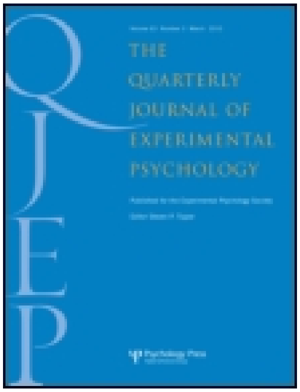

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Factors that affect action possibility judgements: Recent experience with the action and the current body state

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Factors that affect action possibility judgements: Recent experience with the action and the current body state

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It has been suggested that action possibility judgements are formed through a covert simulation of the to-be-executed action. We sought to determine whether the motor system (via a common coding mechanism) influences this simulation, by investigating whether action possibility judgements are influenced by experience with the movement task (Experiments 1 and 2) and current body states (Experiment 3). The judgement task in each experiment involved judging whether it was possible for a person's hand to accurately move between two targets at presented speeds. In Experiment 1, participants completed the action judgements before and after executing the movement they were required to judge. Results were that judged movement times after execution were closer to the actual execution time than those prior to execution. The results of Experiment 2 suggest that the effects of execution on judgements were not due to motor activation or perceptual task experience—alternative explanations of the execution-mediated judgement effects. Experiment 3 examined how judged movement times were influenced by participants wearing weights. Results revealed that wearing weights increased judged movement times. These results suggest that the simulation underlying the judgement process is connected to the motor system, and that simulations are dynamically generated, taking into account recent experience and current body state.

Keywords: Action; Perception; Action possibility judgements; Mental simulation; Fitts' law.

The ability to accurately judge whether it is possible to complete a movement is important for the successful and safe completion of both individual and social tasks. For example, it is equally important to be able to determine whether it is possible for you to safely lift and pour a heavy pitcher of water before picking it up as it is for you to determine whether someone else, such as a small child, can safely handle the pitcher before you pass it to that individual. Although the formation of these

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judgements is clearly complex and engages a number of different mechanisms, it has been suggested that the core process in these judgements involves a simulation of the to-be-judged action, based on the individual's own motor system and capabilities.

The current formulation of this simulation account (see Grosjean, Shiffrar, & Knoblich, 2007) is rooted in common coding theory (Prinz, 1992; see also Decety, 2002; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Prinz, 2005). According to this view, the codes that represent action generation are tightly linked to the perceptual codes representing the effects that these actions have on the environment. The main practical implications of this common coding for the execution of action are that one can select and generate the desired action codes by conceiving of the effect one wants to have on the environment, and, likewise, one can predict the effects a specific action will have on the environment when the response code is activated.

Of particular relevance to the present paper, however, are the possible secondary consequences that a common coding system has for other cognitive processes. One of these secondary consequences is that an observer may be able to perceive and recognize the actions of other people through this common coding system, because the perception of another person's action pattern or action effect can activate the associated response codes in the observer. These observation-activated response codes can then be used by other systems for a variety of purposes, including action perception (recognition), imitation, and observational learning.

Although the ability to recognize actions is not limited to the response codes existing in the observer's own motor repertoire (it is possible to perceive and understand movements we cannot personally perform), recent support for the important role the common codes play in action perception comes from a study by Casile and Giese (2006). In this study, it was shown that the visual recognition of a motor pattern improved after participants learned to perform the movement pattern. This improvement in visual recognition occurred even though during practice the learners wore a blindfold, which prevented them from seeing the movement pattern as they were learning it. Hence, the development of an action/perception representation through the activation of the motor and proprioceptive systems alone improved performance on a visual perception task (see also Hecht, Vogt, & Prinz, 2001). Additional support for the role of common coding in action recognition comes from the repeated finding that people are able to recognize their own movement patterns, such as clapping, writing, and piano playing, better than they are able to recognize the actions of other people (Flach, Knoblich, & Prinz, 2004; Knoblich & Prinz, 2001; Repp & Knoblich, 2004; Mazalek et al., 2009). Presumably, we can recognize our own movements because we have greater experience in performing them and perceiving their consequences, and we have well-developed action/effect codes that allow us to recognize and simulate these movements more efficiently.

Another relevant result is that one can simulate or imagine movement execution by running the common codes offline, either alone or in tandem with the perception of another person's actions. This simulation can then be used for a variety of purposes including predicting the consequences of the simulated action, determining whether an action is possible or not, and coordinating one's movements with the actions of another person (see Sebanz & Knoblich, 2009). In the specific case of action possibility judgements, it is thought that the simulation of the to-be-judged actions is used to determine whether the observed movement is possible or impossible to perform. The key point to bear in mind for the present paper is the proposal that the simulation process employed during such action possibility judgements is rooted in a common action-perception coding that involves one's own motor system.

Initial support for the involvement of an ideomotor simulation mechanism in action possibility judgements comes from a study by Grosjean et al. (2007). In this study, subjects were shown a series of alternating pictures of a person touching their finger to two targets that varied in width and in the distance that separated them across trials.

The rate at which the pictures were alternated was also varied across trials so that the hand appeared to move back and forth between the two targets at varying speeds, thus varying apparent movement times (MTs). The task of the participant was to judge whether it was possible to accurately move between the two targets at the apparent MT. Critical to this study was the manipulation of the width of the targets and the distance between them; according to Fitts' law (Fitts, 1954), the time needed to move as quickly as possible between two targets while maintaining accuracy varies as a function of the width of the targets and the distance between them (for a review see Plamondon & Alimi, 1997). Formally:

$$\mathrm{MT} = a + b(\mathrm{ID})$$

where MT is the movement time, ID is the index of difficulty, and a and b are constants. The index of difficulty itself is a function of the width of the targets (W) and the amplitude (A, distance between the targets):

$$\mathrm{ID} = \log_2(2\mathrm{A}/\mathrm{W})$$

Because the relationship between MT, accuracy, and specific target variables has been quantified and replicated, Fitts' law provides an established control platform to develop specific predictions regarding movement execution and judgements.

Consistent with previous research on reciprocally executed (e.g., Fitts, 1954) and imagined movements (e.g., Decety & Jeannerod, 1995), Grosjean et al. (2007) found that the possibility judgements for the apparent movements followed Fitts' law. Specifically, the shortest MTs judged to be possible were longer for apparent movements in high-ID contexts than for apparent movements in low-ID contexts. As in execution studies, the relationship between judged MT and ID was very strong (e.g., $r^2 = .96$), leading the authors to suggest that the replication of Fitts' law in this action judgement task occurred because participants were using the common coding system to simulate the movements offline. Specifically, they suggested that the observation of the action activated the associated response codes in the participants via the common coding system. The participants then used these activated response codes to simulate their own performance to judge whether it was possible for the person they were observing to move at the observed speed or not. Although the Grosjean et al. study was the first to show that people's perceptual judgements followed Fitts' law, the motor simulation account of the pattern of effects was not explored in this study.

The present series of studies was designed to test the motor simulation account of action possibility judgements. To this end, we explored how two factors that could affect the motor system influenced action possibility judgements. The two factors we manipulated across the present studies were: recent experience with the task (Experiments 1 and 2), and the ease/ability of the motor system to perform the task (Experiment 3). We hypothesized that if action possibility judgements are based on motor simulation, then recent experience and altering the ability of the person to complete a task should change action possibility judgements.

