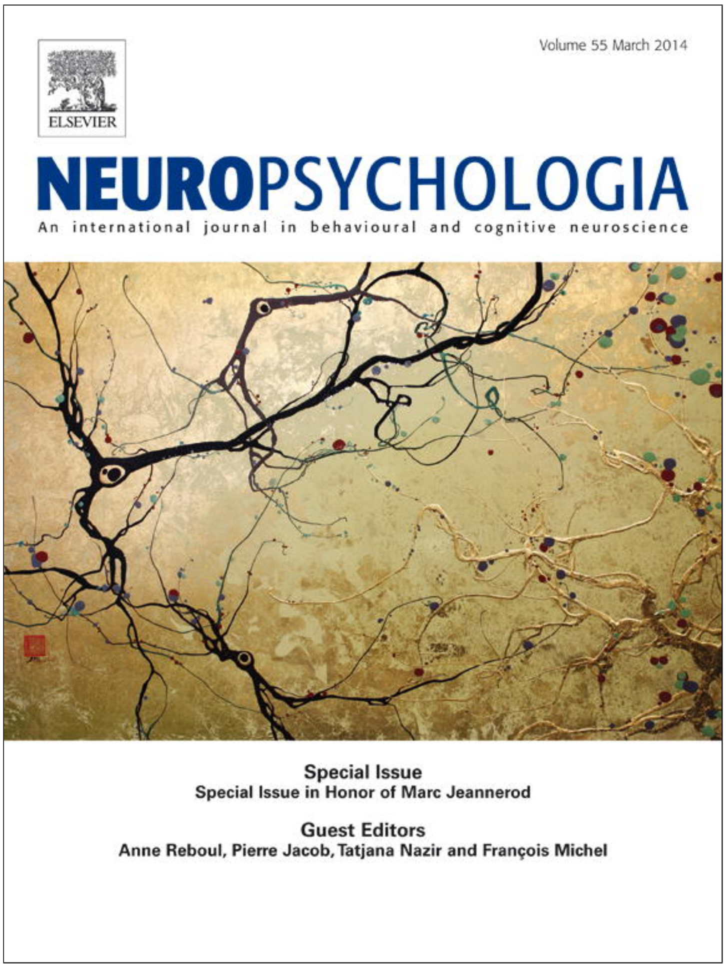
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Our actions in my mind: Motor imagery of joint action

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A R T I C L E I N F O

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A B S T R A C T

How do people imagine performing actions together? The present study investigated motor imagery of joint actions that requires integrating one's own and another's part of an action. In two experiments, individual participants imagined jumping alone or jointly next to an imagined partner. The joint condition required coordinating one's own imagined actions with an imagined partner's actions to synchronize landing times. We investigated whether the timing of participants' own imagined jumps would reflect the difference in jump distance to their imagined partner's jumps. The results showed that participants' jump imagery was indeed modulated to achieve coordination with an imagined task partner, confirming prior findings from a performance task. Moreover, when manipulating both target distance and target size, the same violation of Fitts' law reported for individual jumping was present in imagery of joint jumping. These findings link research on motor imagery and joint action, demonstrating that individuals are able to integrate simulations of different parts of a joint action.

1. Introduction

Imagining a simple action such as pouring coffee into a cup is in many respects similar to actually performing that action except that the observable motor output is lacking. Jeannerod described motor imagery as the "ability to generate a conscious image of the acting self" (Jeannerod, 2004; p. 379) and proposed that many of the principles underlying action performance also hold in action imagery (Jeannerod, 1995, 2004). This proposal has sparked a whole line of research that investigated what is common between covert (internally simulated) action and overt (actually performed) action. Similarities in neurophysiological activity when planning, performing and imagining actions indicate that these phenomena are governed by overlapping processes and brain networks (Decety & Grèzes, 2006; Dietrich, 2008; Grèzes & Decety, 2001; Rizzolatti & Sinigaglia, 2010; but see Dietrich, 2008 for a critical view). In particular, imagined and to-be-performed actions might be represented in a common motor format (Jeannerod, 1995; Prinz, 1997), thereby relying on internal forward models that predict the (imagined) outcome of an action (Grush, 2004; Blakemore & Frith, 2005; Wilson & Knoblich, 2005; Wolpert, Doya, & Kawato, 2003).

Whereas researchers have intensively studied motor imagery of individual actions (e.g., Guillot and Collet (2005), Jeannerod (2004)), motor imagery of joint actions has not been addressed. However, investigating imagery of joint action can help us to better understand the mechanisms underlying motor simulation. The reason is that in order to imagine a coordinated joint action it is neither sufficient to simulate one's own action nor is it sufficient to simulate the other's action. Rather it is also necessary to integrate these two action simulations. This becomes clear when one considers that joint action often requires that two or more individuals adapt their actions in space and time to what the other is doing (Clark, 1996; Sebanz, Bekkering, & Knoblich, 2006). Examples for such joint actions range from carrying a heavy object with a friend to passing a basketball to a team-mate or dancing a tango together. Importantly, co-actors need to represent not only their own and a partner's part of a joint action, but also the shared goal resulting from their combined actions (Vesper, Butterfill, Knoblich, & Sebanz, 2010). For performance, it has been suggested that joint action coordination toward a shared goal is to a large extent achieved by internal simulations that allow co-actors to predict their own and their partner's actions using their own motor system (Keller, 2012; Wolpert et al., 2003). We propose that the same simulation processes that support the planning and execution of joint action also support imagery of joint action. Especially when coordinating actions with others, motor simulations of one's own and a partner's action parts need to be integrated to plan one's own action with respect to achieving the shared goal. Although there is growing evidence that different motor simulations can run in parallel (Hamilton, Wolpert, & Frith, 2004; Kourtis, Sebanz, & Knoblich, 2013), there is hardly any

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evidence that motor simulations can be integrated to simulate different components of a joint action.

