (I-task) and a joint action task (J-task). The purpose of including the I-task was to test the causal discounting hypothesis, which predicted that participants would feel greater control when they performed the task alone. Participants performed one block of the I-task first, followed by the J-task, followed by a second block of the I-task (I–J–I). We opted for this task order to account for possible order effects: In a previous study, the sense of agency for an individual task increased when it followed a joint action task, whereas order had little effect on the joint action task (Van der Wel et al., 2012).

During the I-task there were two factors: Self (abbreviated S− for off, S+ for on), which determined whether the joystick belonging to the self was turned on or turned off, and Noise (N− for off, N+ for on), which determined the presence or absence of noisy perturbations. During the J-task there was a third factor, the Other (O− for off, O+ for on), which determined whether the co-actor's joystick was turned on or off. For example, the condition where the self joystick was on, the other joystick was off, and the noise was off would be abbreviated as S+O−N−. Because the conditions were coded from the first person perspective, the same trial sometimes presented the two participants with different conditions. For example, if agent A's joystick was on and agent B's joystick was off (ignoring the Noise factor for the moment), then from agent A's perspective the condition would be S+O−, whereas from agent B's perspective the condition would be S−O+.

There were three dependent measures. First, participants provided explicit judgments of control (JoC) following every trial (see Procedure for details). This was the main dependent measure of interest by which we assessed the sense of control. Second, we computed the correlation between the position of the self joystick (left, middle, or right) during frame *f* and the change in the cursor's position from frame *f* to frame *f* + 1. We referred to this correlation as the "visuomotor coupling". The visuomotor coupling was equal to 1 when the self joystick was the only influence on the cursor, while the noise and the other modulated this correlation. Third, we computed the mean distance between the cursor and the target during each trial. We referred to this as the "error". The error was an indicator of participants' performance on the task.

Procedure. Following the informed consent procedure, each participant was taken to a separate computer station located in different rooms for the first block of the I-task. The task instructions were to use the joystick to keep the cursor centered on the moving target. Participants were told that the cursor might be influenced by their joystick, by random motions, or some combination of the two. Following each trial, participants gave a judgment of control (JoC) on a Likert scale from 1 (no control) to 9 (complete control). The instructions explained the JoC rating as follows: "Think of this as a rating of how much your actions contributed to the outcome. In other words, how effective was your joystick at controlling the dot." Each block of the I-task consisted of 40 trials, with 10 repetitions of each condition in random order.

After both participants completed the first block of the I-task, they were brought together for the J-task. During the J-task participants sat side-by-side at the same computer station with an occluder between them. The occluder did not extend all the way to the computer screen, so both participants were able to see the entire display. Participants were instructed not to communicate during the experiment. The instructions for the J-task were the same as the I-task, except participants were informed that now the cursor could additionally be influenced by the other person, who shared the same goal of keeping the cursor centered on the target. Following each trial, participants took turns rating their control. The participant sitting on the left gave their JoC after a crosshair appeared on the left side, and the participant sitting on the right gave their JoC after a crosshair appeared on the right side. The order in which the left and right side participants were cued to give their JoC was random. The J-task consisted of 16 repetitions of each of the eight conditions for a total of 128 trials, with an optional break halfway through. Condition order was randomized. The total duration of the experiment was about 50 min.

2.2. Results and discussion

I-task. The results for the I-task are plotted in Fig. 3. Eight participants were excluded from the analysis of the I-task due to a technical issue with recording the joystick positions, resulting in a sample size of 22, including19 females and 3 males (Note that these individuals were not excluded from the analysis of the J-task). Across participants and conditions, JoC ratings were positively correlated with visuomotor coupling (r_p = .73) and negatively correlated with error (r_p = −.42). To investigate the relative

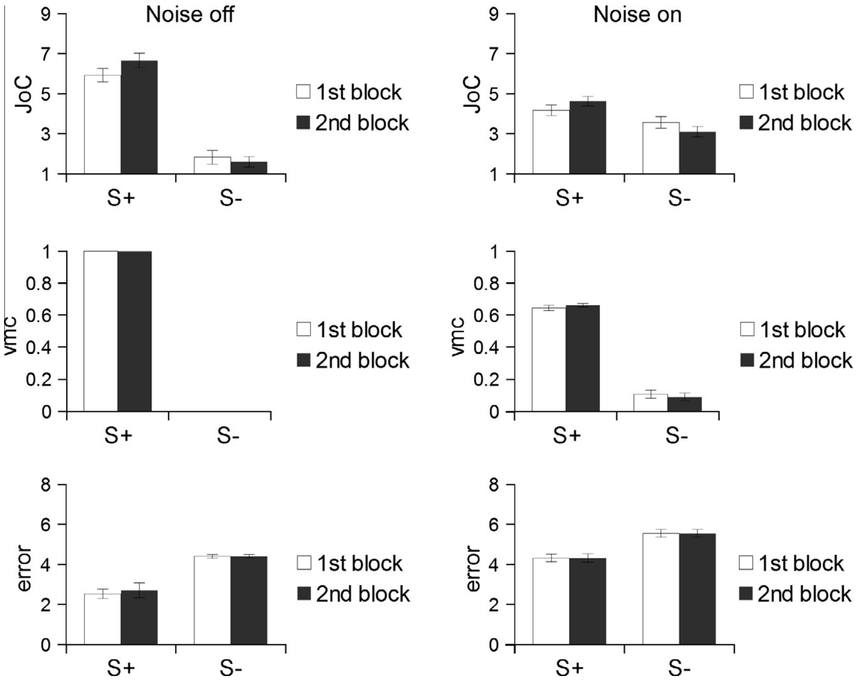

Fig. 3. Mean JoC ratings (top), visuomotor coupling (middle, units are Pearson correlation *r*), and error (bottom, units are degrees of visual angle) from the I-task, Experiment 1. Error bars depict the ± 1 SEM.

impacts of visuomotor coupling and error on JoC ratings, the variables were entered into a stepwise linear regression model. To account for random subject effects, participants' mean JoC ratings over all conditions were included as a third predictor in the model. The overall regression model was statistically significant: $R^2 = .53$, $F(3,184) = 209.27$, $p < .001$. Visuomotor coupling ($B = 3.88$, $t(184) = 14.47$, $p < .001$) explained a significant portion of the variance in JoC ratings, but error did not ($B = .001$, $t(184) = .38$, $p = .71$) (all correlation coefficients are unstandardized B's). This indicates action effect predictability was the major contributing factor to the sense of control during the I-task.

