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Motor Simulation in a Memory Task: Evidence from Rock Climbing

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Abstract

This study concerns the role of motor simulations in a memory task performed by expert and novice climbers. In a behavioural task, expert and novice rock climbers were shown three novel climbing routes: an easy route, a route impossible to climb but perceptually salient, and a difficult route. After a distraction task, they were given a recall test in which they had to write down the sequence of holds composing each route. No difference emerged between experts and novices on the easy and impossible routes. Differently, the performance of expert climbers was better than that of novices on the difficult route. Results suggest that seeing a climbing wall activates a motor, embodied simulation, which relies not on perceptual salience, but on motor competence. Crucially, it is shown that the ability to form this simulation is modulated by individuals' motor repertoire and expertise, and that this strongly impacts recall.

Keywords: simulation, affordance, embodied cognition, grounded cognition, canonical neurons, mirror neurons, motor memory, memory for actions, motor chunks.

Introduction

A number of studies have shown that seeing an object, such as a cup, affords simple actions, such as reaching and grasping. According to the original definition by Gibson (1979) *affordances* are possibilities for action offered by the environment and perceived directly by an observer. A recent view of affordances, which we endorse here, is that they are potential action patterns activated in the observer's brain while observing objects. In other words, they are the product of the conjoining, in the brain, of visual stimuli and action responses (e.g., Ellis & Tucker, 2000), whose neural bases can be found in the discovery, in the F5 area of the ventral premotor cortex of the monkey, of visuomotor canonical neurons which discharge in the presence of graspable objects when no overt response is required (Murata et al., 1997). Evidence in humans confirms the existence of a parietopremotor circuit active during the observation of manipulable objects (Grèzes et al., 2003). Overall, both behavioural and brain imaging studies have shown that perceiving affordances activates in observers specific motor programs (Borghi, 2004; Borghi and Riggio, 2009; Martin, 2007). This phenomenon can be interpreted as activation of a *motor simulation*, where 'simulating' means that the same sensorimotor systems that are activated during interaction with objects are activated during object perception (e.g. when observing objects or when listening their characteristic sound), but without the execution of overt movements (Gallese, 2009; Jeannerod, 2006).

A computational framework proposed by Wolpert and Kawato (1998) and elaborated in Frith et al. (2000); Jeannerod (2006); Wolpert et al. (2003) explains motor simulations as the re-enactment of internal models that allow motor control. Internal models come in two varieties, inverse and forward. During motor control, the former compute the necessary motor commands to achieve a certain goal given a starting position, and the latter predict the sensory consequences of those motor commands. In addition, it is possible to re-enact internal models to form a simulation of possible actions by feeding the inverse model with predicted sensory inputs rather than 'true' sensory inputs, and successively feeding the new motor command to the forward models, and so on. This process permits the linking of multiple predictions in order to obtain simulations of possible actions for an arbitrary long number of steps. Note that for this process to work it is also necessary to inhibit 'true' sensory inputs and motor outputs. Indeed, simulating is not the same as performing an overt action, for a variety of reasons: simulation implies a weaker activation of the interested neural areas. In addition, during simulation some kind of blocking mechanisms might intervene that prevents the action to be executed overtly. Finally, during overt action a sensorial feedback is received, while no such feedback is given while simulating (Jeannerod, 2006).

Even if the activation of motor information elicited by object presentation has been extensively studied in the last years, the majority of studies have focused on how single objects or object pairs (e.g., Riddoch et al., 2003) activate an internal simulation or even overt simple movements, such as reaching or grasping. The role played by multiple affordances for complex actions implying a sequence of movements has not been widely investigated. Imagine observing a mountain path before performing a complex action composed by a sequence of movements, such as hiking. One might observe whether the path is steep or not, how the different stones are displayed, whether tree branches represent obstacles for walking and how to avoid them. In other words, both the characteristics of single objects (e.g., the stones, their orientation and shape) and their placement along the path might afford or impede actions. The same is true for climbing.

Indoor rock climbing consists in reaching the top of a specially-designed wall (i.e., a climbing wall), by grasping climbing holds with the hands and the foots. Climbing routes, which consist in carefully arranged sequences of climbing holds, may have different difficulties depending on the slope of the wall, the length of the route, as well as on the number, kind, and arrangement of the climbing holds. Usually climbers, both during their training and during competitions, spend some time in "studying" climbing routes before climbing them, especially when they have to climb a route for the first time. Then, they can mentally simulate which holds to take, which movements to do, which rest positions they can find, etc. In some cases, they also overtly mimic the hand (and foot) movements that they expect to perform while climbing (see fig. 1).