EXPERIMENT 1

The purpose of Experiment 1 was to determine whether recent experience with a to-be-judged movement task affects the action judgements. To this end, participants in Experiment 1 completed an action possibility judgement task similar to that in the study by Grosjean et al. (2007). Specifically, they watched a series of apparent (i.e., on a computer screen) movements executed to targets of varying IDs at different speeds and judged whether or not it was possible to execute the movement accurately at the displayed speed. Participants completed this judgement task twice, once before and once after they actually performed the series of reciprocal aiming movements that they observed during the judgement task. If action judgements are influenced by experience with the action, then recent experience with the task should affect the possibility judgements and the minimum "possible" MTs following the execution session (i.e., closer to executed MTs).

Method

Participants

The participants in each experiment reported in the present paper were right-hand dominant, had normal or corrected-to-normal vision, and were unaware of the purpose of the study prior to participation. Each participant provided written informed consent and received financial compensation for their time in the study. The procedures of the study complied with the ethical standards of the 1964 Declaration of Helsinki regarding the treatment of human participants in research and were approved by the Conjoint Health Ethics Research Board at the University of Calgary. Twelve participants (7 women and 5 men aged 21–35 years) completed Experiment 1.

Apparatus, stimuli, and tasks

The design of the perception stimuli and task employed in the present study were based on the task and stimuli used in the Grosjean et al. (2007) study. Nine posters were created by pasting identical black strips (targets) of three different widths (2, 4, or 8 cm; height 26 cm) on white poster sheets (57 × 72.5 cm). The distance between the target strips (centre to centre) varied (4, 8, 16, 32, or 64 cm), depending on the width of the black strips. These combinations generated stimuli with three ID values (2, 3, and 4) for each target width (Fitts, 1954).

The stimuli for the action judgement phases consisted of photographs of a young adult male sitting in front of the posters with the index finger of the right hand placed in the middle of a target. Pictures of this hand position, along with the volunteer's torso, were taken for each target (first right, then left), using a digital camera placed on a tripod positioned at a constant distance from the table (Figure 1). The two pictures (one with the finger on the left target and one with the finger on the right target) for each poster were then alternated at different time intervals (stimulus onset asynchronies, SOAs) using a stimulus presentation program (EPrime, V. 1.1), creating apparent motion of the hand between the two targets (Grosjean et al., 2007). For an individual trial, the pictures alternated at only 1 of 11 SOAs that ranged from 120–520 ms in approximately equal intervals with an average size of 40 ms (see Grosjean et al., 2007).[1]

The SOA remained constant throughout a trial until the response of the participant was recorded.

The apparent-motion stimuli were presented to participants on a 17-inch ELO monitor (1,024 × 768 pixels, 60 Hz), placed at eye level, approximately 60 cm from the participant. Participants kept their fingers over the keyboard throughout the task and were asked: "Is it possible to move accurately between the targets at the shown speed?". Participants responded by pressing Y (for "yes" or possible) or N (for "no" or impossible) on the keyboard. Participants were allowed to watch the apparent-motion stimuli for as long as they needed to make the judgement. The order of presentation was randomized for both ID and SOA.

During the action execution phase, participants sat at a table in the view of a three-dimensional motion tracking system (Optotrak Certus). An infrared-light-emitting diode (IRED) was affixed to the fingernail of their right index finger. For a given trial, one of the nine poster boards that were shown in the pictures for the action judgement session was clamped to the table in front of the participant. The order of poster presentation was random for each participant. Participants placed their right index finger in the middle of the left target. When the experimenter gave the signal to start, participants moved their finger back and forth between the two targets as quickly and accurately as they could, until the experimenter said "stop" (approximately 10 s after the "go" signal). The coordinates of the IRED were captured by the camera (at 500 Hz, for the entire 10 seconds), and these data were stored for later analysis.

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[1] Because the refresh rate of the monitor was 60 Hz (i.e., one refresh every ~16.67 ms), the images were typically displayed on the screen refresh immediately after the planned SOAs. Thus, actual SOAs ranged from 133–533 ms in intervals of 33.33 or 50 ms and differed from the planned SOAs by an average of approximately 7 ms.

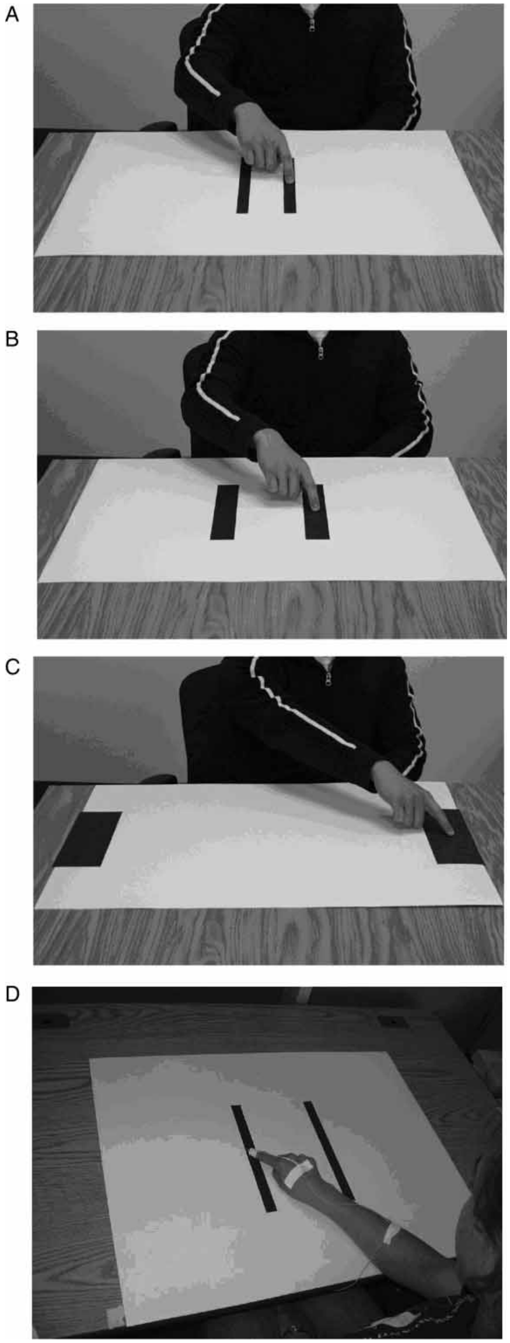

Figure 1. *(A–C) Examples of the pictures used to generate apparent-motion stimuli for different-sized targets in the judgement tasks used in Experiment 1. (D) A model demonstrating the actual execution task in Experiment 1 with the infrared-light-emitting diode (IRED) attached to her finger.*

Procedure and design

Each participant completed the action possibility judgement task twice—once before and once after performing the aiming task. For the pre- and post-execution action possibility judgement tasks, participants were informed both verbally and through written instructions that they would see a person's hand moving between two targets at different speeds, and that they were to judge whether it was possible to move between the two targets accurately at that speed. Each judgement phase consisted of two blocks of 99 trials. The 99 trials in each block consisted of one combination of the 9 width/amplitude arrangements and 11 SOAs presented in a random order. Thus, each participant made two "possible"/"impossible" judgements for each of the 99 possible combinations (Width × Amplitude × SOA) within a single judgement phase. The execution phase consisted of one 10-s trial at each of the nine posters. The entire experiment took approximately 60 minutes to complete.

