Investigating prospective action control: when and how actions supporting cognition are generated

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Abstract

Mechanisms underlying prospective action control (such as involved in generating actions that take up resources in the short run, but provide benefit in the long run) are less well-understood than mechanisms underlying monitoring and allocation of control (Miller & Cohen, 2001). One possible case of prospective action control is compatible actions generated in parallel with tasks (such as hand movements in the same direction as mental rotation), which have been shown to improve cognitive performance. Such actions are triggered spontaneously, but unlike reflex actions, they can be brought under cognitive control. We report two mental rotation experiments that investigated when such actions are generated, and the cognitive benefits of such actions. Our results show that such actions are generated during high cognitive load situations, but they do not provide any cognitive benefit in our task. To explain these results, as well as previous results reporting cognitive benefits, we develop a theoretical model of the control mechanism underlying the generation of such actions. We conclude with a discussion of how our experimental paradigm and model could contribute to the understanding of prospective action control as well as disorders of volition.

Keywords: Prospective Control; Common Coding; Mental Rotation; Cognitive Load; Volition

Introduction

Monitoring and allocation of control is a core function of the central executive system. Examining the mechanisms underlying these aspects of control, Miller and Cohen (2001) suggest that the anterior cingulate cortex (ACC) and prefrontal cortex (PFC) work in a coupled fashion to provide adaptive monitoring and allocation of control (say, pausing conversation while driving in a dark stretch of road). Such adaptive control, usually leading to stopping or slowing a task or switching to another, is needed because of the capacity limits in the control of actions (difficult to do both talk and attend to road at the same time). A recent review (Aron, 2008) breaks down the mechanisms underlying allocation of control further, and localizes it to a more fine-tuned coupling, involving the inferior frontal cortex (IFC), subthalamic nucleus (STN) and pre-supplementary motor area (SMA). Much of this work is based on “task-stopping” (go-nogo) or task switching paradigms, where participants know when to stop a movement or switch to another task.

There is another aspect of control – prospective action control – that is related to planning and less well-understood, from both behavioral and mechanism standpoints (Miller & Cohen, 2001). An interesting case of prospective action control is the generation of actions that can provide positive effects in the long term, but have negative effects in the short-term (such as generation of pheromone trails; see Chandrasekharan & Stewart, 2007). In contrast to the monitoring and allocation situations such as stopping/slowing or switching cognitive tasks, such prospective action control involves computing the costs of possible actions during a cognitive task, and then generating one of these possible actions in parallel to the task, if such actions could be beneficial. An interesting instance of such actions generated in parallel to tasks is the case of ‘complementary actions’ (Kirsh, 1995), which are actions that arise spontaneously during some cognitive tasks, such as hand movements during mental rotation, pointing while counting coins on a screen, and gestures during learning. Some of these complementary actions have been shown to contribute beneficially to task performance (Kirsh & Maglio, 1994; Kirsh, 1995; Wexler, Kosslyn, & Berthoz., 1998; Goldin-Meadow & Wagner, 2005; also see Kosslyn, 1994; Thomas & Lleras, 2007; Wilson & Gibbs, 2007). Complementary actions are usually compatible with the cognitive task. For instance, the hand movements during mental rotation are usually in the same direction as the mental rotation. Incompatible actions, such as hand movements made in the direction opposite to mental rotation, lower performance in the mental rotation task (Wexler et al., 1998).

These actions are mostly reported in the cognition literature, and have not been studied from the point of view of prospective action control. If these actions contribute to the cognitive task, and are generated for this benefit, how does the control system generate such compatible actions in parallel to cognitive tasks? This is the question we explore in this paper. For example, hand movements are generated when people perform a mental rotation task (Kosslyn, 1994). Such action generation is of theoretical interest for two reasons. One, little is known about the control mechanisms that support the generation of actions in parallel to tasks, particularly how they are generated to lower cognitive load. Two, in many instances of such parallel actions during cognitive tasks, including the experimental paradigm we present in this paper, the activation of the parallel action appears un-intentional. Such actions are neither voluntary nor reflex actions, but share characteristics of both. Like reflex actions, they “break out” spontaneously under different conditions (usually high cognitive or emotional load), but like voluntary actions, they can be controlled if needed. The mechanisms underlying the generation and control of these non-voluntary actions are mostly unknown, as these in-between actions are difficult to generate and study in the laboratory. Complementary actions provide a window into how such involuntary actions could be generated by the control system during high cognitive and emotional loads.