Figure 1. Athletes studying a climbing route before climbing it. Note the overt hand movements.

The simulation they build might include both information on specific affordances, i.e. the characteristics of the holds (shape, orientation, etc.), and information on their displacement, i.e. the way they are arranged on the wall. Given that routes involve multiple climbing holds, clearly any simulation of a part of the route changes the way the rest of the route is perceived. For example, simulating grasping a certain hold with the right hand makes some other holds affordable to be grasped with the left hand, and some other holds out of reach; see fig. 2. At the same time, the need of reaching a certain 'goal' hold determine which holds are affordances retrospectively, and disrupts the affordances of some holds (e.g., far holds) in the climbing wall. For all these reasons, motor simulation in rock climbing should be considered an *affordance calculus* rather than a response to a sequence of individual affordances. Crucially, the motor competence of climbers also determines what constitutes an affordance. Experienced climbers can hold small holds that are difficult for weak climbers to grasp, and can simulate sequences of actions that are too complex to be picked up by novice climbers, much like how expert chess players 'see' complex strategies. We hypothesize that the proficiency of expert climbers allow them to climb better the routes also by understand them better, where understanding should be intended as proficiency in the affordance calculus and in the associated building of appropriate mental simulations before climbing.

Figure 2. A sample sequence of movements in rock climbing. Notice that (i) climbing holds afford different grips, and (ii) the way holds can be grasped depend on which holds were grasped before (and how) as well as which holds the climber intends to reach.

Aims and objectives of the study

Our study addresses the role multiple affordances play in the recall of routes by rock climbers with different level of expertise. An open issue in this field pertains to the extent to which affordances are elicited automatically, upon seeing objects, or are activated when a specific action goal is pursued. In addition, studying recall in expert and novice climbers can contribute by showing to what extent the activation of affordances is modulated by observers' experience and competence. Finally, we still know very little on how affordances improve recall. Acquired motor skills offer a unique way to test this question.

Here, novice and expert climbers were asked to observe and recall the position of holds of 3 routes that they never climbed: an easy route (ER), a difficult route (DR), and a (motorically) impossible but perceptually salient route (IPSR). Predictions were that their performances would not differ for the ER, because both groups would be able to perform a motor simulation, and for the IPSR route, when for both it was impossible to form a motor simulation of climbing. If this were true, this would demonstrate that the simulation formed is a motor one, and would be activated only when participants have the motor competence necessary to perform the sequence of actions. Accordingly, the performance of experts should overcome that of nonexperts in the DR, when the actions required climbing the route they are shown are part of their motor repertoire.

Method and Materials

Participants

Eighteen climbers who attended to the "Lanciani Climb" arena in Rome volunteered to study. Experts had between 5 and 10 years climbing experience, whereas novices had less than six months climbing experience. Groups were balanced for gender (6 men and 3 women each group) and age. To balance the order in which the different routes were presented, as well as to avoid assigning the task to large groups, we divided the participants in 6 groups of 3 randomly selected participants: 3 groups composed by experts, and 3 by novices.

Materials

Two climbing trainers set up three novel routes from a climbing wall containing 110 holds. Each route was composed of 10 holds (the typical average length for most training routes). Route difficulty depends on the configuration of the holds (their graspability) and the configuration of the limbs in transition between the holds (Smyth and Waller, 1999). Both experts and novices, because of the orientation and arrangement of the holds, could climb the Easy Route (ER) without difficulty. In order to control for perceptual factors that might facilitate memorization, the two other routes differed in perceptual salience. The Difficult Route (DR) was difficult to climb because the holds were not easily graspable due to their shape and orientation, and only expert climbers could benefit from their affordances. All holds in the ER and DR were grey- or dark-coloured and did not differ in size or other perceptual characteristics. The third route, (motorically) Impossible but Perceptually Salient Route (IPSR), was impossible to climb as a whole (but parts of it could be climbed). The difficulty of such route was not due to the fact that participants had to simulate biologically impossible movements (Costantini et al., 2005) but rather on the arrangement of the holds. Specifically, it was impossible to benefit from the affordances offered by the holds and to configure the limbs for a transition from one hold to the other. To facilitate memorization, however, we rendered the holds perceptually salient: they were vividly coloured, compared to the standard grey- or dark-coloured holds.