Data reduction and analysis

For the possibility judgement tasks, the MT (SOA) where participants reliably changed their responses from "impossible" judgements to "possible" judgements was determined. This MT point was identified as the lowest MT value for which the participant answered "possible" for both judgements. This MT, and all MTs higher than this MT, was considered as possible to execute by the individual participant.

MTs from the action execution session were determined using custom analysis software written in Matlab (Mathworks, 2009). The displacement data were filtered using a second-order Butterworth filter (dual pass, low-pass cut-off 10 Hz) and then were differentiated (3-point central-finite difference) to obtain velocity values. MT was defined as the time interval between points of zero velocity in the primary axis of movement (i.e., reversal points). MTs for movements that did not land on the target were eliminated from the analysis (less than 6% of all movements).

The specific statistical tests are outlined below. *Post hoc* analyses of effects involving three or more means were completed using Tukey's honestly significant difference (HSD). Alpha was set at .05 for all analyses.

Results and discussion

Assessment of Fitts' law in the experimental tasks

Our initial analysis consisted of a series of linear regressions between the group mean MTs for each of the nine combinations of target width and movement amplitude (categorized according to ID) and the ID to determine whether judged and executed MTs followed Fitts' law. Consistent with previous work (e.g., Fitts, 1954; Grosjean et al., 2007), MTs increased linearly with ID: pre-execution action judgement, $r^2 = .93$, $F(1, 7) = 90.64$, $p < .001$, $MT_{Pre} = 44 + 80(ID)$; action execution, $r^2 = .68$, $F(1, 7) = 15.13$, $p < .01$, $MT_{Exec} = 79 + 47(ID)$; and post-execution action judgement, $r^2 = .94$, $F(1, 7) = 117.2$, $p < .001$, $MT_{Post} = 19 + 73(ID)$; see Figures 2a–2c. Although the r^2 for the execution MTs is numerically smaller than those for the two judged MTs, the correlations between ID and execution MTs were not statistically weaker than those for ID and pre-execution MTs, $Z = 1.41$, $p > .05$, and ID and post-execution MTs, $Z = 1.62$, $p > .05$.

The effect of execution on action possibility judgements

To determine whether the execution of the observed action influenced action judgements, we compared the lowest MTs judged as possible in the pre- and post-execution phases to the actual MTs recorded during the execution phase. Because the MTs conformed to Fitts' law in each task (see above), the MTs for the individual combinations of target amplitude and width were averaged across ID and were then submitted to a 3 (task: pre-execution judgement, execution, post-execution judgement) by 3 (ID: 2, 3, 4) repeated measures analysis of variance (ANOVA; Greenhouse–Geisser corrected degrees of freedom are reported when violations of sphericity existed). This analysis revealed a main effect for ID, $F(1.74, 19.12) = 161.65$, $p < .001$, $\eta_p^2 = .936$. Post hoc analysis of the main effect for ID revealed that MTs for ID4 (320 ms) were significantly longer than those for ID3 (238 ms), which were in turn longer than those for ID2 (187 ms).

Of greater theoretical relevance, the ANOVA revealed a main effect for task, $F(1.73, 19.05) = 9.17$, $p < .005$, $\eta_p^2 = .454$, and an interaction between task and ID, $F(3.07, 33.74) = 6.93$, $p < .001$, $\eta_p^2 = .387$. As can be seen from Figure 3, the judged MTs before execution were significantly longer than the actual execution MTs for each ID. Note also that the MTs judged before execution were also significantly longer than the judged MTs after execution. In contrast, the judged MTs in the post-execution phase were not statistically different from the MTs during action execution. Thus, it appears that experience with the to-be-judged movement task honed the ability to make judgements. The only exception was at ID4 where possible movements were judged to be slower than actual MTs. However, the judged MTs for ID4 during the post-execution phase were statistically shorter than judged MTs for ID4 during the pre-execution phase. Hence, there was a benefit from execution for the judgements, even at the most difficult ID.[2]

To further explore the potential influence of experience on the judged MTs, the slopes of the regression lines for the pre- and post-execution MTs were separately compared to those of the execution MTs. The results of these analyses revealed that slopes of the equations for the MT_{Pre} (80) were reliably different from the slope of MT_{Exec} (47), $F(1, 14) = 5.21$, $p < .05$, whereas the slopes for MT_{Post} (73) and MT_{Exec} (47) did not reliably differ, $F(1, 14) = 3.91$, $p > .05$. Although there is a trend toward differences between these lines, the general pattern of absence of reliable differences

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[2] It is conceivable that the residual difference between the post-execution and execution MTs occurred because it is more challenging to accurately simulate more difficult movements, and, hence, participants were more variable and conservative in the simulations of more difficult movements (leading to longer post-execution MTs than execution MTs). This explanation is consistent with Weber's law, whereby people become more variable in any estimate as the magnitude (index of difficulty, in the present case) of the percept increases.

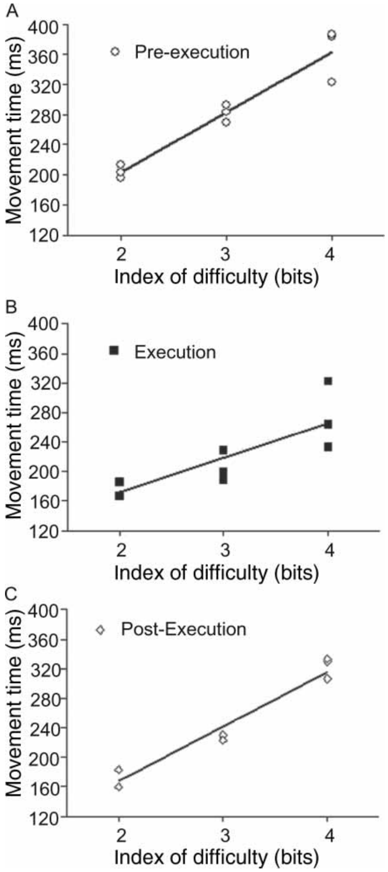

Figure 2. *Mean judged or executed movement times (ms) as a function of index of difficulty (bits) for (A) the pre-execution judgement task, (B) the execution task, and (C) the post-execution judgement task in Experiment 1.*

between MT_{Post} and MT_{Exec} is consistent with the mean MT data and the conclusion that experience with the movement task increased the accuracy of the judgements. In sum, the finding that experience with the task modulated the action possibility judgements in a manner consistent with actual performance provides support for the hypothesis that the common coding and the motor system are involved in the simulation process.