Next, we looked at the specific effects of the independent variables. The JoC ratings were analyzed with a three way 2 (Self: S− vs. S+) × 2 (Noise: N− vs. N+) × 2 (Block: first vs. second) ANOVA. Paired-sample *t*-tests were used to follow up the significant interactions. Effect sizes are given in generalized eta squared (η^2G).

As expected, there was a significant main effect of Self, $F(1,21) = 47.42$, $p < .001$, $\eta^2G = .52$, indicating higher JoC ratings in the S+ condition ($M = 5.34$, $SEM = .25$) compared to the S− condition ($M = 2.51$, $SEM = .24$). There was also a significant Self × Noise interaction, $F(1,21) = 103.16$, $p < .001$, $\eta^2G = .29$. Noise reduced the sense of control in the S+ condition, $t(43) = 9.55$, $p < .001$, but increased the sense of control in the S− condition $t(43) = 9.07$, $p < .001$. Overall, noise reduced participants' ability to discriminate their control.

The Self × Block interaction was also significant, $F(1,21) = 12.20$, $p = .002$, $\eta^2G = .028$, indicating a larger difference between the S− and S+ conditions during the second block. This shows that participants improved at discriminating their control over time. The other effects in the model were all non-significant ($p > .05$).

J-task. The results from the J-task task are plotted in Fig. 4. Again, JoC ratings during the J-task were strongly correlated with visuomotor coupling, $r_p = .69$, and negatively correlated with the mean cursor-to-target error (plotted in the bottom row of Fig. 3), $r_p = -.20$. To investigate the relative impacts of visuomotor coupling and error on JoC ratings, the variables were entered into a stepwise linear regression model. The overall regression model was statistically significant: $R^2 = .59$, $F(3,236) = 169.22$, $p < .001$. Visuomotor coupling explained a significant portion of the variance in JoC ratings ($B = 3.21$, $t(236) = 15.43$, $p < .001$), but error did not ($B = -.002$, $t(236) = 1.69$, $p = .09$) (all coefficients are unstandardized B's). As in the I-task, action effect predictability was the major determinant of the sense of control. The correlation between the movements of self and other was also predictive of JoC ratings: When the movements of self and other were more tightly correlated, the visuomotor coupling also increased because the other's movements did not interfere with the intentions of the self.

To investigate the specific effects of each independent variable, the JoC ratings from the J-task were submitted to a three way 2 (Self: S− vs. S+) × 2 (Other: O− vs. O+) × 2 (Noise: N− vs. N+) repeated measures ANCOVA. To control for possible gender differences in cooperative behavior, the gender of Self and Other were included as covariates.

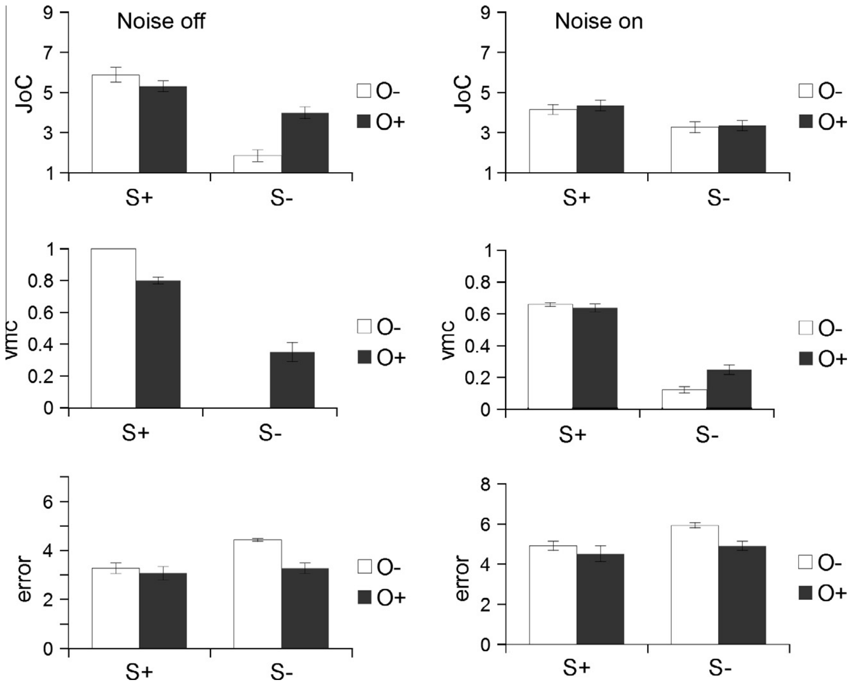

Fig. 4. Mean JoC ratings (top), visuomotor coupling (middle, units are Pearson correlation *r*), and error (bottom, units are degrees of visual angle) from the J-task, Experiment 1. (Note that the error for S+O− is always identical to S−O+, as the two conditions are identical from the 3rd person perspective). Error bars depict the ± 1 SEM.

Every main effect and interaction in the model was statistically significant. The main effect of Self, $F(1,29) = 45.08$, $p < .001$, $\eta^2G = .32$, indicated higher ratings in the S+ compared to the S− condition. Thus, participants were sensitive to whether or not they had control. The main effect of Other, $F(1,29) = 5.29$, $p = .03$, $\eta^2G = .03$, indicated higher ratings in the O+ compared to the O− condition. Thus, participants also felt some sense of control over action effects produced by their co-actor. The main effect of Noise, $F(1,29) = 16.44$, $p < .001$, $\eta^2G = .03$, indicated higher ratings in the N− compared to the N+ condition. Thus, random perturbations reduced the sense of control.