The current study attempted to test this assumption using motor imagery. Imagining performing actions is a pure form of motor simulation as imagery is not subject to any sensorimotor or perceptual influences that are present when movement is actually performed (cf. Schmidt and Richardson (2008)). If people were able to engage in imagery of joint action that constrained their own as well as their partner's action parts in the same way as during actual joint action planning and performance, this would provide evidence for an integration of motor simulations of one's own and others' actions.

Previous research on individual motor imagery has compared how people actually perform actions to how they imagine performing the same actions (e.g., Jeannerod (1995, 2004)). A highly consistent finding in such studies is that constraints present in performance also govern motor imagery. For example, when people imagine walking a specific distance then the time their movement takes is similar to actually walking that distance (Decety, Jeannerod, & Prablanc, 1989). Moreover, if a to-be-imagined action is more difficult reported movement times increase systematically. In one study where individual participants were asked to imagine walking through doors of varying width, their reports of the imagined movement time scaled as a function of the distance toward the door and its width (Decety & Jeannerod, 1995), thereby complying with the speed-accuracy trade-off known as Fitts' law (Fitts, 1954). Similarly, the same biomechanical constraints determining in which way people lift objects were found in their self-reports of imagining grasping the object (Johnson, 2000).

Based on these previous findings, the present study asked whether the constraints imposed by the requirement to coordinate with another person would influence imagery in the same way as when two people perform coordinated actions together. Two experiments tested whether behavioral effects previously observed in joint action coordination could be observed in a motor imagery task where participants imagined both parts of the joint action. To this end, we adapted and extended an existing joint action task (Vesper, van der Wel, Knoblich, & Sebanz, 2013) and asked participants to imagine coordinating their own action with an imagined partner. If participants' action imagery resembled actual performance this would demonstrate that participants take the same aspects of another person's task or action into account when imagining interpersonal coordination. This, in turn, would support the assumption that they can engage in an integrated motor simulation of their own and another's part of a joint action.

2. Experiment 1

Experiment 1 investigated motor imagery of joint action coordination based on a joint action task in which pairs of participants were asked to synchronize the landing times of forward jumps of varying distance (Vesper et al., 2013). In this study, co-actors knew how far they themselves had to jump and how far their partner had to jump. However, they had no perceptual information about their partner. The results demonstrated that the information received prior to jumping was sufficient for participants to adapt to the partner's jump distance so that a high degree of synchronicity in landing times was achieved. For the current study, we adapted this previous task to investigate imagery of joint action. Individual participants were asked to imagine jumping either alone (individual condition; Fig. 1a) or jointly, next to an imagined second person (joint condition; Fig. 1b). In the latter condition, they imagined coordinating their own jumping with the imagined partner's jumping such that their imagined landing would occur at exactly the same time. Participants reported their imagined jump take-off by releasing a button and their imagined landing by pressing the button again.

We predicted that participants' self-reported imagery would show the same pattern that was previously found during actual performance of individual and joint jumping (Vesper et al., 2013). More specifically, we predicted that the duration of imagined individual jumps should increase with increasing jump distance, indicating that participants succeeded in imagining jumping as a ballistic movement that is dependent on the jump distance (Juras, Slomka, & Latash, 2009). Our second prediction was that the imagined duration of a joint jump should take into account not only the jump distance that participants needed to cover but also the jump distance their imagined partner needed to cover. This should become particularly visible when the partner's jump covered a larger distance than the participant's jump. Such a finding would mirror the prior performance results where co-actors modulated the duration of both jump preparation and jump execution to achieve synchronization at landing. If the same adaptation would be observed in joint action imagery this would provide evidence that participants could integrate motor simulations of their own and an imagined person's jumping even in the absence of actual sensorimotor or perceptual feedback. On an alternative account, if individuals were only able to imagine either their own or their partner's actions, but were not able to integrate both imagined actions, then the results should not mirror those found during performance. In particular, participants' imagined jump duration should then either just reflect their own jump distance or just reflect their partner's jump distance.

2.1. Method

2.1.1. Participants

Twenty-four university students participated (17 women; mean age=21.8 years, SD=3.1 years; one left-handed and three left-footed). Their mean body height was 172.4 cm (SD=9.8 cm). On average they were 2.6 cm shorter than the experimenter. Participants were naïve to the purpose of the study, gave prior informed consent, and received monetary compensation or course credits. The experiments conformed to the standards of the Declaration of Helsinki.

2.1.2. Materials and apparatus

The experimental setup (Fig. 1) was mostly identical to that used in a previous performance study (Vesper et al., 2013). An opaque black cloth (220 cm × 400 cm) divided two jumping areas consisting of a row of five rectangles (35 cm × 50 cm) each. Next to each rectangle was a pair of red and green light-emitting diodes (LEDs) covered by a transparent matted plastic cube (edge length 4 cm). Participants pressed and released a button on a standard computer mouse to indicate the imagined point in time for take-off (release) and landing (press). Half the group of participants performed the task on the right side of the occluder, the other half on the left. Auditory information was provided via headphones. The experimental procedure was controlled by the software Presentation (Neurobehavioral Systems Inc., version 14.0) run on a standard Hewlett Packard PC (Windows Vista).

2.1.3. Procedure

Participants completed two experimental parts within one session. Part 1 was the individual condition in which participants were instructed to imagine jumping on their right leg to the target highlighted by the LED-light right next to them. In Part 2, the joint condition, participants imagined synchronizing their landing time with the landing time of an imagined person on the other side of the occluder. The experimenter always served as a reference for imagining the second person. A second light indicated the distance the imagined partner needed to cross with her jump. Detailed written instructions were given before each part.