EXPERIMENT 2

The data from Experiment 1 suggest that recent experience with a to-be-judged task can alter action judgements. It is argued here that the observed change in pre- to post-execution judgement was an enhancement that occurred because there is an improvement in the simulation process. The accuracy of the simulation process improved due to an experience-based improvement in the accuracy of the common codes that underlie this simulation process. There are, however, several alternative accounts of the change in pre- to post-execution judgement. These alternative explanations are in large part based on the reinterpretation of the data that the pre-/post-execution change in judged MTs is not an *increase* in accuracy, but instead simply a pre/post *decrease* in judged MT.

One possible explanation of the pre- to post-execution difference is that the decrease in judged MTs was an effect of exposure to the judgement task. That is, the change in judged MTs was not the result of experience with the movement task, but instead was due to the fact that participants performed the judgement task a second time.

A second alternative account is that the intervening motor task did have an effect on the judgements, but that it was not a task-specific effect as we suggest. Instead, it could be that any execution of a motor task, regardless of its relevance to the to-be-judged task, could cause a decrease in judged MTs, perhaps because motor system activation caused an overall increase in the activation of the central nervous system (CNS). This nonspecific CNS activation could affect the other cognitive systems that are involved in forming the

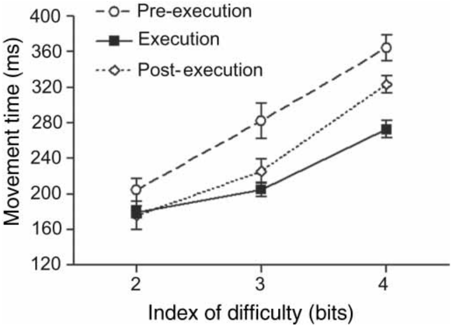

Figure 3. *Mean judged and executed movement times (ms) as a function of index of difficulty (bits) and task in Experiment 1.*

judgements. In sum, it is possible that the change (decrease) in judged MTs observed in Experiment 1 was due to multiple exposures to the perceptual task or the nonspecific effects of a motor task, or both. If either of these alternative explanations were true, then one would expect a decrease in judged MTs regardless of the nature (or even presence) of an intervening motor task.

Experiment 2 was conducted to distinguish between the different accounts by asking participants to complete the same set and order of tasks as those in Experiment 1, but with one key difference. The key difference was that both the participants and the person pictured in the judgement task in Experiment 2 executed the movements with an unusually shaped stylus that consisted of a cylindrical shaft with a point at one end and flat square object and a cord at the other (see Figure 4A). In addition to the awkward shape, two light weights were fixed to the back of the square section of the stylus (see Figure 4B). The pictures used in the judgement tasks were taken at such an angle that the participants could not see the additional weights (see Figure 4A).

It was expected that, relative to the finger-aiming task employed in Experiment 1, the awkward and weighted object would cause participants to have longer actual MTs during the execution phase. In addition, because the participants were unaware of the extra weight (because it was hidden from view), it was expected that participants might underestimate the weight or awkwardness of the stylus and, as a result, underestimate the shortest possible MTs relative to what they could actually do. Thus, it was expected that the pre-execution judged MTs would be shorter than the actual MTs. Through experience with the stylus via the execution of the task, however, it would be predicted that the participants would have a better understanding of the use of the stylus (i.e., their actions and the consequences) and improve the accuracy of the simulation process. The outcome of this improvement would be that, as in Experiment 1, post-execution MTs would be similar to the actual MTs from the execution phase. Further, because it was anticipated that the actual MTs would be longer than the pre-execution MTs, it was predicted that post-execution MTs would also be longer than the pre-execution MTs.

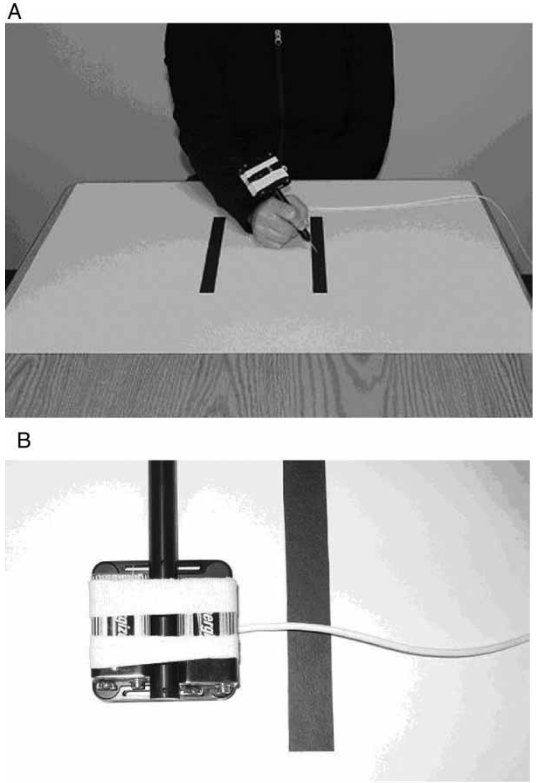

Figure 4. *(A) An example of the pictures used to generate apparent-motion stimuli for different-sized targets in the judgement tasks used in Experiment 2. Note that the stylus in the pictures was the same stylus as that used by the participants in the execution task. (B) The two batteries attached to the back of the stylus to increase the weight of the stylus. The weights were hidden in the pictures, so the participant could not see them in the judgement task.*

On the other hand, if the alternative exposure or nonspecific CNS priming via movement execution accounts of the results of Experiment 1 are correct, then there should be a decrease in judged MTs from pre- to post-execution phases. Importantly, this decrease should be independent of (i.e., occur regardless of) the actual MTs. A pre/post decrease in judged MTs regardless of performance would be expected because neither of these accounts predict a task-specific benefit from execution. According to the exposure account, the decrease in judged MTs was simply due to repeated exposure to, and experience with, the judgement task. According to the CNS priming account, the decrease in judged MTs occurred because activation of the motor system primed the other cognitive systems involved in making the judgements. Thus, regardless of the presence or the results of the execution of the to-be judged task, a decrease in judged MTs should be observed.

In sum, the critical difference between the predictions based on the common coding-based simulation and the alternative accounts is that predictions based on the exposure or CNS priming accounts would be a decrease in pre-/post-execution MTs regardless of actual MTs, whereas the predictions based on the common coding-based simulation account would be that a change in pre-/post-execution MTs would only be observed if there is a difference between the actual MTs and the initial (pre) MT judgements. More specifically, predictions based on the common coding-based simulation account would be that the presence and direction of pre-/post-execution differences would be dependent on the accuracy of the initial judgements. If there are no differences between initial judgements and actual MTs (initial judgements were accurate), then there should be no difference between pre- and post-execution MTs. In contrast, if pre-execution judgements were inaccurate and were too long or too short relative to actual MTs, then post-execution judgements should be longer or shorter than pre-execution judgements, respectively.

Method

Participants

Ten people (5 women and 5 men aged 21–35 years) completed the protocol of Experiment 2.