Overall, contributions from the co-actor and the noise made it more difficult for participants to discriminate whether or not they had control, as the difference between S− and S+ was greatest in the O−N− condition (Fig. 4, top left panel). Next, we describe the specific interactions between Self, Other, and Noise.

The Self × Other interaction, $F(1,29) = 27.68$, $p < .001$, $\eta^2G = .06$, indicated that the co-actor's contribution increased JoC ratings in the S− condition, $t(29) = 4.10$, $p < .001$, but had no effect on JoC ratings in the S+ condition, $t(29) = .97$, $p = .34$. This means that when individuals had no control, action effects produced by their co-actor induced an illusion of control.

The Self × Noise interaction, $F(1,29) = 79.02$, $p < .001$, $\eta^2G = .10$ indicated that the noise increased JoC ratings in the S− condition, $t(29) = 2.87$, $p = .008$, but decreased JoC ratings in the S+ condition, $t(29) = 8.11$, $p < .001$. When individuals had no control, noisy perturbations induced an illusion of control, but when individuals did have control, the noise interfered with control.

The Other × Noise interaction, $F(1,29) = 13.03$, $p = .001$, $\eta^2G = .01$, indicated that the noise had no effect on the JoC ratings in the O− condition, $t(29) = .90$, $p = .38$, but decreased JoC ratings in the O+ condition, $t(29) = 6.74$, $p < .001$. Thus, noisy perturbations interfered with the vicarious sense of control participants felt over the action effects produced by their co-actor.

Finally, the Self × Other × Noise interaction, $F(1,29) = 79.16$, $p < .001$, $\eta^2G = .07$, indicated that noise increased JoC ratings more in the S−O− condition compared to the S−O+ condition, $t(29) = 2.30$, $p = .03$. Thus, noisy perturbations were most likely to induce an illusion of control, as opposed to interfering with control, when neither agent had any actual control.

As a side note, the error and JoC ratings within conditions were fairly consistent over the course of the experiment. Collapsing across conditions, there was no significant difference in the amount of error during the first four repetitions of the experiment compared to the last four repetitions, $t(14) = .43$, $p = .67$, although minor shifts in the JoC ratings indicated that participants were slightly better at discriminating between the S− and S+ conditions by the final four repetitions, $t(29) = 2.05$, $p < .05$. The present study was not designed to address the effects of learning on the sense of control, but it seems plausible that the contribution of sensory predictions to the sense of control might become even more dominant over time, assuming predictions become increasingly accurate with practice.

Causal discounting. To test whether the mere presence of the co-actor had any impact on the sense of control apart from the modulation of visuomotor coupling, the JoC ratings from the I-task were compared against the subset of conditions from the J-task in which the co-actor's joystick was deactivated (O−). The data were analyzed with a three way 2 (Self: S− vs. S+) × 2 (Noise: N− vs. N+) × 2 (Task: I-task vs. J-task) repeated measures ANOVA. The first and second blocks of the I-task were averaged together for this comparison.

There was a small but significant main effect of Task, $F(1,21) = 6.00$, $p = .02$, $\eta^2 G = .01$, indicating higher JoC ratings on the I-task ($M = 3.93$, $SEM = .14$) compared to the J-task ($M = 3.70$, $SEM = .17$). This result is consistent with causal discounting. However, the small effect size indicates causal discounting played a relatively minor role in determining the sense of control. There were no significant interactions between Task and the other factors, indicating that causal discounting was relatively uniform across conditions.

Summary. To recap, the results of Experiment 1 indicated that for a cooperative joint action where two agents made perceptually similar contributions to the outcome, the sense of control was largely determined by action effect predictability, while causal discounting and performance cues had relatively minor impacts. However, this result alone is insufficient to determine whether or not the sensory predictions which give rise to a sense of control are egocentric, because the two agents' actions were considerably overlapping. This leads to Experiment 2.

3. Experiment 2

The purpose of Experiment 2 was to test the hypothesis that for complementary joint actions, the sense of control depends on performance at the group level, over and above egocentric sensory predictions. To this end, we modified the J-task from Experiment 1 so each agent's contribution was perceptually distinctive, but both were necessary for the success of the joint action. According to the joint control hypothesis, individuals acting together in a cooperative manner should enter into a "we-mode" where their sense of control depends on the degree of control exhibited by the group as a whole. The key prediction was that the sense of control would be higher in the O+ condition compared to the O− condition, because only when both agents had control would the joint action be successful.

3.1. Methods

Participants. Twenty-eight participants (17 females and 11 males, mean age 19.89, 26 right handed and 2 left handed) were recruited from student organizations in the Budapest area in exchange for small monetary payments. Participants were recruited in pairs, with appointments to arrive at the lab at the same day and time. Participants did not know each other prior to the experiment and all participants were naïve to the purpose of the study.

Procedure. Participants performed a modified version of the J-task from Experiment 1. In the new version of the task, one participant could only move the cursor to the left, and the other participant could only move the cursor to the right (Fig. 5). There were no mechanical constraints on the joysticks, but nothing would happen if participants moved their joystick in the ineffective direction. The instructions were modified accordingly, so each participant was aware that their joystick only worked in the one direction. The instructions also made it clear to participants that their co-actor's joystick worked in the opposite direction as their own, so cooperation would be necessary to succeed at the task. For example, in the S+O− condition (ignoring the Noise factor), only one participant could influence the cursor, and they could only push the cursor in one direction. Thus, it was only possible to perform the task with good accuracy in the S+O+ condition.

The instructions for the JoC ratings were the same as the first experiment: participants were told to rate "how much your actions contributed to the outcome. In other words, how effective was your joystick at controlling the dot".

Participants performed 16 repetitions of each of the eight conditions for a total of 128 trials, with an optional break halfway through. Condition order was randomized. The total duration of the experiment was about 35 min.