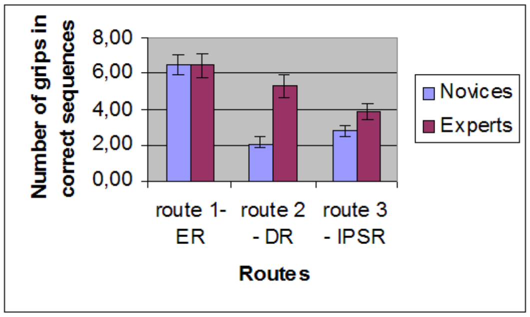
Procedure

Two experimenters and the trainer were present in the Lanciani Climb arena to administer the task. Before entering the arena, participants were instructed that they have to memorize a route made up of 10 holds, and that later they had to perform an additional task. Groups (of 3 participants) were then invited to enter and to sit in front of the climbing wall. The wall includes 110 holds with different size and orientation, placed uniformly to cover its entire surface. The trainer indicated twice the holds of each route with a stick. After this demonstration, participants had to turn their backs to the wall and perform a distracting task (i.e. to pronounce the letters from A to L). The procedure was repeated for each route. The presentation order of the routes (ER, DR and IPSR) was balanced across participants. Participants were given a folder containing three A3 sheets, each displaying a picture of the climbing wall (which included all the holds). After the first of the three routes had been shown, they were asked to extract the first sheet and to mark down as quickly as possible (with a time limit of 2 minutes) the sequence of holds composing the first route. The same procedure was repeated for the two remaining routes. Participants were then required to fill in a post-experiment questionnaire in which they were asked to report (by responding yes or no) whether they mentally imaged climbing the wall while being shown the route and while recalling them, whether they believed that imagining the route might be helpful for them, and which route appeared to them the easiest to climb.

Results

All participants performed the task without difficulties. The number of holds reported in a correct sequence for each route was computed for each participant, and submitted to a 3x2 mixed ANOVA with Route (ER, DR and IPSR) as within factor, Expertise (Expert vs. Novice) as between factor and participants as the random factor. Data are plotted in fig. 3. All analyses were conducted using a Type I error rate of .05.

Figure 3. Results of the task. Legenda. ER - Easy Route; DR - Difficult Route; IPSR – (Motorically) Impossible but Perceptually Salient Route



Expertise factor was not significant (F (1, 16) = 1.35; MSe = 20.92; p = .26), whereas Route factor was highly significant (F (1,32) = 15.45; MSe = 3.35; p < .0001). Post-hoc Newman-Keuls showed this was due to the difference between the ER (M = 6.44) and the two other routes, DR and IPSR (M = 3.72; M = 3.33, respectively). As predicted, the ER led to a better performance compared to the two other routes, independently from the degree of expertise of participants. It is worth noting that the average number of remembered sequences was exactly the same for experts and novices (M = 6.44).

Crucially to our hypotheses, the interaction between Expertise and Route was significant (F (1,32) = 3.60; MSe = 3.35; p < .04). Post-hoc test confirmed that there was no difference between Novices and Experts on the Easy Route (p = 1). More importantly, the difference between Novices and Experts was not significant with the IPSR (Newman-Keuls, p = .21, respectively M = 2.78, M = 3.89), whereas the performance of Novices was significantly worse than that of Experts with the DR (Newman-Keuls, $p < .004$, respectively $M = 2.11$, $M = 5.33$). This suggests that the two groups did not differ in memory capabilities when for both of them it was impossible to mentally simulate the motor task, i.e. in the IPSR. This indicates that the impossibility to form a motor simulation clearly affects recall. The impact of motor simulation on recall is confirmed by results with the DR, where the difference between the two groups clearly emerged. Namely, in the DR, the capability to climb the wall was part of the experts' motor repertoire, thus they were able to build a motor simulation. In the post-experimental questionnaire, Experts and Novices did not differ in responding to whether they mentally imagined climbing the route while being shown it (55% of both groups responded using imagination) and while recalling it (44% for both groups responded positively). However, compared to novices, experts seem more aware of the effects of the simulation (22% of novices and 44% of experts reported that imagination helped), even though neither group seemed to believe that imaging was strategically important, as participants did not believe it helped them during recall (only 33% of athletes responded positively for both groups). Experts and Novices differed also in that Novices were less aware of the differences between the routes (55% of novices did not distinguish between them).