Apparatus, stimuli, and procedure

The design and procedure of Experiment 2 were the same as those used in Experiment 1 except for the following differences. First, the model in the pictures was a young adult female (as opposed to the young adult male model in the pictures of Experiments 1 and 3). Second, the model in the pictures was holding a stylus with a large flat square surface at one end (4-Marker Digital Probe, Northern Digital Inc; see Figure 4). This stylus was 178 mm long, and the square plate at the end of the stylus was 64 mm × 64 mm. The stylus weighed 146 g, and two 45-g weights (90 g total added) were added to the back side of the square end of the stylus to create an additional imbalance. Note that the additional weight was kept hidden from the participant in pictures used in the judgement tasks by keeping the stylus oriented such that the weights were not easily observed (see Figure 4).

During the action execution phase, participants completed the reciprocal tapping tasks with the stylus. Because the stylus is an established rigid-body tool for digitizing locations using the Optotrak Certus motion capture system, there is a software routine that calculates the location of a "virtual" IRED at the tip of the stylus. The coordinates of the virtual IRED on the tip were calculated and captured at 500 Hz, for the entire 10 s that the participants performed the reciprocal tapping task. These positional data was stored for later analysis using the same custom Matlab program as that used in Experiment 1 (Mathworks, 2009). MTs for movements in which the calculated virtual IRED did not land on the target were eliminated from the analysis (less than 5% of all movements).

Results and discussion

Assessment of Fitts' law in the experimental tasks

Consistent with Experiment 1 and previous work, the series of linear regressions between the group mean MTs for each specific combination of target width and amplitude and the ID analyses revealed that MTs increased linearly with ID: pre-execution action judgement, $r^2 = .98$, $F(1,\ 7) = 450.5$, $p < .001$, $\mathrm{MT}_{\mathrm{Pre}} = 24 + 73(\mathrm{ID})$; action execution, $r^2 = .66$, $F(1,\ 7) = 13.67$, $p < .01$, $\mathrm{MT}_{\mathrm{Exec}} = 70 + 59(\mathrm{ID})$; and post-execution action judgement, $r^2 = .93$, $F(1,\ 7) = 95.01$, $p < .001$, $\mathrm{MT}_{\mathrm{Post}} = -35 + 85(\mathrm{ID})$; see Figures 5a–5c. Although the strength of the relationship between $\mathrm{MT}_{\mathrm{Post}}$ and ID was not statistically different from that between ID and $\mathrm{MT}_{\mathrm{Exec}}$, $Z = 1.51$, $p > .05$, the r^2 for the $\mathrm{MT}_{\mathrm{Exec}}$ were statistically smaller than those for the $\mathrm{MT}_{\mathrm{Pre}}$, $Z = 2.84$, $p < .01$. The exact

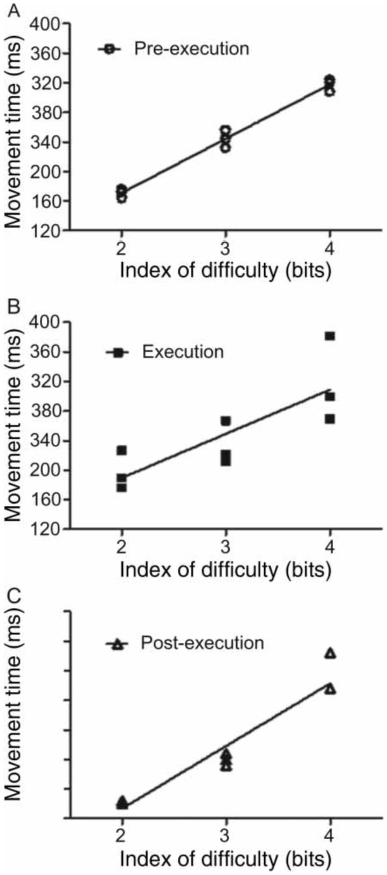

Figure 5. *Mean judged or executed movement times (ms) as a function of index of difficulty (bits) for (A) the pre-execution judgement task, (B) the execution task, and (C) the post-execution judgement task in Experiment 2.*

reason for this between-task difference in the strength of the relationship is not clear. One speculative explanation for this pattern of effects is that the awkward and weighted instrument heightened the influence of movement amplitude on the relationship between speed and accuracy in the actual execution task. Note that Heath, Weiler, Marriott, Elliott, and Binsted (in press) recently showed that movement amplitude had a greater influence on the slope of the relationship between ID and MTs than did target width in discrete aiming movements without an awkward stylus. Because the values of ID that were entered into the regression were based on the relationship between width and amplitude as characterized in Fitts' equation, the increased influence of the single factor of amplitude (possibly due to the additional force requirements to initiate the movement and achieve peak velocity and then subsequently terminate the movement) affected the fit of the overall equation and, hence, the strength of the relationship.

The effect of execution on action possibility judgements

Because the MTs conformed to Fitts' law in each task (see above), the MTs for the individual combinations of movement amplitude and target width were averaged across ID and were then submitted to a 3 (task: pre-execution judgement, execution, post-execution judgement) by 3 (ID: 2, 3, 4) repeated measures ANOVA. This analysis revealed a main effect for ID, $F(1.5,\ 13.51) = 120.07$, $p < .001$, $\eta_p^2 = .93$. *Post hoc* analysis of the main effect for ID revealed that MTs for ID4 (315 ms) were significantly longer than those for ID3 (226 ms), which were in turn longer than those for ID2 (170 ms).

Of greater theoretical relevance were the effects involving task. Recall the prediction that if either the alternative perceptual exposure or CNS priming account of the effects in Experiment 1 is correct, then there should be a pre- to- post decrease in judged MTs (a decrease that will not be linked to the actual MTs). In contrast to this prediction (and the results of Experiment 1), there were no significant differences between the MTs across the tasks—the main effect for task, $F(1.38,\ 12.47) = 1.46$, $p > .26$, $\eta_p^2 = .139$, and the interaction between task and ID, $F(2.96,\ 26.62) = 2.76$, $p > .05$, $\eta_p^2 = .238$; see Figure 6.

To further explore the potential influence of experience on the judged MTs, the slopes of the regression lines for the pre- and post-execution MTs were separately compared to those of the execution MTs. The results of this series of analyses revealed that none of the slopes of the equations reliably differed (ps $> .19$). The general absence of reliable differences between the slopes of the regression lines is consistent with the results of the analysis of the mean MT data.

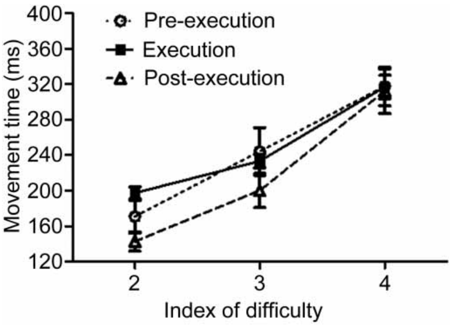

Figure 6. *Mean judged and executed movement times (ms) as a function of index of difficulty (bits) and task from Experiment 2.*

Overall, the absence of a pre/post decrease in judged MTs is not consistent with either of the alternative explanations of the results of Experiment 1. That is, if the change in judged MTs in Experiment 1 was the result of a general CNS priming caused by motor system activation associated with task execution, then a similar decrease in judged MTs should have been observed in Experiment 2. Similarly, if experience with the perceptual task alone generated a change in the judgement of MTs, then there should have been a similar significant decrease in judged MTs. The absence of such a pre-/post-execution decrease suggests that the change in judged MTs was not the result of task experience (see also the absence of an order effect in Experiment 3).