At the beginning of a trial, participants stepped from outside the jump area into the first rectangle and simultaneously pressed the mouse button with their right index finger or thumb. The LED-lights on the ground were switched on indicating the targets for the participant's own imagined jump and the imagined partner's jump (participants were told to ignore the second LED in the individual condition). After a randomized interval of 1.7 s, 2.0 s or 2.3 s, an auditory start signal (440 Hz, 100 ms) informed participants that they should now, at their own speed, imagine jumping by releasing (time of jump take-off) and pressing (time of landing) the mouse button. At imagined landing, a short feedback tone (1320 Hz, 100 ms) was played.

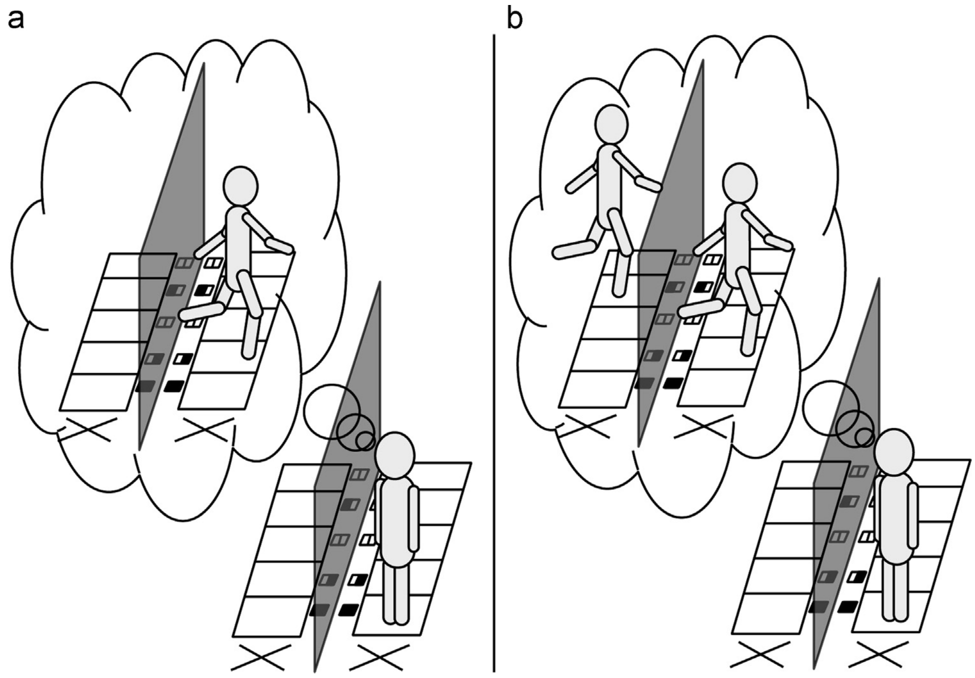

Fig. 1. Experimental setup: (a) individual condition in which participants imagined jumping on their own; (b) joint condition in which participants imagined coordinating their own jumps with an imagined second person. Cues on the ground indicated the target of participants' own and the imagined partner's jumps.

The 16 target combinations (four possible targets for participants' own jumps and four for their imagined partner's jumps) were counterbalanced and presented in random order. Breaks between trials were self-paced. Both the individual and the joint part consisted of 64 trials. After every 16 trials, participants gave a rating of their vividness of imagery on a scale from 1 ("very difficult to imagine") to 5 ("very easy to imagine"). In the individual condition this judgment referred to their own jumping, whereas they separately rated the vividness of the imagery of their own and their imagined partner's jumping in the joint condition. Overall duration of the experiment was 30 min.

2.1.4. Data analysis and design

We performed all data analyses on jump duration, measured as the time from the start signal to landing. Linear regression analyses on jumps in which both partners crossed the same distance (same-distance jumps) determined whether increasing jump distance prolonged the imagined jump duration as would be predicted from the motor imagery literature (e.g. Decety and Grèzes (2006), Jeannerod (1995, 2004)). Next, we calculated difference scores as an index of adaptation (relative jump duration; see Vesper et al. (2013), for details). The relative jump duration captures the amount of change compared to the baseline of same distance jumps (e.g. both jumping 35 cm) for a given distance difference between the participant's own and the imagined partner's jump (e.g. own jump = 35 cm, partner's jump = 105 cm, resulting distance difference = Δ 70 cm), thereby reflecting how much participants adapted their actions to their imagined partner in order to achieve coordination. This parameter was computed separately for 'closer' jumps (participant's own jump shorter than the partner's) and for 'farther' jumps (participant's own jump longer than the partner's). Separate one-factorial analyses of variance (ANOVAs) with the single factor distance difference (Δ 35 cm, Δ 70 cm, Δ 105 cm) were conducted and supplemented by linear regression analyses. All statistical analyses were performed with the program R (version 2.15.1).

2.2. Results

As predicted, the duration of imagined same-distance jumps (Fig. 2a) increased significantly with longer jump distances, both in the individual condition, $\beta = .304$, $t(94) = 3.09$, $p < .01$, and the joint condition, $\beta = .504$, $t(94) = 5.66$, $p < .001$. Thus, participants' imagery accurately reflected the dependence between jump distance and jump duration. A descriptive comparison with the data from the earlier performance study (Fig. 2c) further suggests that the imagery quite accurately reflected the timing of real jumping, although participants generally over-estimated absolute jump duration (see Guillot and Collet (2005)). Adaptation to the imagined partner in the joint condition (Fig. 2b) was also consistent with actually performed joint coordination (Fig. 2d). When a participant's own jump was closer than their imagined partner's, the participant's imagery was influenced by the distance difference, $F(2,46) = 10.32$, $p < .001$, such that imagined jump duration was longer the larger the distance difference to their partner was, $\beta = .285$, $t(70) = 2.49$, $p < .05$. When the participant's own jump was farther than the partner's the difference in distances had no influence on the duration of their imagined jumps, $F(2,46) = 1.37$, $p > .2$. The same was true in the individual condition, F's $< .4$, p's $> .6$.