3.2. Results and discussion

Joystick dynamics. Consistent with the purpose of Experiment 2, the mean correlation between the two joysticks ($r_p = .19$) was reduced compared to Experiment 1 ($r_p = .29$). Fig. 6 provides an illustrative example of joystick inputs recorded during a single trial from each experiment. In Experiment 1 (Fig. 6a), both agents often responded to the stimulus in a similar way at the same time, whereas in Experiment 2 (Fig. 6b) there was a natural division of labor which resulted in fewer simultaneous actions. An analysis of joystick axis positions confirmed that none of the participants ever attempted to move their joystick in the ineffective direction.

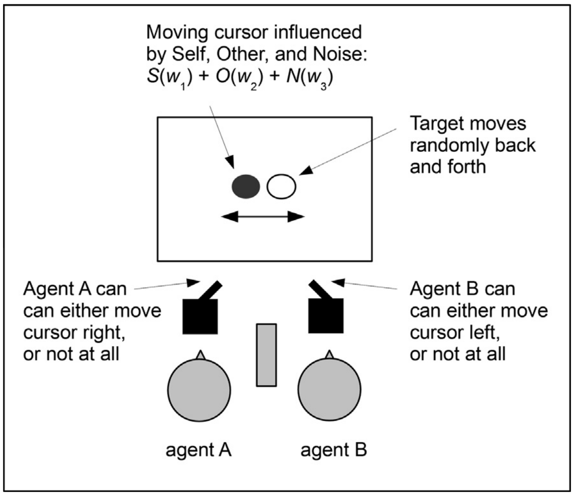

Fig. 5. Apparatus and stimuli for Experiments 2 and 3. Each agent could only move the cursor in one direction. Thus the agent's contributions were complementary and perceptually distinctive.

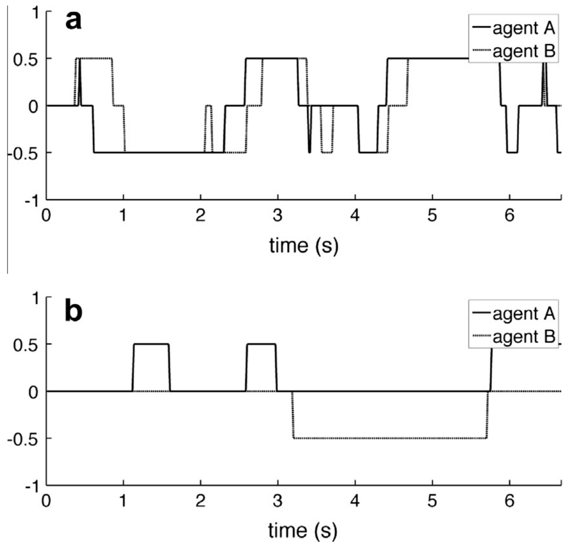

Fig. 6. A representative example of changes in joystick inputs over time in (a) Experiment 1 and (b) Experiment 2. Both plots depict the same condition (S+O+N+). In Experiment 1, there was no clear delineation of roles, so both agents moved their joysticks left (−0.5) and right (0.5), often at the same time. In Experiment 2, each agent was only responsible for moving in a single direction, so there were fewer overlapping inputs.

JoC ratings. As in the first experiment, JoC ratings were positively correlated with visuomotor coupling, $r_p = .62$, and negatively correlated with error, $r_p = -.38$. To investigate the relative impacts of visuomotor coupling and error on JoC ratings, the variables were entered into a stepwise linear regression model. The overall model was statistically significant: $R^2 = .63$, $F(3,220) = 122.23$, $p < .001$. In contrast to Experiment 1, both visuomotor coupling ($B = 3.42$, $t(220) = 13.36$, $p < .001$) and error ($B = -.006$, $t(220) = 4.21$, $p < .001$) explained significant portions of the variance in JoC ratings, although visuomotor coupling still had a much larger impact (all coefficients are unstandardized B's). Thus, both action effect predictability and external performance cues seemed to play a role in determining the sense of control for the complementary joint action.

Next, the JoC ratings were submitted to a three way 2 (Self: S− vs. S+) × 2 (Other: O− vs. O+) × 2 (Noise: N− vs. N+) repeated measures ANCOVA. The gender of Self and Other were added as covariates. There was a significant main effect of Self, $F(1,27) = 72.61$, $p < .001$, $\eta^2G = .46$, indicating higher ratings in the S+ condition compared to the S− condition. Thus participants were sensitive to whether or not they had control. There was also a significant main effect of Other, $F(1,27) = 20.38$, $p < .001$, $\eta^2G = .06$, indicating higher ratings in the O+ condition compared to the O− condition. Thus, on average, the contributions of the co-actor increased the sense of control. These main effects were qualified by three significant two-way interactions.

The Self × Other interaction, $F(1,27) = 49.28$, $p < .001$, $\eta^2G = .10$, indicated that the co-actor's contribution increased JoC ratings in the S+ condition, $t(27) = 6.61$, $p < .001$, but had no effect in the S− condition, $t(27) = 1.44$, $p = .16$. Notably, this is opposite from Experiment 1, where the co-actor's contribution increased the sense of control in the S− condition but had no effect in the S+ condition. We offer the following interpretation: In Experiment 1, the sense of control was dominated by low-level visuomotor correlations, and therefore the co-actor's contribution increased the self's sense of control only when this contribution happened to increase the self's visuomotor coupling (i.e. in the S− condition). By contrast, in Experiment 2 the sense of control was driven by control at both the individual and the group level (this is discussed in more detail below). In this case, the co-actor's contribution increased the sense of control in the S+ condition because the co-actor's contributions also contributed to the predictability and success of the joint action when both agents had control (S+O+).

The Self × Noise interaction, $F(1,27) = 104.90$, $p < .001$, $\eta^2G = .21$, indicated that noise increased JoC ratings in the S− condition, $t(27) = 7.08$, $p < .001$, but decreased JoC ratings in the S+ condition, $t(27) = 6.95$, $p < .001$. This result was also found in Experiment 1. Noisy perturbations reduced gave participants an illusory sense of control when they had no actual control, but reduced the sense of control when they did. Another way of putting it is that noise made it harder to discriminate between control and lack of control.