Another interesting contrast between the data of Experiments 1 and 2 was that there were no differences between the pre-execution, actual execution, and post-execution MTs. It was predicted that executing the reciprocal aiming movements with the unusual and weighted stylus would cause an increase in actual MTs. Such an increase in actual MTs was observed, as revealed by a significant main effect for experiment in a mixed 2 (experiment: 1, 2) by 3 (ID: 2, 3, 4) ANOVA on the actual MTs, $F(1, 20) = 6.85$, $p < .05$. Thus, the absence of differences among the judged and actual MTs seems to have occurred because the initial judgements were consistent with the actual MTs. It is unclear why participants were initially conservative in their judgements in the pre-execution task. It is possible that the peculiar shape of the pointer and the way the actor holds the pointer provided subtle cues that the object was heavy, which was what led to the conservative judgements. The critical point here is that it appears that the experience the participants had in performing the actual movement task informed them that their initial judgements were consistent with the actual MTs. As a result, the motor simulation was not modified for the second set of judgements.

In sum, the results of Experiment 2 clearly show that the alternative exposure and CNS activation explanations of the results of Experiment 1 do not hold. Although the common coding-based simulation mechanism can account for the results of both Experiments 1 and 2, there is at least one other way to interpret the patterns of effects observed here. Specifically, it is possible that performance of the to-be-judged task provided participants with the opportunity to learn a rhythm or a speed (i.e., movement time) at which it was possible for them to move between the different sets of targets. Participants then matched this memorized visual movement time to the timing of the visual information presented in the post-execution judgement trials. Such a visual-based perceptual learning explanation could account for the task-specific nature of the changes (or absence of change) in judgements seen across Experiments 1 and 2. In Experiment 1, the memorized movement times (and hence the matched post-execution MTs) were shorter than those judged to be possible in the pre-execution task. In Experiment 2, however, the learned movement times were similar to those prior to task performance, and so there was no pre- to post-execution change in judged MT.

With the present data set, it is not possible rule out such a visual learning account because to be able to rule out a visual learning explanation, we would have had to eliminate visual information during task performance. That is, to be able to argue that visual learning was the sole driver of the effects, participant would have had to be prevented from receiving perceptual (especially visual) information about the task during task performance. For example, in related studies, Casile and Giese (2006) and Hecht et al. (2001) have actually found pre-/post -execution improvements in visual perception without visual information of task performance during the execution or learning stages of their studies. Specifically, they reported that participants improved in the accuracy of perceptual judgements of a visual rhythm after learning a movement task with a similar rhythmic structure. Critically, the improvement in the visual perceptual task occurred even though participants were blindfolded during the movement learning stage and so did not have visual information about the spatiotemporal components of the task. In this way, even though proprioceptive information originating from task performance was available to the participant, the authors could rule out a within-modality (i.e., visual) perceptual learning explanation of their pre-/post -execution improvement. In the present studies, however, it is simply not possible to eliminate vision of movement execution because "fast and accurate" performance in the Fitts' aiming task is hinged on visual access to the environment. The impossibility of preventing visual information during task performance leaves open the prospect that the influences of task performance on action possibility judgements observed here were the result of visual learning alone.

Although it is difficult to completely rule out a strict visual–perceptual learning explanation of the present data, we feel that it might not be possible or even desirable to consider perceptual learning as a process that is completely isolated from the motor system, especially in the present case. On the theoretical level, it may be a significant challenge, and perhaps misleading or erroneous, to make a case for perceptual learning and/or memorization of a particular rhythm as the sole and independent driver for the pattern of effects observed across these studies. It may be difficult to isolate perceptual learning because the theoretical framework adopted for this series of experiments and similar studies is firmly grounded in ideomotor theory, which holds that actions and the perceptual consequences of those actions are tightly coupled (see Hecht et al., 2001; Prinz, 1997). Hence, it is our contention that action and the perception of action are not independent or easily dissociable and that perceptual learning in the present case, and perhaps even in perceptual processes more broadly, is intricately linked to motor control and learning. The simulation account of the present findings is based on the notion that it is through the experience of executing the task that there is enhancement or refinement of one or both of the bound perception–action codes. In other words, task experience engages a *visual–motor* learning process in which perception and action representations are formed and/or enhanced. In this way, predictions for the present studies based on a visual perceptual learning account and the simulation accounts are identical even though the proposed mechanisms (simulation vs. memorization) are different. Likewise, a common coding mechanism can account for the cross-modality improvements observed in Casile and Giese (2006) and Hecht et al. (2001). Because vision and proprioception are essential to the accuracy of movements, it is possible that participants in those studies were using the proprioceptive feedback about the movement patterns to drive a covert visual simulation of the task performance. These simulations subsequently improved performance on the visual perceptual task.

In sum, it is difficult to discount a visual learning explanation of the present data. It is our view, however, that it is equally difficult to draw the firm conclusion that the change in performance on the perceptual task that occurred during that condition was due to perceptual learning alone. While acknowledging this limitation, we maintain the position that a common coding-based simulation account is the most comprehensive explanation of the pattern of effects of Experiments 1 and 2, and Experiment 3 below (as well as a series of other studies, Welsh & Chandrasekharan, 2011).

EXPERIMENT 3

To further explore the potential role of a common coding-based simulation process and the systems involved in action possibility judgements, we conducted a third experiment in which we sought to determine whether current body state affects possibility judgements. This experiment used the same Fitts' law paradigm with participants performing the same judgement task as that performed in Experiments 1 and 2. The critical manipulation in Experiment 3 was that participants performed the task twice—once with a weight attached to their wrists and once without the weight. Although the participants wore a weight during one set of judgements, the pictures were identical in both the weight (W) and no weight (NW) judgement tasks, and the person in the pictures used for the judgement task did not wear weights in either set of judgements (in fact, the pictures used in Experiment 3 were the same as the pictures used in Experiment 1). Thus, the weight worn by the participant in the W task, as far as the participant was concerned, was completely incidental to the task, and, importantly, participants were exposed to identical visual stimuli during the two tasks.

It was reasoned that performing the judgement task (i.e., the act of lifting the hand from the lap to touch the button) with the weight would be more energy demanding than performing the task without the weight. Previous studies have shown that there is a close correspondence between the increase in MTs in executed and imagined (i.e. simulated) movements that occur when participants wear weights (e.g., Papaxanthis, Schieppati, Gentili, & Pozzo, 2002) in the range of weight used in the present study (see Slifkin, 2008). If a simulation process underlies action possibility judgement, and this simulation process is influenced by current body states and movement capabilities, the movements observed during the weight task should be judged to be as possible at slower speeds as are the same movements seen during the without-weight task. This result would, in turn, suggest that judgements are based on action simulations, and these action simulations are not generated purely from a memory store, but utilize real-time inputs from the motor system. If the judgement is not based on a simulation process, or the simulation process is unaffected by current body state, then there should be no differences between the judged MTs in the W and NW tasks.

Method

Participants

Twenty-one people (16 women and 5 men aged 20–32 years) participated in Experiment 3.