Discussion

Our results support the hypothesis that visually perceiving multiple affordances (here, climbing holds disposed in a climbing wall) leads to the activation of a motor simulation, which improved recall. The activation of the simulation is specific, and depends on whether or not the holds are disposed so to afford climbing, and on climbers' motor competence.

We found that both experts and non-experts performed equally well with the Easy Route. This suggests that, when participants have the motor competence allowing them to climb a given route, they simulate doing it, and this very fact improves their recall of the route. In addition, our results allow us to understand what happens with difficult routes, that is, when, for some of the participants, it is difficult or impossible to construe a simulation. Specifically, the design we used allow us to distinguish situations in which participants could rely on perceptual salience for memorization and situations in which only a subset of participants might build a motor simulation grounded on previous climbing experience. We found that the expert participants, who were able to rely on a mental simulation strategy, had better performance than novice ones, who were only able to rely on visual strategies. The advantages of motoric vs. visual strategies were also highlighted by the poor performance of both groups in the (motorically) impossible but perceptually salient route, despite the high salience of the holds that composed the route. Our results indicate that a simulation is evoked only when the holds have perceptual characteristics and also afford actions. Namely, no simulation is activated when climbers observe holds that are perceptually salient (i.e. having vivid colors) but not useful for climbing the route, that is, when the holds do not represent good affordances. This result helps to qualify the kind of simulation evoked: holds (affordances) elicit an embodied, motor simulation, not a purely visual simulation.

Notice that in this study we do not consider the specificity of the climbing method experts and non-experts adopt; we simply focus on different climbing competence. A few studies have addressed and demonstrated that experts and novices might use different patterns of action. Boschker et al. (2002) found that, differently from inexperienced climbers, experts focused on the functional aspects of a climbing wall, whereas they did not consider its structural features. In Boschker and Bakker (2002) inexperienced climbers who were shown a video of expert climbers learned to use experts modes of climbing (e.g., arm crossing) and climbed faster and with more fluent movements than those who were shown videos of novice climbers or a control video. Overall, our results fit well in the embodied cognition (Glenberg, 1997) literature and have implications, concerning the role of affordances for both simulation and recall, as well as the relationship between motor competence and the capability to form and use motor simulations.

In addition, this finding helps us comprehend the mechanisms on which memory of action relies (see for example Daprati et al., 2005). Overall, our study suggests that the ability to benefit from objects' (holds') characteristics and from their arrangement can help a climber form *motor chunks*, i.e. chunks based on sequences of real action possibilities, which, in turn, leads to better recall of a given route. The idea of "chunks" derives from the study of Chase and Simon (1973) on how competence influences recall of chess positions in novice and expert chess players. The main finding of such study is that expert chess players outperformed novices in the recall of meaningful chess positions, but not in non-meaningful positions. The authors proposed that this is due to the experts' larger set of 'chunks' of chess positions, which permits them to recognize complex patterns of chess positions as individual units and therefore to recall them better. Our study shares resemblances with the study of Chase and Simon (1973), the two main differences being that: (i) we focus on motor competence rather than abstract problems like chess, and (ii) unlike chess players, climbers see the climbing routes for the first time, and there is an immense variety of combinations of holds, orientations, inclinations of the climbing walls, etc. Although the climbers could still pick up abstract similarities between old and new patterns of holds, these similarities are meaningless if untied to body possibilities and more in general (competence-specific) motoric information. For this reason, we could hypothesize that a chunking mechanism could be in play that is similar to the one described in (Chase and Simon, 1973); it can be called motor chunking due to the importance of motoric information. However, if this is the case, motor chunks cannot be simply retrieved from memory, but should be built anew (or at least reassembled) as part of the planning (and simulation) process, which is of course highly competence-specific, and involves the (partial) re-enactment of motor processes. Note that this view of motor chunking is compatible with the idea of Glenberg (1997) that simulations can be *meshed* with (episodic) memories. Overall, this view could explain why memory performance is better when climbers are allowed to form motor chunks, not when they use memory strategies relying on the visual saliency of some holds. This finding is also compatible with the idea that motor simulations elicit procedural memories (see Pezzulo, 2008; in press; Pezzulo and Castelfranchi, 2009, for a discussion).