Finally, there was also a significant Other × Noise interaction, $F(1,27) = 13.98$, $p < .001$, $\eta^2G = .02$, indicating that noise decreased JoC ratings in the O+ condition, $t(27) = 4.34$, $p < .001$, but made no difference in the O− condition, $t(27) = 1.14$, $p = .26$. As the contributions of the co-actor tended to increase the sense of control, it makes sense that noisy perturbations which thwarted the co-actor reduced the sense of control.

Although the degree of visuomotor coupling was strongly predictive of JoC in Experiments 1 and 2, the most interesting result of Experiment 2 is that the overall pattern of the JoC ratings (Fig. 7, top row) diverged from the egocentric visuomotor coupling (Fig. 7, middle row). Specifically, while the visuomotor coupling was significantly higher when the self joystick was the only influence on the cursor (S+O−N−) compared to when the other joystick was also influencing the cursor (S+O+N−), $t(27) = 9.22$, $p < .001$, the JoC ratings were significantly higher in the latter condition, $t(27) = 5.47$, $p < .001$. Visuomotor coupling and JoC ratings were also dissociated in the S−O+ condition, as adding noise decreased visuomotor coupling, $t(27) = 2.63$, $p = .01$, but increased JoC ratings, $t(27) = 4.18$, $p < .001$. This pattern of results cannot be explained by processes which monitor the degree of match between self generated motor predictions and observed action effects alone. Rather, they support the hypothesis that during complementary joint actions, the sense of control depends on amount of control exhibited by the group as a whole. As in the case of individual action, control at the group level is indicated by action effect predictability, as well as the success or failure of the joint action. The error data are consistent with this interpretation, as the error was lower when both joysticks were turned on (S+O+) compared to when only one agent had control (S+O− or S−O+) (Fig. 7, bottom row).

Summary. To recap, the results of Experiment 2 indicated that for a cooperative joint action where two agents made perceptually distinctive contributions to the outcome, the sense of control was strongly correlated with

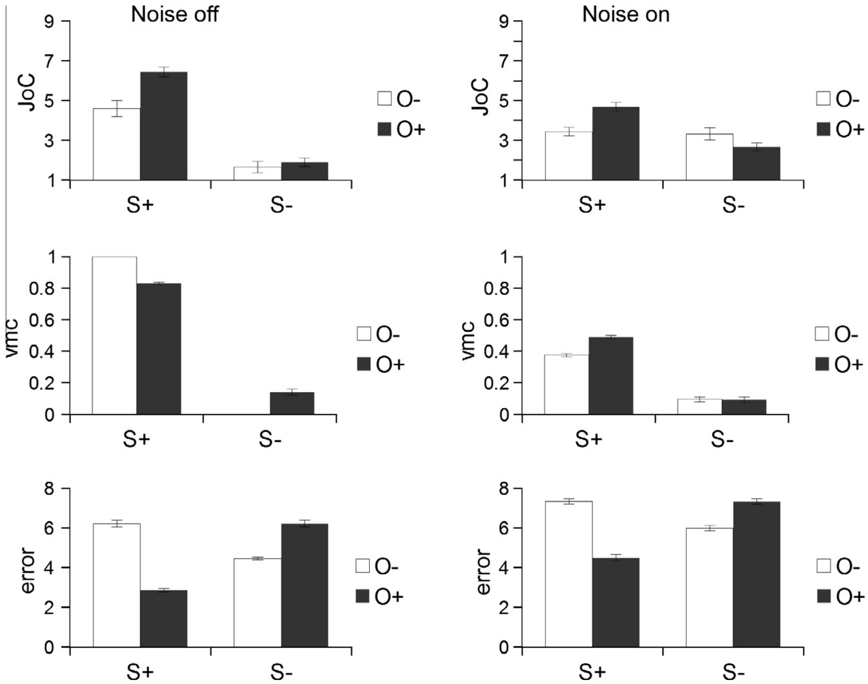

Fig. 7. Mean JoC ratings (top), visuomotor coupling (middle, units are Pearson correlation *r*), and error (bottom, units are degrees of visual angle) from Experiment 2. Error bars depict the ± 1 SEM.

egocentric sensory predictions, but was also influenced by the amount of control exhibited by the group as a whole. We suggest that, in contrast to Experiment 1, the complementary nature of the task in Experiment 2 induced participants to evaluate their control from a "we mode" perspective (i.e. "we are in control", as opposed to "I am in control"). This implies that for complementary tasks where the contribution of self and other are both necessary to succeed, individuals should not only rate their own control higher when the joint action is successful, but should also rate their co-actor's control higher. Alternatively, there might be a self-serving bias to attribute more control to oneself when the joint action is successful, but not to the co-actor. To arbitrate between these two possibilities, in Experiment 3 participants performed the same J-task as in Experiment 2, but alternated between blocks in which participants rated their own control, and blocks in which they rated the co-actor's control.

4. Experiment 3

The aims of Experiment 3 were (1) to replicate the results of Experiment 2; and (2) to compare how individuals rated their own control vs. their co-actor's control. The joint control hypothesis predicted participants would rate both their own control and their co-actor's control highest when both joysticks were turned on and the noise was turned off (S+O+N−).

4.1. Methods

Participants. Twenty-four participants (19 females and 5 males, mean age 21.25, 21 right handed and 3 left handed) were recruited from student organizations in the Budapest area in exchange for small monetary payments. Participants were recruited in pairs, with appointments to arrive at the lab at the same day and time. Participants did not know each other prior to the experiment and all participants were naïve to the purpose of the study.

Procedure. The procedure was the same as Experiment 2, except that the experiment was divided into four blocks. During two of the blocks, participants were instructed to rate their own control as in the previous experiments. During the other two blocks, participants were instructed to rate their co-actor's control. The order of the blocks was ABBA, with order counterbalanced across dyads. Each block consisted of 8 repetitions of each combination of the Self, Other, and Noise factors. Condition order was randomized within blocks. Participants were encouraged to take a break following each block. The total duration of the experiment was about 70 min.