Apparatus, stimuli, procedure, and design

The task, apparatus, and stimuli used in Experiment 3 were the same as those used in the Experiment 1 judgement task, except for three important differences. First, there was no execution phase in Experiment 3—that is, participants did not actually perform the to-be-judged movement task. Second, participants completed the judgement two times —once with a 0.5-pound weighted wristband on both wrists (the weight or W task) and once without the weight on their wrists (the no weight or NW task). Participants completed W and NW tasks in a blocked fashion. The order in which participants completed the tasks was alternated such that 11 participants completed the tasks in the W–NW order, and the remaining 10 participants completed the tasks in the NW–W order. The increase in the number of total participants (relative to Experiments 1 and 2) and the counterbalanced order were implemented to explore for any possible effects of task order and exposure (see alternative accounts of Experiment 1). As is reported below, however, order did not influence performance.

The final important change from Experiment 1 was that participants were strictly instructed to keep their right hand on their lap until they were ready to select their response. They were told that when they were ready to make their response, they could lift the hand from the lap, press the appropriate key, and then return the hand to the lap after selecting the response. Participants were not told anything about the weight on their wrist other than that they were to wear it throughout one of the blocks of trials. Specifically, experimenters were careful to not provide the participants with any instructions to, or to not to, take the weight into account when they make their judgements. This specific set of instructions was given so that participants experienced the feel of the weight on their wrist during the W task, but were not made explicitly aware of the role the weight might play in their judgements because it was felt that such instructions might bias the participant in an unknown direction. Such a conscious awareness would spoil the implicit nature of any effects the weight might have had on the judgements.

Results and discussion

Assessment of Fitts' law in the experimental tasks

To examine whether the judgements followed Fitts' law, mean judged MTs for all participants (i.e., regardless of task order) were calculated separately for the W and NW tasks. The results of the linear regression revealed that the MTs conformed to Fitts' law in that they increased linearly with ID: no weight, $r^2 = .85$, $F(1,\ 7) = 39.69$, $p < .001$, $\mathrm{MT_{NW}} = 61 + 55(\mathrm{ID})$; and weight, $r^2 = .91$, $F(1,\ 7) = 68.81$, $p < .001$, $\mathrm{MT_{W}} = 24 + 72(\mathrm{ID})$ (see Figures 7a and 7b). The strength of the correlations for the two tasks were not reliably different, $Z = 0.44$, $p > .32$.

The effect of weight on action possibility judgements

To determine whether the incidental weight affected the action possibility judgements, we compared the lowest MTs judged as possible when the participants wore the weighted wristband and when they did not wear the weight. Because the MTs conformed to Fitts' law (see above), the MTs for the individual combinations of target amplitude and width were averaged across ID. These mean MTs were then submitted to a 2 (order; W–NW, NW–W) by 2 (weight task: W, NW) by 3 (ID: 2, 3, 4) mixed ANOVA with order as a between-subjects factor and weight task and ID as within-subjects factors. The results of this ANOVA revealed a significant main effect for ID, $F(1.57,\ 29.85) = 115.16$, $p < .001$, $\eta_p^2 = .858$, which revealed that judged MTs for ID4 (315 ms) were significantly longer than those for ID3 (239 ms), which were in turn longer than those for ID2 (182 ms).

Of greater theoretical relevance was a significant interaction between weight task and ID, $F(1.61,\ 30.64) = 6.89$, $p < .01$, $\eta_p^2 = .266$. *Post hoc* analysis of this interaction revealed that judged MTs in the W task were longer than those in the NW task (Figure 8). These differences between the tasks were only significant at the higher IDs (ID3 and ID4). This pattern of findings is consistent with the hypothesized role that the motor system plays in the simulations that form the basis of the action possibility judgements.[3]

Finally, it should be noted that there was no significant main effect or interaction involving order (Fs < 1). The absence of an effect of order suggests that there were no reliable differences between the groups and that the effect of the weight was not modulated by the order in which the participants experienced the weight. This result also suggests that there is no significant exposure effect in the judgement task, thus further ruling out the exposure effect alternative explanation for the results from Experiment 1. Overall, these results provide converging support for the hypothesis that judgements are made using action simulations, and current body states affect action possibility judgements based on such simulations.

GENERAL DISCUSSION

Grosjean et al. (2007) proposed that people use a common coding system to help shape action possibility judgements, such as those completed in the present study. The common coding model has previously been used to account for action perception and recognition effects (Casile & Giese, 2006; Knoblich & Prinz, 2001—the observer uses the observation-evoked response codes to identify the

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[3] Although the pattern of effects is consistent with the simulation account, it is possible that, despite our best efforts to maintain the naivety of the participants with respect to purpose of the study and the predicted influence of the weight, participants worked out the purpose of the study and systematically altered their judgements to fit with our (and presumably now their) expectations. We cannot completely rule out this explanation, but suggest that it is highly unlikely. We feel it is unlikely because the design of the experiment would make it extraordinarily difficult to keep track of the individual trial types to purposefully manipulate their responses. It is unlikely that participants could track the stimuli because each of the two weight conditions consisted of 198 judgements completed in two blocks of 99 trials, with each block consisting of only a single instance of a specific combination of the 11 SOAs and 9 ID combinations presented in a random order.

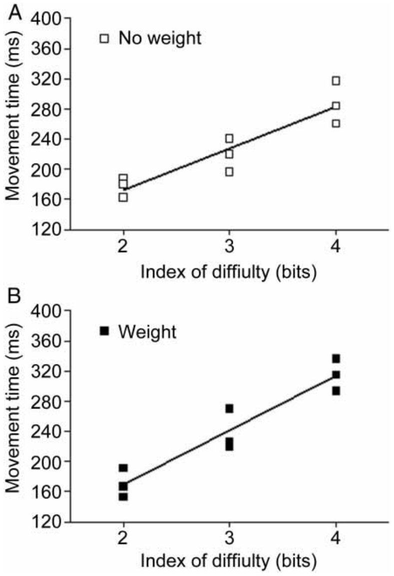

Figure 7. *Mean judged movement times (ms) as a function of index of difficulty (bits) for the (A) without weights and (B) with weights tasks in Experiment 3.*

action of another person. It is suggested here, however, that the processes leading up to action possibility judgements are much more complex and need at least three steps. First, the observer uses the activated response codes to identify the type and characteristics of the observed movement pattern. Second, the observer simultaneously runs a simulation of their own performance of that observed movement. It is suggested here that this simulation in turn engages the motor system and involves the offline activation and execution of the person's own response codes to generate a set of perceptual consequences of those actions. Third, the individual forms the judgement by comparing the characteristics of the simulated response effects to the characteristics of the observed response to determine whether the observed movement characteristics can be reasonably captured by the simulated response. These steps seem to require mechanisms beyond common coding such as self/other perspective-based simulation and comparison of two simulation outputs.