A main effect of mean rating of vividness of imagery, $F(2,46) = 12.65$, $p < .001$, indicated that participants found it significantly more difficult to imagine the jumping of the imagined partner ($M = 2.65$, $SD = .8$) compared to their own jumping, $p < .01$ (individual) and $p < .001$ (joint). However, imagining how they jumped themselves was equally easy in the individual ($M = 3.17$, $SD = .8$) and the joint condition ($M = 3.29$, $SD = .6$), $p > .2$.

2.3. Discussion

Consistent with our predictions, imagining coordinated jumps in Experiment 1 led to the same pattern of results as actually planning and performing joint jumps (Vesper et al., 2013). There were two main results. First, the duration of participants' imagined individual jumps increased with increasing jump distance, indicating that participants correctly imagined jumping as a ballistic movement that depends on the jump distance (Juras et al., 2009). Second, in the joint condition, the duration of jump imagery was influenced by the difference in jump distance between participant and task partner. When the partner needed to jump farther, the duration of the imagined jump increased as the distance difference between the participant's own and the partner's imagined jumps increased. In contrast, in the individual condition, only participants' own jump distance had an influence on the duration of their jump imagery as would be expected when no coordination with an imagined task partner is required.

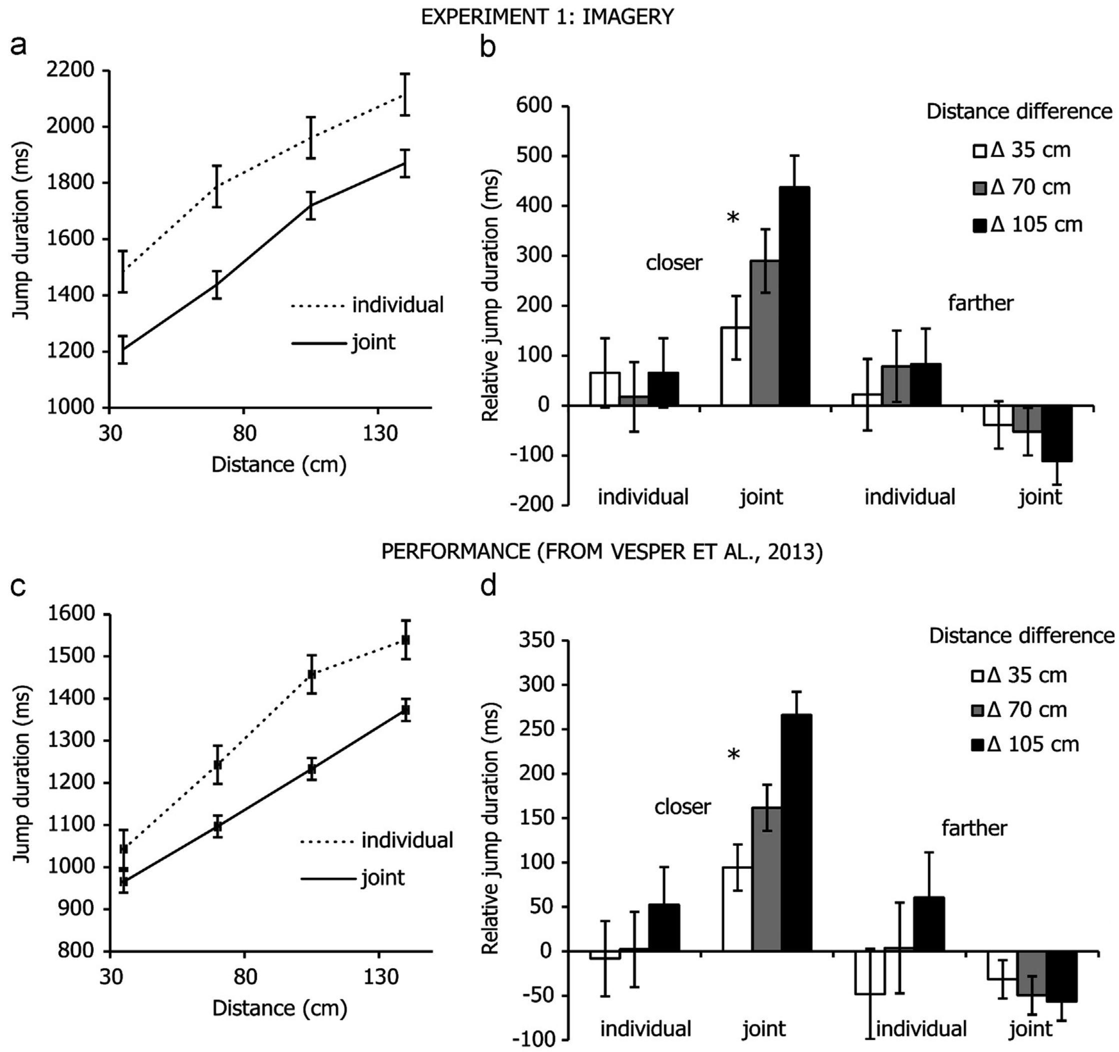

Fig. 2. (a and b) Results of Experiment 1: (a) the duration of jump imagery when participants' and their imagined partner's jumps had the same jump distance; (b) relative jump duration, an index of adaptation, in different distance trials. (c and d) The same parameters as in (a) and (b) taken from the earlier joint action performance study (adapted from Vesper et al. (2013)). Error bars display within-subject confidence intervals (Loftus & Masson, 1994).