Actions supporting cognition

Many studies examining the link between action and cognition report that actions compatible with cognitive tasks play a beneficial role in cognitive tasks. An influential study is Kirsh and Maglio (1994), which showed that people playing the Tetris video game use actions to lower computational load. Tetris involves maneuvering falling shapes (zoids) into specific arrangements on the screen. The primary computations involved in Tetris are mental rotation of the zoids and matching of zoids to available slots. The authors showed that, in addition to the actions to move the zoids to a desired slot, players also execute exploratory rotation and translation actions on the falling zoids – to expose information early, to prime themselves to recognize zoids faster, and to perform external checks and verifications to reduce the uncertainty of judgments. The authors term such actions ‘epistemic actions’, which are defined as “physical actions whose primary function is to improve cognition by: 1) reducing the memory involved in mental computation (mental rotation in this case); 2) reducing the number of steps involved in mental computation; 3) reducing the probability of error in mental computation” (Kirsh & Maglio, 1994).

The epistemic actions in Tetris are generated based on an ongoing visual comparison between slots and the physical rotation. However, a visual comparison is not required for actions to aid in mental rotation – actions could contribute to cognition via proprioception. Wexler et al. (1998) show that *unseen* motor rotation in the Cooper-Shepard mental rotation task (Cooper & Shepard, 1973) leads to faster reaction times and fewer errors when the motor rotation is compatible with the mental rotation than when they are incompatible. They also report that in some cases motor rotation made complex mental rotations easier. Also, speeding (slowing) the motor rotation speeded (slowed) the mental rotation. Similar effects have been shown to exist in children (Frick, et al. 2005). Manipulating virtual objects have also been reported to improve subsequent mental rotation and recognition of such objects (Wexler & van Boxtel, 2005).

On a different vein from mental rotations, Kirsh (1995) reports higher accuracy in a coin-counting task when participants pointed at the stimulus, compared to a no-pointing condition. Supporting this, hand movements during saccades have been shown to lower variability in moving the eyes to a target (Rolheiser et al, 2006). Gestures during cognitive tasks have also been shown to lower cognitive load and promote learning (Goldin-Meadow & Wagner, 2005). Body movements appropriate to metaphorical phrases (such as *push the argument*) facilitate people's comprehension of such phrases, compared to mismatched actions (Wilson & Gibbs, 2007). Moving eyes in patterns related to a problem solution improves problem-solving (Thomas & Lleras, 2007). Humans and other animals exploit head and eye movements to better perceive depth, absolute distance, heading and 3D objects (Wexler & van Boxtel, 2005). In related work, Bergen (2004) reports that processing time for sentences involving actions increases when participants perform incompatible actions in parallel.

Besides the above direct evidence, Kosslyn (1994) reports extensive indirect evidence for a role of action in mental rotation, including a study that showed participants need more time to perform mental rotations that are physically awkward, and another one where incompatible movements disrupted memory. Kosslyn also refers to a brain-damaged patient who consistently reached up to the screen and pretended to ‘twist’ the stimulus in a rotation task (as in Tetris), and participants in the classic Shepard and Metzler experiment reporting “kinesthetic imagery” in their hands.

All the actions discussed above do not meet the epistemic action criteria (Kirsh & Maglio, 1994). Hence, we will use the more general term ‘complementary actions’ (Kirsh 1995) to refer to actions generated in parallel to cognitive tasks. However, note that since epistemic actions are a special case of complementary actions, the mechanism generating the latter would also underlie the former to a significant extent.

From a control perspective, complementary actions raise the following questions: Under what conditions are such actions generated? How does the control system ‘decide’ whether it should generate such actions, and the points at which to generate them? Further, how does the control system ensure that mostly compatible actions are generated during cognitive tasks? In other words, since incompatible actions have been shown to lower performance, how does the control system ‘know’ how to generate ‘compatible’ actions in a task?

To explore these questions, two experiments were conducted using a mental rotation task with two levels of cognitive load. Briefly, the experiments consisted of showing participants a rotation operation, which they had to remember. They were then presented a target pattern along with four rotated versions of the same pattern (answers). The participants were then asked to mentally execute the remembered rotation operation on the target pattern, and choose from the four options the right answer, i.e. the result of the rotation. The rotation operation had two levels of complexity, low and high. Pilot studies showed that participants tended to significantly generate hand or head rotations during the task.