Our results suggest also that the activation of a motor simulation is possible only when performing a given sequence of actions is part of participants' motor competence. The better recall of Experts compared to Novices is totally due to the fact that, given that they were able to climb the difficult route, they could mentally simulate climbing (do the 'affordances calculus') and, with the help of the affordances, they were able to recall the sequence of required movements. Novices were impeded from simulating because they did not possess the motor capability to climb the Difficult Route. This suggests that the ability to simulate is modulated by previous motor experiences, in keeping with ideomotor theories of perception and action (Hommel et al., 2001).

Differently from other sports, like dance, in rock climbing both the simulation elicited by action observation (of another rock climber) and the simulation elicited by affordances (simply observing a rock or climbing wall) can be studied. Therefore, our research extends also the results showing that a motor resonance phenomenon occurs when we observe others performing complex movements, such as dancing and playing basketball (e.g., Cross et al., 2006). This phenomenon has its neural basis in the mirror neuron system, which, differently from canonical neurons, are activated both during performance of an action (say, grasping, manipulating and holding objects), and during observation of others performing the same action (Gallese et al., 1996). In line with our results, this motor resonance is stronger when participants observe actors sharing their motor repertoire. Aglioti et al. (2008) demonstrated with a psychophysical study that elite basketball players predicted the success of free shots at a basket earlier and better than expert observers and novice players. The experts' advantage was due mainly to their higher capability to predict by reading body kinematics in the early movement phases. A transcranial magnetic stimulation (TMS) study showed a time-specific motor activation while observing videos of errors. The results of the combined physiological and TMS studie reveal that fine-grained motor resonance occurs after motor practice and that motor expertise specifically contributes to anticipating the actions of others.

Studying a special case, that of rock climbers, our behavioural study showed for the first time that multiple affordances activate a motor simulation, and that this strongly impacts recall, which is then modulated by participants' motor expertise and motor repertoire. Further studies are needed to better understand the neural underpinnings of the complex mechanisms of recall based on affordances and embodied simulation.

One alternative explanation for our results is that experts might be better in fitting visual images of climbers' postures, and thus they could use visual imagery rather than motor simulations. Although our study cannot rule out this possibility, there are reasons to believe that this is not the case. First, while this hypothesis explains the advantage of experts in the DR, it does not explain the good performance of novices in the ER. To explain why novices are better in recalling the ER than the DR, one should say that visual imagery is specifically modulated by one's own (motoric) climbing competence. Second, the exclusive use of visual imagery could hardly help solving our task. Namely, climbers experience the routes for the first time, and cannot see other climbers, so any visual simulation they build has to be done anew. However, spatial and configurational information (position of limbs in space) is not enough to determine which are the climbing positions one should remember, since valid climbing positions also depend on which affordances are offered by the holds, and which are the past and future movements. In other terms, although climbers could use visual imagery as part of their strategies, at least some of the processing required to recall climbing positions is better understood in motoric than purely visual terms. Another possibility is that experts are more experienced with some patterns of holds, much like chess players are supposed to be. As already discussed, however, climbers see the routes for the first time, and there countless dispositions of holds. More importantly, the visual appearance and the spatial configuration of the holds is not sufficient to understand the best path in a route, or its difficulty. To do so, climbers have to take into account at the same time the individual affordances offered by the holds, the previous movements, etc. Overall, then, due to the highly specific and situated nature of climbing, it is unlikely that a memory retrieval strategy could be sufficient (although it might help), and how memory retrieval could be done in purely abstract terms, without accessing one's own motoric information. (This is why we suggested that motor chunks should be built anew as part of the motor planning.)

Before concluding, it is worth mentioning that several studies distinguish between two kinds of motor simulations: conscious and unconscious (see Jeannerod, 2006 for a discussion). Most of the afore-mentioned studies address unconscious motor simulations; in this context, the idea is that seeing a climbing wall automatically activates specific motor processes in climbers. There is, however, another kind of motor simulation, a conscious one, which can be performed by climbers, and is indeed routinely done as part of the athletes' training, and before the start of competitions.

Jeannerod (2006) suggests that the representational content of conscious and unconscious simulations are the same, with different time constraints determining their level of access (e.g., most unconscious motor images arise for the demands of immediate action and simply do not have the time to become conscious). In this study, the climbers were not explicitly instructed to mentally simulate. However, the procedure adopted in this study, and in the afore-mentioned ones, does not permit us to discriminate whether or not participants used a conscious strategy. Further studies are necessary to shed light on the differences between conscious and unconscious mental simulations, and their respective roles in motor planning.