4.2. Results and discussion

Self ratings. When participants rated their own control (plotted in Fig. 8), the JoC ratings were once again strongly positively correlated with the visuomotor coupling, $r_p = .81$, and negatively correlated with error, $r_p = -.26$. To investigate the relative impacts of visuomotor coupling and error on JoC ratings, the variables were entered into a stepwise linear regression model. The overall model was statistically significant: $R^2 = .70$, $F(3,188) = 221.36$, $p < .001$. Visuomotor coupling ($B = 5.43$, $t(188) = 20.50$, $p < .001$) and but not error ($B = .002$, $t(188) = 1.14$, $p = .26$) explained significant portions of the variance in JoC ratings (all coefficients are unstandardized B's). Consistent with

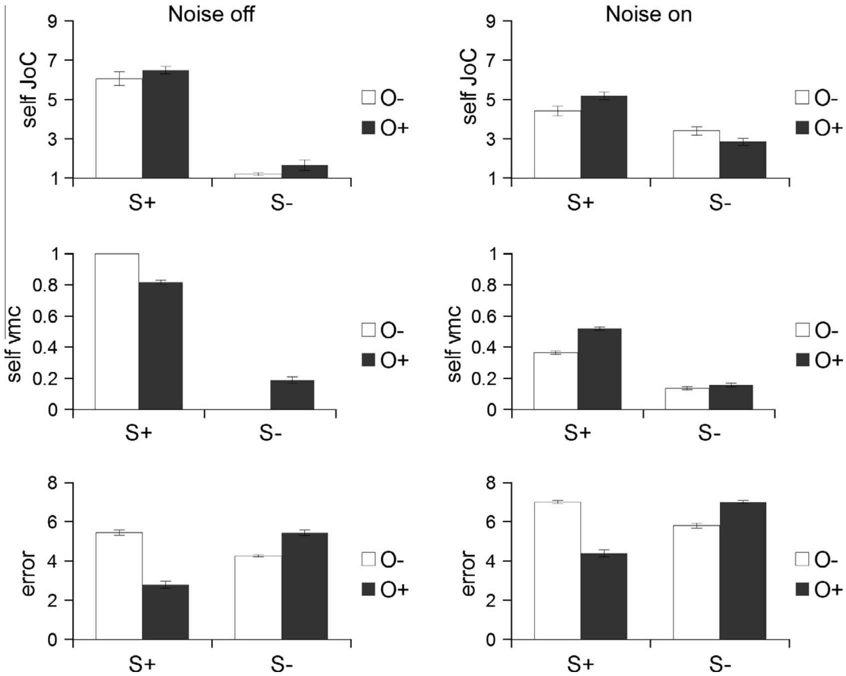

Fig. 8. Mean JoC ratings (top), visuomotor coupling (middle, units are Pearson correlation *r*), and error (bottom, units are degrees of visual angle) from the blocks of Experiment 3 where participants rated their own control. Error bars depict the ± 1 SEM.

the previous experiments, action effect predictability was once again more important to the sense of control than external performance cues.

Next, the JoC ratings were submitted to a three way 2 (Self: S− vs. S+) × 2 (Other: O− vs. O+) × 2 (Noise: N− vs. N+) repeated measures ANCOVA, with the gender of Self and Other as covariates. The main effect of Self, $F(1,23) = 168.84$, $p < .001$, $\eta^2G = .70$, indicating higher JoC ratings for S+ compared to S−. There were also a pair of significant two way interactions: Self × Other, $F(1,23) = 6.77$, $p < .02$, $\eta^2G = .02$, and Self × Noise, $F(1,23) = 227.40$, $p < .001$, $\eta^2G = .35$. The three way Self × Other × Noise interaction was also significant, $F(1,23) = 11.81$, $p = .002$, $\eta^2G = .02$.

The Self × Other interaction indicated that the co-actor's contribution increased JoC ratings in the S + condition, $t(23) = 2.13$, $p = .04$, and had no effect in the S− condition,, $t(23) = .23$, $p = .82$. This replicated the corresponding interaction from Experiment 2. The Self × Noise interaction indicated that noise decreased JoC ratings in the S+ condition, $t(23) = 8.39$, $p < .001$, and increased JoC ratings in the S− condition, $t(23) = 9.90$, $p < .001$. This also replicated Experiment 2.

The Self × Other × Noise interaction indicated that the difference between the S−O−N− and S−O−N+ conditions was larger than the difference between the S−O+N− and S−O+N+ conditions, $t(23) = 4.07$, $p < .001$. In other words, noisy perturbations led to an illusion of control when participants lacked control, and the effect was stronger if the co-actor also lacked control.

The main finding of Experiment 2 was successfully replicated: participants rated their control highest when both joysticks were turned on (S+O+N−) (Fig. 8, top row) despite the fact that the egocentric visuomotor coupling was greatest when the self joystick was the only influence on the cursor (S+O−N−) (Fig. 8, middle row).

Other ratings. The JoC ratings when participants rated their co-actor's control were positively correlated with the co-actor's visuomotor coupling, $r_p = .64$, and negatively correlated with error, $r_p = -.21$. To investigate the relative impacts of visuomotor coupling and error on JoC ratings, the variables were entered into a stepwise linear regression model. The overall model was statistically significant: $R^2 = .56$, $F(3,188) = 119.84$, $p < .001$. Visuomotor coupling ($B = 3.78$, $t(188) = 13.23$, $p < .001$) and but not error ($B = .001$, $t(188) = .61$, $p = .54$) explained significant portions of the variance in JoC ratings (all coefficients are unstandardized B's). This indicates that action effect predictability influenced participants' sense of their co-actors' control similarly to their sense of their own control. Since participants could not directly observe their co-actor's joystick movements through the occluder, this indicates an effect of action effect predictability at the level of shared visual information.

Next, the JoC ratings were submitted to a three way 2 (Self: S− vs. S+) × 2 (Other: O− vs. O+) × 2 (Noise: N− vs. N+) repeated measures ANCOVA, with the gender of Self and Other as covariates. There was a significant main effect of Other, $F(1,23) = 142.42$, $p < .001$, $\eta^2G = .51$, indicating higher JoC ratings for O+ compared to O−, and a significant main effect of Noise, $F(1,23) = 18.26$, $p < .001$, $\eta^2G = .09$, indicating higher JoC ratings for N− compared to N+. There were also a pair of significant two way interactions: Self × Other, $F(1,23) = 29.29$, $p < .001$, $\eta^2G = .06$, and Other × Noise, $F(1,23) = 139.28$, $p < .001$, $\eta^2G = .33$.