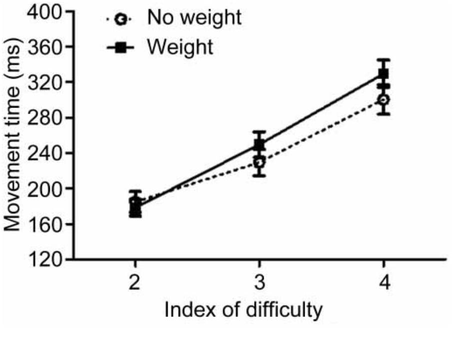

Figure 8. *Mean judged movement times (ms) as a function of index of difficulty (bits) and weight task from Experiment 3.*

In the present studies, two possible factors that could influence people's action possibility judgements were examined—actual execution of the observed action (Experiments 1 and 2) and current body state (Experiment 3). It was found that both these variables significantly influenced action possibility judgements. Specifically, judged movement times after executing the action were closer to the actual movement times during execution (Experiment 1). Further, judged movement times while wearing a weight were longer than the judged movement times without wearing a weight (Experiment 3). These data provide converging support for the hypothesis that a simulation process underlies action possibility judgements and that this simulation makes use of the current state of the motor system. While some alternative mechanisms (such as exposure effects and CNS activation) could possibly account for parts of the results, we argue that the common coding mechanism provides a more cohesive account of the results from all the three experiments.

In addition to supporting the notion of an active ideomotor simulation mechanism in action possibility judgements, Experiment 1 also provides new insight into the time-course over which action execution affects common coding and the subsequent perception and simulation. In previous work on judgements, participants were trained to perform the to-be-observed movement task for a relatively long period of time—from 1 to 2 hours of practice on a novel movement task in the study by Casile and Giese (2006) to many years in the own-action effect studies (Flach et al., 2004;

Knoblich & Prinz, 2001; Repp & Knoblich, 2004; see also Holt & Beilock, 2006). The present experiments involved a very short action execution period (< 10 min) in which participants only had a single 10-s experience with each individual target width/amplitude combination. The results of Experiment 1 show that perceptual judgements—and, by extension, action simulations—improve in accuracy with even brief experience.

In related work, Proffitt and colleagues have shown that judgements about distance vary based on the weight carried by participants (Proffitt, Stefanucci, Banton, & Epstein, 2003), and perceived distance increases as the effort associated with walking increases (Witt, Proffitt, & Epstein, 2004). Motor simulation has been proposed as the mechanism underlying these effects (Witt & Proffitt, 2008), though initially the effect of effort on perceptual tasks was interpreted in the context of Gibson's theory of affordances (Gibson, 1977, 1979) and the ecological psychology framework in general (Proffitt et al., 2003). Further, Ramenzoni, Riley, Davis, Shockley, and Armstrong (2008) showed that estimated judgements of how high an actor could jump-and-reach were influenced by the observer wearing a weight in his ankle. The weight led to a reduction in estimated heights, but only when the observer walked around with the weights. While Ramenzoni et al. offered a direct perception/affordance account of these effects, their results could also be explained by the motor resonance/simulation mechanism. The results from the present weight experiment (Experiment 3) are consistent with the affordance account, but we consider motor simulation a better candidate mechanism for such action possibility judgements, for a number of reasons.

First, the common coding-based simulation mechanism explains the effects of recent task experience seen in Experiment 1 (through the enhancement of action after effect codes), whereas it is unclear how the affordance theory could explain this effect. Second, a common coding account lays a foundation upon which to investigate the neural and cognitive mechanisms underlying action possibility judgements, whereas, currently, the theory of affordance is descriptive in nature and does not outline any such mechanisms. Finally, it has been argued that common coding is complementary, and not in opposition, to the original ecological psychology view (Hommel et al., 2001), and common coding could be seen as the mechanism supporting direct perception (Chandrasekharan & Osbeck, 2010). In this integrative view, motor simulation is compatible with the affordance theory. Clearly, additional research is needed to clarify these issues.

Considerations of perspective taking in the simulation process

Our results suggest that people use a simulation of their own motor capabilities to form action possibility judgements. However, because we asked the relatively open question "is it possible to move accurately between the targets at the shown speed?", it is unclear exactly how this simulation is being used to make these judgements. One possibility is that participants were making a first-person judgement—they were judging whether *they* could execute the movement at a particular speed. The mental simulation involved here is straightforward and involves the use of one's current common codes and memories and knowledge of recent experiences. A second possibility is that the participants were making a third-person judgement—they were judging whether *the person seen on the screen* could make the movement at that speed. This type of judgement is more complex because the person making the judgement must first generate a mental simulation of the action based on their own motor schema and then alter the simulation using what knowledge they have of the person on the screen (e.g., young adult male) to estimate the movement capabilities of the person. A third possibility is that the participants were making the judgement for an abstract category of "people"; they were judging whether *anyone* could make the movement at that speed. This is an even more complex operation, as this would involve generating a simulation and then altering it to fit an abstract, generalized range of body types and capabilities.

Our experimental method does not distinguish between these three cases. However, we tentatively suggest that participants in the present study made the judgement from the first-person perspective. We suggest this for two reasons. First, the first-person simulation is arguably the least complex of the processes (the third-person and abstract versions require altering the first-person simulation based on estimated characteristics). Two, the data suggest that executing the action, and changing the body state, led to a change in the action judgements. Such experience-based influences would not be expected if participants were abstracting the simulation to the general category of "people" or to the person on the screen, because the characteristics of these individuals did not change. This conclusion is tentative, however, and future work should address the mental simulation involved in the second and third cases because it is these types of judgement that would allow people to coordinate task performance by anticipating the abilities and limitations of their partners. To understand these cases, manipulations should explicitly make the participant think of another person, or group, executing the actions. We are currently developing experiments based on these manipulations to understand these cases better.

Summary and further implications

The experiments reported here examined how action possibility judgements are affected by two variables—recent experience of actions, and current body state. We found that both these variables affect action possibility judgements. Taken together, these results indicate that the motor simulation mechanism, considered to underlie action possibility judgements, is a highly adaptive process and closely connected to recent and current states of the motor system. Such modulation of the action code by real-time variables supports the idea that action possibility judgements require mechanisms that go beyond action recognition. These findings provide a better understanding of the nature of the simulation mechanism involved in judgement tasks.

One implication of our results is that the motor simulations involved in action possibility judgements are not instantiated entirely by brain areas implicated in action recognition (primarily premotor and parietal areas, considered part of the human mirror neuron system). The data suggest a larger network because the judgements made in the present study appear to be generated through a real-time simulation that is influenced by the current and recent states of the motor system. Thus, other areas, such as those involved in action generation (primary motor cortex) and proprioception (primary somatosensory cortex), are probably involved.

A second implication of our results relates to recent claims that the mirror neuron system supports a "direct social perception' (Gallagher, 2008). The proposal is that the triggering of action codes when watching another person's action amounts to experiencing the other person's actions oneself, and this is considered to result in a "direct perception" of others' intentions and feelings. The jump from simulation of action to the understanding of intentions and feelings is not supported by empirical evidence. But even if we grant this postulated link, our results show that this view is not tenable; the simulation mechanism is influenced by our own recent experience and body states, which means the perception of the other person's internal states is not "direct", but heavily modulated by our own system variables. Therefore, if at all, the simulation will produce an inaccurate representation of the other person's inner states.

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