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References

Aglioti, S. M., Cesari, P., Romani, M., and Urgesi, C. (2008). Action anticipation and motor resonance in elite basketball players. *Nature Neuroscience, 11*, 1109-1116.

Borghi, A. M. (2004). Object concepts and action: extracting affordances from objects parts. *Acta Psychologica, 115*, 69-96.

Borghi, A.M., Riggio, L. (2009). Sentence comprehension and simulation of objects temporary, canonical and stable affordances. Brain Research, 1253, 117-128.

Boschker, M. S. J. and Bakker, F. C. (2002). Inexperienced sport climbers might perceive and utilize new opportunities for action by merely observing a model. *Perceptual Motor Skills, 95*, 3-9.

Boschker, M. S. J., Bakker, F. C., and Michaels, C. F. (2002). Memory for the functional characteristics of climbing walls: perceiving affordances. *Journal of Motor Behavior, 34*, 25-36.

Costantini, M., Galati, G., Ferretti, A., Caulo, M., Tartaro, A., Romani, G. L., and Aglioti, S. M. (2005). Neural systems underlying observation of humanly impossible movements: an fmri study. *Cerebral Cortex, 15*, 1761-1767.

Cross, E. S., de C Hamilton, A. F., and Grafton, S. T. (2006). Building a motor simulation de novo: observation of dance by dancers. *Neuroimage, 31,* 1257-1267.

Daprati, E., Nico, D., Saimpont, A., Franck, N., and Sirigu, A. (2005). Memory and action: an experimental study on normal subjects and schizophrenic patients. *Neuropsychologia, 43,* 281-293.

Ellis, R., & Tucker, M. (2000). Micro-affordance: the potentiation of components of action by seen objects. *British Journal of Psychology*, *9*, 451-471.

Frith, C. D., Blakemore, S. J., and Wolpert, D. M. (2000). Abnormalities in the awareness and control of action. Philos Trans R Soc Lond B Biol Sci, 355(1404):1771–1788.

Gallese, V. (2009). Motor abstraction: a neuroscientific account of how action goals and intentions are mapped and understood. *Psychological Research, 73*, 486-498.

Gibson, J. (1979) The ecological approach to visual perception. *Lawrence Erlbaum Associates, Inc*

Glenberg, A. (1997). What memory is for. *Behavioral and Brain Sciences, 20*, 1-55.

Grèzes, J., Tucker, M., Armony, J., Ellis, R., and Passingham, R. E. (2003). Objects automatically potentiate action: an fmri study of implicit processing. *European Journal of Neuroscience, 17*, 2735-2740.

Hommel, B.; Musseler, J.; Aschersleben, G. & Prinz, W. (2001) The Theory of Event Coding (TEC): a framework for perception and action planning *Behavioral and Brain Science,* 24(5), 849-78

Jeannerod, M. (2006). *Motor Cognition*. Oxford University Press.

Martin, A. (2007). The representation of object concepts in the brain. *Annual Review Psychology, 58*, 25-45.

Murata, A., Fadiga, L., Fogassi, L., Gallese, V., Raos, V., and Rizzolatti, G. (1997). Object representation in the ventral premotor cortex (area f5) of the monkey. *Journal of Neurophysiology, 78*, 2226-2230.

Pezzulo, G. (in press). Grounding procedural and declarative knowledge in sensorimotor anticipation. *Mind and Language*.

Pezzulo, G. (2008). Coordinating with the Future: the Anticipatory Nature of Representation. *Minds and Machines, 18,* 179-225.

Pezzulo, G., and Castelfranchi, C. (2009). Thinking as the Control of Imagination: a Conceptual Framework for Goal-Directed Systems. *Psychological Research, 73,* 559-577.

Riddoch, M. J., Humphreys, G. W., Edwards, S., Baker, T., and Willson, K. (2003). Seeing the action: neuropsychological evidence for action-based effects on object selection. *Nat Neurosci*, 6(1):82–89.

Smyth, M. M. and Waller, A. (1999). Movement imagery in rock climbing: patterns of interference from visual, spatial and kinaesthetic secondary tasks. *Applied Cognitive Psychology, 12*, 145-157.

Wolpert, D. M. and Kawato, M. (1998). Multiple paired forward and inverse models for motor control. *Neural Networks*, 11(7-8):1317–1329.

Wolpert, D. M., Doya, K., and Kawato, M. (2003). A unifying computational framework for motor control and social interaction. *Philos Trans R Soc Lond B Biol Sci*, 358(1431):593– 602.