The findings from the joint condition confirm the hypothesis that people are able to integrate motor simulations of their own and another person's actions. By imagining an action as if one would perform it, one's own motor system is activated in a similar way as during preparing to perform or actually performing such movements. Specifically, both imagination and performance rely on motor simulations that allow anticipating how an action will unfold in the near future (Grush, 2004; Jeannerod, 1995, 2004; Wolpert et al., 2003). The results of Experiment 1 demonstrate that in a joint action context, the duration of another (imagined) person's actions can be simulated and integrated with similar predictions about the duration of one's own (imagined) action. Moreover, given that the pattern of adaptation in the joint action context of Experiment 1 clearly resembles that found in the earlier performance study (Vesper et al., 2013), one can conclude that the same constraints affecting action planning and performance also influence action imagery. This provides further evidence that similar motor processes underlie covert (internally simulated) and overt (actually performed) action. These conclusions drawn from Experiment 1 can be based entirely on a within-condition comparison of participants' motor imagery reports because modulations of the duration of participants' jump imagery in the joint context are only expected if participants took the imagined task partner's jump distance into account for their own imagined action.

Although the present study clearly indicates that action imagery resembles action performance, the absolute jump duration of the earlier joint action performance study (Vesper et al., 2013) and the present experiment do not match very well. Individuals in Experiment 1 consistently over-estimated the time it would take them to prepare and execute a jump. Based on prior literature, however, this finding is not very surprising. It is well established that the duration of rapid, complex, and attention-demanding movements tends to be over-estimated because people prioritize visual accuracy of the image over exact timing (Guillot & Collet, 2005). The present task was novel and highly demanding both in terms of the type of movement (jumping on one leg only and with high spatial accuracy) and its complexity (imagining a second person and that person's actions in addition to one's own). Crucially, despite the general over-estimation of jump duration, participants' imagined jump duration was influenced by an imagined partner's jump distance in the same way as when actually performing the joint action.

Another important aspect of the current results is that imagined jump duration only scaled with the difference of jump distance between participant and the imagined partner when the participant's own imagined jump was closer than the partner's, i.e. when it covered a shorter distance. This finding mirrors the results from the performance study, suggesting that it is something specific about joint action coordination. Most likely, this reflects a strategic distribution of the coordination effort (Vesper et al., 2010) that can be seen both in performance and motor imagery. During actual joint action performance, such a task distribution might prevent over-adaptation occurring if both people changed their actions to the same extent to compensate for large asynchronies between their actions (Konvalinka, Vuust, Roepstorff, & Frith, 2010). Thus, distributing a joint task is a way to support successful coordination.

Taken together, the results of Experiment 1 suggest that participants simulated the imagined partner's jump in addition to their own imagined jump. This provides evidence that people are able to integrate motor simulations of their own and a partner's parts of a joint action (Keller, 2012; Wolpert et al., 2003).

3. Experiment 2

Having established that individuals can integrate motor simulations about their own and their partner's imagined actions, we tested the hypothesis that only those motor parameters that actually constrain movement execution would be taken into account during imagery of joint action coordination. For this purpose, we systematically manipulated the size of the jump targets in addition to distance, thereby creating three indices of movement difficulty (Table 1). Fitts (1954) showed that the time to prepare and perform a movement lawfully depends on the relation between movement distance and target width. This relation is captured by the formula $ID=\log_2(2D/W)$, whereby D is the movement distance, W is the target width and ID is a scale-free index of difficulty. Whereas previous studies have shown that Fitts' law holds not only in action preparation and performance but also in perception of others' actions (Eskenazi, Rotshtein, Grosjean, & Knoblich, 2012; Grosjean, Shiffrar, & Knoblich, 2007) and in individual motor imagery (Decety & Jeannerod, 1995; Decety et al., 1989), recent findings have revealed that the law does not hold in ballistic movements such as jumping (Juras et al., 2009). In movements with a ballistic trajectory, only distance, but not target width systematically influences the time it takes to plan and perform the movement. This is most likely related to the ballistic nature of jumping which does not allow flexible online corrections of the movement path during target approach. Fitts' law indicates that, in addition to the movement distance, the size of the target affects planning and performance of simple aiming movements such that smaller targets require higher precision and are therefore approached more slowly and with more care (Fitts, 1954; Juras et al., 2009). In contrast during jumping, it is not possible to correct or carefully perform the homing-in phase of the movement because of gravity constraints.

Based on these previous findings, we predicted that the same violation of Fitts' law would also be present in motor imagery of one's own jumping. More importantly, if participants integrated simulations about their own and their partner's actions we would expect that the violation should also influence motor imagery of joint action. Specifically, we predicted that participants' imagined jump duration would reflect only the difference in distance between their own and their imagined partner's jumps, but not the difference in *ID*. That is, if participants accurately simulate their own and their partner's jumping using their motor system then imagery of joint action should be constrained specifically by those task parameters that constrain individual and joint action performance.

Table 1
Target sizes (cm) for each respective jump distance/index of difficulty combination used in Experiment 2.

Index of difficulty		2	3	4
Distance (cm)	28	14	7	3.5
	56	28	14	7
	112	56	28	14

3.1. Method

3.1.1. Participants

Twenty-four naïve participants were recruited from the same subject pool (17 women; mean age 22.3 years, $SD=2.2$ years; no left-handed and two left-footed). Participants' mean body height was 175.4 cm ($SD=9.3$ cm) so they were on average 6.9 cm taller than the experimenter.