The Self × Other interaction indicated that when the self had control (S+), this increased JoC ratings in the O+ condition, $t(23) = 3.58$, $p = .002$, but decreased JoC ratings in the O− condition, $t(23) = 2.32$, $p = .03$. Consistent with the joint control hypothesis, participants attributed the most control to their co-actor when the level of control exhibited by the group as a whole was the highest (S+O+).

The Other × Noise interaction indicated noise decreased JoC ratings in the O+ condition, $t(23) = 4.45$, $p < .001$, and increased JoC ratings in the O− condition, $t(23) = 10.18$, $p < .001$. This is analogous to the Self × Noise interaction. Noisy perturbations made it more difficult to discriminate the co-actor's control.

The most critical result of Experiment 3 is that the overall pattern of JoC ratings when participants rated their co-actor's control was quite similar to when participants rated their own control. In particular, JoC ratings of the co-actor were highest in the S+O+N− condition when both agents had control (Fig. 9).

Comparison of self and other JoC ratings. Although both self and other JoC ratings were highest in the S+O+N− condition, there were also some interesting asymmetries. To directly compare the JoC ratings of self and other, a factor labeled Judgment (self vs. other, referring to the target of the JoC) was added to the ANOVA. For this analysis, the levels of the Self and Other factors were swapped when the target of the judgment was the co-actor in order to make the two sets of JoC ratings comparable.

There was significant main effect of Judgment, $F(1,23) = 14.46$, $p < .001$, $\eta^2G = .04$. On average, participants rated their co-actor's control ($M = 4.34$, $SD = .75$) slightly higher than their own ($M = 3.91$, $SD = .41$). There was also a significant Self × Judgment interaction, $F(1,23) = 10.85$, $p = .003$, $\eta^2G = .04$, and a Noise × Judgment interaction, $F(1,23) = 42.40$, $p < .001$, $\eta^2G = .02$. These interactions indicated that in the S− and N+ conditions, participants rated their own control lower than their co-actor did. Another way of putting this is that participants were more sensitive to their own lack of control than to their co-actor's lack of control.

Was there any evidence of a self-serving bias? In other words, did participants take credit for successful trials, while blaming their partner when the joint action was unsuccessful? To test this, we divided the 16 repetitions of each condition into 8 trials with relatively low error, and 8 with relatively high error. Not surprisingly, there was a main effect of Low vs. High error, $F(1,23) = 48.22$, $p < .001$, $\eta^2G = .04$, indicating higher ratings on low error trials. However, the two-way Low vs. High error × Judgment interaction was not significant, $F(1,23) = 1.29$, $p = .27$, $\eta^2G = .001$. Thus, there was no evidence of a self-serving bias in the JoC ratings of self and other.

Summary. The results of Experiment 3 showed that participants rated both their own and their co-actor's control highest when both joysticks were turned on (S+O+). This demonstrates that for a cooperative joint action where two agents made perceptually distinctive contributions to the outcome, participants experienced a shared sense of control (i.e. "we are in control", as opposed to "I am in control").

5. General discussion

In the past two decades there has been an upswing of interest in the sense of agency and control. One of the most prominent and successful accounts of these phenomena is

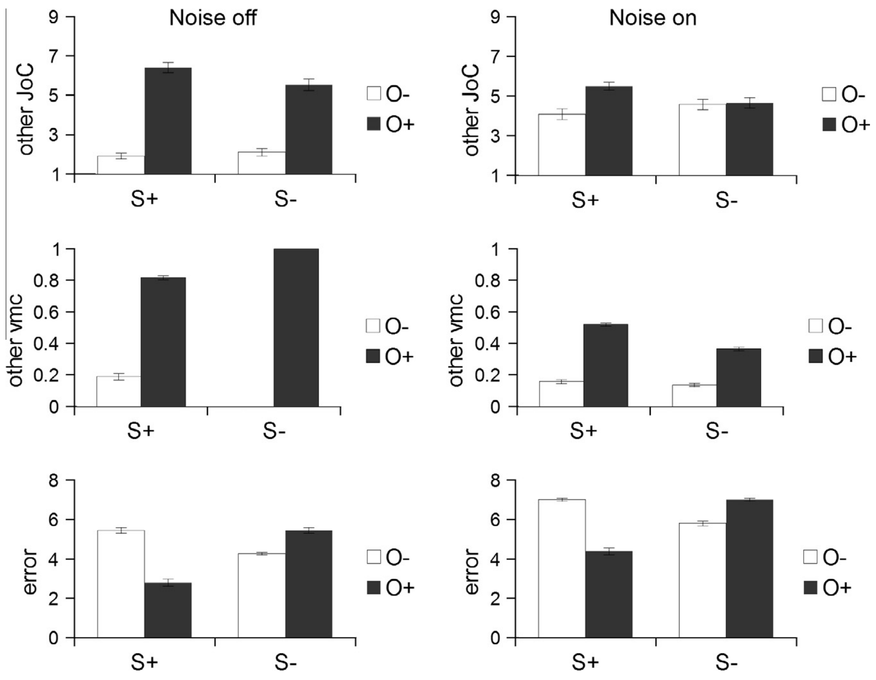

Fig. 9. Mean JoC ratings (top), visuomotor coupling (middle, units are Pearson correlation *r*), and error (bottom, units are degrees of visual angle) from the blocks of Experiment 3 where participants rated their co-actor's control. Error bars depict the ± 1 SEM.

the comparator model (Frith, 2012). In a simple version of the comparator model, sensory predictions that accompany motor efferences are compared with intended actions and reafferent sensory feedback, and the degree of match at these various comparators determines the sense of control over action effects. This account is appealing because it directly connects the phenomenology of control with action perception and motor processes, as well as offering an explanation of disturbances in the normal sense of agency experienced by schizophrenic individuals (e.g. Feinberg, 1978; Franck et al., 2001; Knoblich, Stottmeister, & Kircher, 2004).

At the same time, there has been an increasing recognition that the comparator model may need to be expanded or modified to account for the full range of situations in which people experience a sense of control (Synofzik et al., 2008). For example, sensory predictions generated from motor commands may not be entirely sufficient to explain the sense of control experienced during complex goal-directed activities. Here, one needs to consider not only the short-term correspondence between actions and their consequences (for which the relevant time scale is usually on the order of milliseconds), but also agents' longer term plans and intentions (Pacherie, 2008). Joint actions present another intriguing challenge for theories of agency and control. How do other people's actions, which may be more or less predictable, but certainly never as predictable as one's own actions, factor in to the sense of control? The present study represents a first stab at identifying parameters relevant to the sense of control during a goal-directed joint action lasting several seconds.

There were two main findings of the present study. First, causal discounting influences the sense of control during joint action, but plays a relatively minor role compared to action effect predictability (Experiment 1). Second, although the sense of control is largely determined by the correspondence between self-generated motor signals and action effects, predictable effects produced by cooperative co-actors can also increase the sense of control (Experiments 2 and 3). This was demonstrated by the fact that predictable, goal-directed action effects produced by a cooperative co-actor increased the sense of control despite being uncorrelated with self-generated joystick movements. This indicates that the sense of control during joint actions is evaluated with respect to both egocentric and group-level intentions.

While it has been shown previously that performance influences the sense of agency, this has mainly been the case for situations where control is highly ambiguous. By contrast, in Experiments 2 and 3 of the present study, participants showed good awareness of their partner's contributions as distinct from their own, but still felt a greater sense of control when the joint action was more successful. This is not indicative of an attribution error, but rather suggests that participants identified with the control of the group as a whole. Another novel aspect of our study is the finding that private sensorimotor correlations are highly predictive of the sense of control during joint action when actors' contributions are highly ambiguous, whereas publically available performance cues increase in importance when actors' contributions are perceptually unambiguous.

Our results have implications for any theory attempting to explain how the sense of control emerges from the interplay of sensory predictions and higher order inferences. Optimal behavior requires an accurate representation of confidence in one's ability to affect certain outcomes (Friston et al., 2013) and it has been suggested that the sense of control depends on an optimal integration of internal and external cues (Moore et al., 2009). According to this proposal, a variety of cues may serve as evidence of control, and their relative influence depends on their reliability. Consistent with this view, individuals with schizophrenia, who are known to be impaired at tracking the correspondence between actions and feedback for those actions, are more likely than normal populations to be influenced by external cues about performance when judging their control in a visuomotor task (Metcalfe, Van Snellenberg, DeRosse, Balsam, & Malhotra, 2012).

In the present study, egocentric sensory predictions did a good job explaining the sense of control in Experiment 1 but could not account for the full results of Experiments 2 and 3. In relation to the optimal integration hypothesis, the perceptual distinctiveness of each agent's contribution to the moving cursor was much greater in Experiments 2 and 3 than in Experiment 1. We suggest that in the ambiguous case, participants relied on private sensory predictions generated from motor commands, whereas when each agent's contribution was perceptually distinctive, the sense of control was shaped by a sensory predictions derived from publically available perceptual information. These predictions need not depend on overt motor commands nor be egocentric. One possibility is that individuals used known perception action mappings to simulate intentional actions performed by their co-actor (Knoblich & Sebanz, 2008). Alternatively, action effect anticipation (without the motoric component) alone might be sufficient to drive the sense of control. For example, given the current state of the world (here, where the cursor is located with respect to the target at time *t*) and the joint goal (keep the cursor on the target) one could derive what should be done next and predict that this is what will happen on the basis of visual cues (e.g. trajectory).

It is an open question to what extent the influence of the co-actor on the sense of control should be characterized as bottom-up (e.g. the co-actor's contribution makes the joint action effect more predictable) vs. as a top-down inference (i.e. we succeeded, so we must have had good control). These possibilities might be dissociated by manipulating success rate independently of true control (as in Dewey et al., 2010; Metcalfe & Greene, 2007). In any case, our results demonstrate that contributions from other agents can increase personal feelings of control, despite the principle of causal discounting. We suggest that the complementary joint action context contributed to a sense of "we-ness" where both agents felt in control of the cursor simultaneously, despite the fact that the movements were not entirely self-initiated.

A recent study on attributions of responsibility in group dynamics (Zultan, Gerstenberg, & Lagnado, 2012) found that agents incurred more blame for negative outcomes in the presence of a successful complementary co-actor (in the sense of performing different roles) compared to a successful substitute (the same role). Zultan et al. (2012) explained their results in terms of the notion of pivotality: an agent is pivotal if they could have changed the group outcome by their actions. It is an open question how the sense of control relates to judgments of responsibility and blame, but our results also seem consistent with this idea of pivotality, in the sense that the co-actor's contribution had a larger impact on the sense of control when their contribution was pivotal to the outcome (Experiments 2 and 3).

A potential future direction for this work would be to investigate how the sense of control scales up for joint actions with group sizes larger than two. Real world examples might include collaborative office projects or internet crowd-sourcing projects. Reasoning by analogy from our present results, we would predict that individuals' sense of control should be more tightly coupled to the performance of the group as a whole when individuals are assigned distinctive as opposed to redundant responsibilities.

In conclusion, the sense of control during joint action is influenced by a combination of action effect predictability, causal discounting, and performance cues. Beyond this, our take home message is that the sense of control during cooperative joint actions depends crucially on the perceptual distinctiveness of each agent's contribution. A co-actor whose actions overlap significantly with one's own may seem to be competing for control, so that any discrepancy between egocentric sensory predictions and the action effect reduces the sense of control. By contrast, when a co-actor's actions are complementary and non-overlapping, this may encourage a shift into the "we-mode", such that individuals identify their control with the control exhibited by the group as a whole. In this case, the sense of control takes into account joint action performance as well as egocentric sensory predictions.

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