3.1.2. Materials and apparatus

The same setup as in Experiment 1 was used with two changes. First, targets did not have a fixed size, but consisted of nine black soft rubber mats that could flexibly be changed. Their sizes were used to create *ID*s of 2, 3 and 4 (see Table 1 for the exact sizes and distances). Second, to match the maximum jump distance in both experiments and still have target sizes of reasonable width, only three, slightly shorter jump distances were used (28 cm, 56 cm and 112 cm).

3.1.3. Procedure

The procedure in Experiment 2 closely followed that of Experiment 1 with two exceptions to accommodate the extra factor *ID*. First, participants performed 54 trials in six blocks of nine trials. Second, after each block, the experimenter changed the target sizes. Target sizes for each block were pseudo-randomized such that within a block, all three *ID*s were present. Vividness ratings of the imagery were also assessed after each block. The experiment took 40 min.

3.1.4. Data analysis and design

The same analyses as in Experiment 1 were performed for distance and *ID* separately, thereby controlling for the influence of the respective other task parameter. For *ID*, *t*-tests instead of linear regression analyses were used to determine the influence of distance difference on jump duration.

3.2. Results

The analyses performed on the factor distance (controlling for *ID*) replicated the findings from Experiment 1. First, the duration of imagined same-distance jumps (Fig. 3a) increased significantly with longer jump distances (individual condition, $\beta=.422$, $t(70)=3.9$, $p<.001$; joint condition, $\beta=.355$, $t(70)=3.17$, $p<.01$). Second, adaptation to the distance difference between participants' own and their imagined partner's jumps (Fig. 3b) was only found for closer jumps, $F(2,46)=8.6$, $p<.001$, such that jump duration was longer the larger the distance difference was, $\beta=.269$, $t(70)=2.33$, $p<.05$, and not for farther jumps, $F(2,46)=.002$, $p>.9$, or in the individual condition, F's <1.8, p's $>.2$.

As expected, Fitts' law did not hold for imagery of jumping, i.e. *ID* did not significantly influence jump performance in same or different distance jumps. First, jump duration in same distance jumps was the same for all *ID*s when controlling for distance, $\beta<.056$, $t(70)<.4$, $p>.6$. This is demonstrated graphically by the flat line in Fig. 3c which shows that, if the influence of distance is controlled for (because all data points contain the same number of jumps with 28 cm, 56 cm and 112 cm distance), there are no effects of *ID* on participants' estimates of their jump duration. Second, participants also did not take *ID* into account for coordinating their jumps with an imagined partner. In particular, participants' imagined jump durations did not depend on the difference in movement difficulty (*ID*) between their own and their imagined partner's jumps (Fig. 3d) when their own jumps were closer, $F(1,23)=1.59$, $p>.2$, when their own jumps were farther, $F(1,23)=1.92$, $p>.2$, or when they imagined jumping individually, F's $<.3$, p's $>.5$.

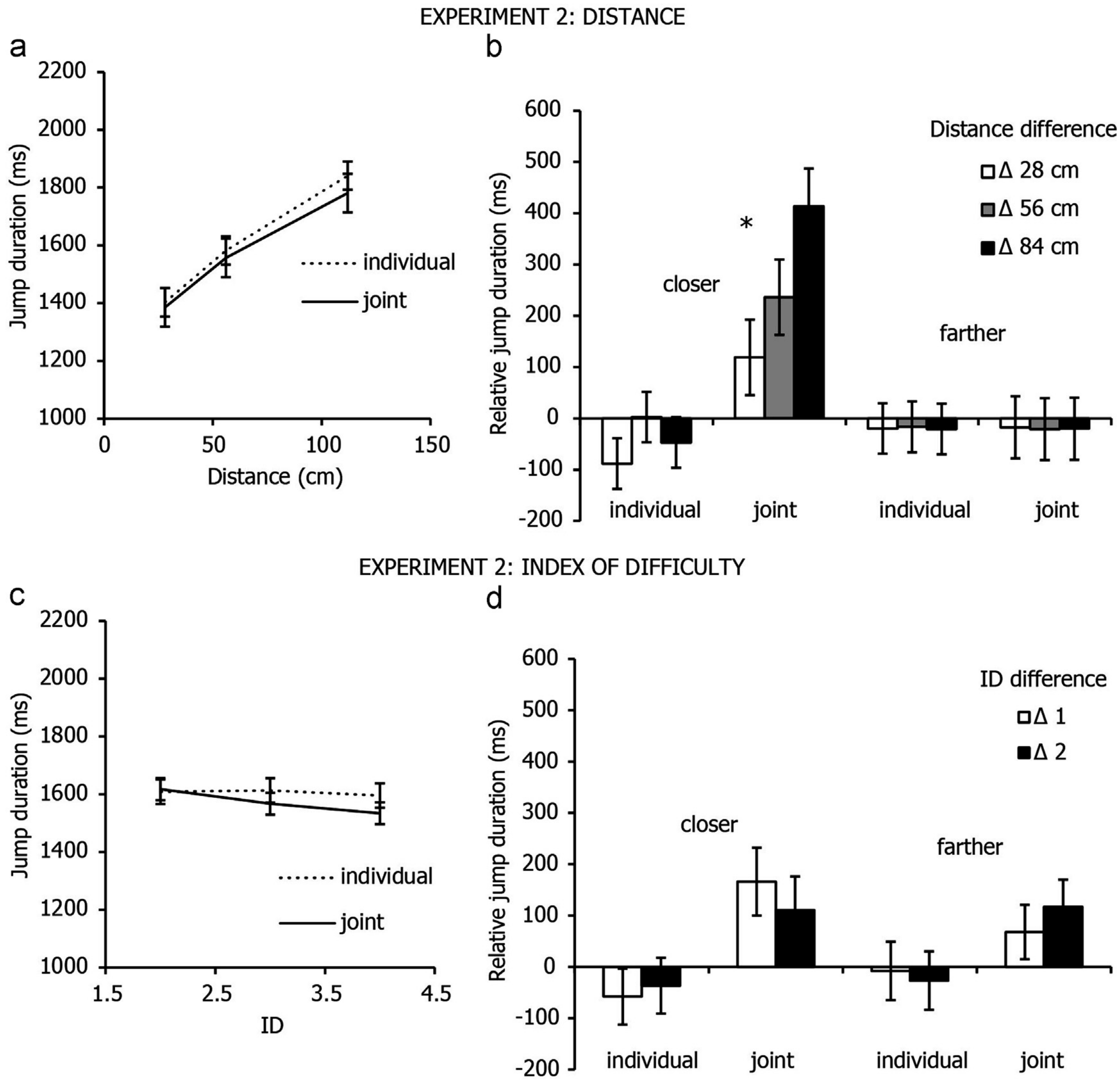

Fig. 3. Results of Experiment 2. The findings of Experiment 1 were replicated with respect to jump distance in (a) same distance jumps and (b) different distance jumps. In contrast, index of difficulty did not significantly influence motor imagery in (c) same *ID* jumps or (d) different *ID* jumps. Error bars display within-subject confidence intervals (Loftus & Masson, 1994).

As in Experiment 1, there was a main effect of participants' mean rating of vividness of their imagery, $F(2,46)=8.64$, $p<.001$. Imagining how the imagined partner would jump ($M=3.02$, $SD=.6$) was significantly more difficult than imagining their own jumping, $p<.01$ (individual) and $p<.01$ (joint), but there was no difference between imagining how they jumped themselves in the individual ($M=3.4$, $SD=.6$) and the joint condition ($M=3.37$, $SD=.6$), $p>.6$.

3.3. Discussion

The findings of Experiment 2 suggest that Fitts' law is violated for imagery of individual jumping as well as for imagery of joint jumping. This corresponds to recent findings on individual jumping performance (Juras et al., 2009) and demonstrates that the duration of imagined ballistic movements depends only on the distance and not on the index of difficulty, implying that target size is irrelevant. This finding extends prior knowledge on motor imagery by showing that the violation of Fitts' law in ballistic movements holds for imagined jumps. To our knowledge, this has not been demonstrated before.

More importantly for the field of social interaction, Experiment 2 showed that individuals' imagery of jumping reflected only the difference in distance between their own and their imagined partner's jumps and not the difference in *ID*. This finding strengthens the case for a motor simulation approach to joint action because it shows that only those task parameters that would constrain one's own performance are taken into account when integrating simulations of one's own and another person's actions.

4. General discussion

The aim of the present study was to determine whether people are able to engage in integrated motor simulations of self and other when imagining to perform coordinated actions together. We predicted that constraints imposed by the requirement to coordinate one's own actions with another person would influence motor imagery. Experiment 1 showed that behavioral effects obtained in joint action coordination (Vesper et al., 2013) could be observed in a motor imagery task where participants imagined both parts of the joint action. In particular, when intending to coordinate, participants' jump duration was influenced not only by their own jump distance, but also by the difference between their own and the partner's jump distance. This finding provides evidence for an integration of motor simulations of participants' own and another's (imagined) part of a joint action. Experiment 2 further supported this conclusion by showing that only task parameters that would constrain one's own performance are taken into account when integrating simulations of one's own and another person's actions.

Together, the current findings extend previous research on motor simulation (Grush, 2004; Keller, 2012; Wilson & Knoblich, 2005; Wolpert et al., 2003) that has shown commonalities between perceiving, planning and performing actions (Brass, Bekkering, & Prinz, 2001; Kilner, Paulignan, & Blakemore, 2003; Kourtis et al., 2013) and between imagining and performing actions (Ramsey, Cumming, Eastough, & Edwards, 2010). During joint action tasks, one's own and others' action parts need to be integrated to achieve coordination toward a shared goal. Whether and how motor simulations of one's own and another person's actions can be integrated has not directly been addressed before.

In an attempt to answer this question, this study showed that people can integrate simulations of their own and another's action parts when engaged in imagined joint actions and that these integrated simulations use a person's own motor system. Future experiments are needed to investigate whether people engage in an integrated motor simulation of the complete joint action right away or whether they simulate their own and their partner's actions separately and then integrate them in an additional step. Furthermore, determining the boundaries of the ability to integrate simulations of own and others' actions is an important goal for future research (Sartori, Cavallo, Bucchioni, & Castiello, 2012). Do people simulate all action parts if they interact with multiple people? Is there an upper boundary for the number of actions that can be simulated and what are the parameters that would determine this boundary? Motor imagery might be a useful way of empirically addressing these relevant questions.

The integration of simulations of self and other is also currently discussed as one of the core mechanisms aligning speaker and listener during discourse (Pickering & Garrod, in press). This opens an interesting link between imagery of joint action and linguistic discourse (Clark, 1996; Fusaroli et al., 2012). Testing whether predictions in the linguistic domain and predictions in the action domain follow the same integration principles can lead to an improved understanding of how language enables practical joint action and vice versa.

In summary, by extending motor imagery to the domain of joint action, our study shows that people can simulate both their own and a partner's actions and, importantly, integrate these predictions for coordination. Thus, the coordination of "our" actions can entirely take place in "my" mind.

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References

Blakemore, S. -J., & Frith, C. (2005). The role of motor contagion in the prediction of action. *Neuropsychologia*, *43*, 260–267.

Brass, M., Bekkering, H., & Prinz, W. (2001). Movement observation affects movement execution in a simple response task. *Acta Psychologica*, *106*, 3–22.

Clark, H. H. (1996). *Using language*. Cambridge, England: Cambridge University Press.

Decety, J., & Grèzes, J. (2006). The power of simulation: Imagining one's own and other's behavior. *Brain Research*, *1079*, 4–14.

Decety, J., & Jeannerod, M. (1995). Mentally simulated movements in virtual reality: does Fitt's law hold in motor imagery? *Behavioral Brain Research*, *72*, 127–134.

Decety, J., Jeannerod, M., & Prablanc, C. (1989). The timing of mentally represented actions. *Behavioral Brain Research*, *34*, 35–42.

Dietrich, A. (2008). Imaging the imagination: The trouble with motor imagery. *Methods*, *45*, 319–324.

Eskenazi, T., Rotshtein, P., Grosjean, M., & Knoblich, G (2012). The neural correlates of Fitts's law in action observation: An fMRI study. *Social Neuroscience*, *7*, 30–41.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, *47*, 381–391.

Fusaroli, R., Bahrami, B., Olsen, K., Frith, C. D., Roepstorff, A., & Tylén, K. (2012). Coming to terms: Quantifying the benefits of linguistic coordination. *Psychological Science*, *23*(8), 931–939.

Grèzes, J., & Decety, J. (2001). Functional anatomy of execution, mental simulation, observation, and verb generation of actions: A meta-analysis. *Human Brain Mapping*, *12*, 1–19.

Grosjean, M., Shiffrar, M., & Knoblich, G. (2007). Fitts's law holds for action perception. *Psychological Science*, *18*, 95–99.

Grush, R. (2004). The emulation theory of representation: Motor control, imagery, and perception. *Behavioral and Brain Sciences*, *27*, 377–442.

Guillot, A., & Collet, C. (2005). Duration of mentally simulated movement: A review. *Journal of Motor Behavior*, *37*(1), 10–20.

Hamilton, A. F. C., Wolpert, D., & Frith, U. (2004). Your own action influences how you perceive another person's action. *Current Biology*, *14*, 493–498.

Jeannerod, M. (1995). Mental imagery in the motor context. *Neuropsychologia*, *33*, 1419–1432.

Jeannerod, M. (2004). Actions from within. *International Journal of Sport and Exercise Psychology*, *2*(4), 376–402.

Johnson, S. H. (2000). Thinking ahead: The case for motor imagery in prospective judgements of prehension. *Cognition*, *74*, 33–70.

Juras, G., Slomka, K., & Latash, M. (2009). Violations of Fitts' law in a ballistic task. *Journal of Motor Behaviour*, *41*(6), 525–528.

Keller, P. E. (2012). Mental imagery in music performance: Underlying mechanisms and potential benefits. *Annals of the New York Academy of Sciences*, *1252*, 206–213.

Kilner, J. M., Paulignan, Y., & Blakemore, S. J. (2003). An interference effect of observed biological movement on action. *Current Biology*, *13*, 522–525.

Konvalinka, I., Vuust, P., Roepstorff, A., & Frith, C. D. (2010). Follow you, follow me: Continuous mutual prediction and adaptation in joint tapping. *Quarterly Journal of Experimental Psychology*, *63*, 2220–2230.

Kourtis, D., Sebanz, N., & Knoblich, G. (2013). Predictive representation of other people's actions in joint action planning: An EEG study. *Social Neuroscience*, *8*, 31–42.

Loftus, G., & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin and Review*, *1*, 476–490.

Pickering, M.J., & Garrod, S. An integrated theory of language production and comprehension. *Behavioral and Brain Sciences*, in press.

Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology*, *9*(2), 129–154.

Ramsey, R., Cumming, J., Eastough, D., & Edwards, M. G. (2010). Incongruent imagery interferes with action initiation. *Brain and Cognition*, *74*, 249–254.

Rizzolatti, G., & Sinigaglia, C. (2010). The functional role of the parieto-frontal mirror circuit: Interpretations and misinterpretations. *Nature Reviews Neuroscience*, *11*(4), 264–274.

Sartori, S., Cavallo, A., Bucchioni, G., & Castiello, U. (2012). From simulation to reciprocity: The case of complementary actions. *Social Neuroscience*, *7*, 146–158.

Schmidt, R. C., & Richardson, M. J. (2008). Dynamics of interpersonal coordination. In: A. Fuchs, & V. K. Jirsa (Eds.), *Coordination: Neural, behavioral and social dynamics* (pp. 281–308). Berlin, Heidelberg: Springer.

Sebanz, N., Bekkering, H., & Knoblich, G. (2006). Joint action: Bodies and minds moving together. *Trends in Cognitive Sciences*, *10*, 70–76.

Vesper, C., Butterfill, S., Knoblich, G., & Sebanz, N. (2010). A minimal architecture for joint action. *Neural Networks*, *23*, 998–1003.

Vesper, C., van der Wel, R. P. R. D., Knoblich, G., & Sebanz, N. (2013). Are you ready to jump? Predictive mechanisms in interpersonal coordination. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(1), 48–61.

Wilson, M., & Knoblich, G. (2005). The case for motor involvement in perceiving conspecifics. *Psychological Bulletin*, *131*(3), 460–473.

Wolpert, D. M., Doya, K., & Kawato, M. (2003). A unifying computational framework for motor control and interaction. *Philosophical Transactions of the Royal Society of London B*, *358*, 593–602.