We hypothesized that actions would be generated mostly during the high complexity conditions, and, in general, the actions would provide an improvement in accuracy. We also expected the generated actions to be compatible with the rotation, i.e. in the same direction as the observed rotations.

Experiment 1

In the first experiment, we presented participants with the stimuli, keeping track of the trials where participants rotated their hands (and heads), and the accuracy for the action and no-action cases. This experiment had two objectives: one, to examine how often actions were generated and when; two, to examine how the actions affected accuracy in the rotation task.

Method

Participants

Twenty three student volunteers from University of Allahabad, with normal or corrected-to-normal vision participated in the experiment. None had laboratory experience with mental imagery. Written consent was provided by all the participants.

Apparatus

A computer screen, microphone and keyboard, placed on a table in front of the subjects was used in the experiment. The screen was parallel to participants' frontal plane, at eye level and approximately 75 cm from the participant.

Stimuli

A set of four small 2D patterns within a white square (frame) were prepared on a 3x3 matrix with only five cells being filled, as illustrated in Figure 1. The visual angle was 1.5° x 1.5°. With each of these patterns, three more patterns were generated by rotating the original four patterns by 90°, 180° or 270°. Any one of the four orientations of a particular stimulus pattern was randomly used as a stimulus in a particular trial.

Insert Figure 1 about here

There were eight rotational operations (see Figure 2) with two levels of complexity (low or high). Each level of complexity had four operations. Low complexity operations were rotations of 90° (right and left) and 180° (right and left). High complexity operations were vertical and horizontal flips followed by a rotation of 90° (left or right).

Insert Figure 2 about here

The rotational task was given a reference by providing an empty-blank white square (frame). To demonstrate the operations, video clips were created using Flash (sample Flash files at: http://www.sce.carleton.ca/~schandra/CAflash). Each rotation in the low complexity condition took twenty seconds of display time. In the high complexity condition, each flip operation took twenty seconds in addition to each rotation operation, which also took twenty seconds to complete. There was a two second gap between flip and rotation. The end position (frame), after the rotational operation completed, stayed for five seconds.

Procedure

The experiment consisted of thirty two trials (8 operations x 4 patterns), presented randomly. Each trial had two phases. In the first phase, a rotation was demonstrated using a video clip. Participants were asked to remember the rotation they saw, apply the same operation on the pattern coming up in the second phase and select the answer that best fitted the mentally rotated pattern.

The second phase started after four seconds, during which the screen was blank. This phase presented a pattern to be mentally rotated, along with four possible answers (as shown in Figure 3), which remained on screen until participants produced a voice response. Participants first said their choice (1, 2, 3 or 4) aloud into the microphone, and then typed their choice in the textbox that appeared a few moments after the voice response. They then pressed the *Enter* key to initiate the next trial, which started after two seconds. The microphone option freed participants' hands while doing the rotation task, and avoided any interaction with preparing for a keystroke, a possibility in a keyboard-only option. Commercially available software (DirectRT, running on a PC with a SVGA monitor) was used for stimuli presentation and data collection.

Insert Figure 3 about here

The actions (presence or absence in a given trial) was tracked by an experimenter who sat a little away from the participant, facing her hands, and noted on a chart the trials in which the participant generated actions. The chart had trials numbers 1-32, and the experimenter primarily focused on the participant's hands, noting a yes/no for each trial. These notes were later mapped to the randomized sequence to link complexity and hand movement. In general, there were three kinds of actions – finger, wrist and elbow movements. Only major movements with an arc of roughly more than 30 degrees were considered as actions, as movements smaller than this cannot be considered rotations. There were head movements as well, but except in one participant, they were always associated with hand movements. All movements were basically unseen, i.e. participants did not look at their moving hands. The experimental procedure was approved by the University of Allahabad review board.

Results and Discussion

All participants generated actions in at least one trial, and these actions were compatible with the rotation movement (same direction). Head movements were ignored in this analysis, as only one participant used them in isolation (i.e. without parallel hand movements), and those head movements were minute. We examined the rate of action generation and its relationship to performance in the mental rotation task.

The effect of complexity on action generation was examined using a one variable (complexity: low, high) repeated measures ANOVA on the rate of action generation. Actions were generated more in the high complexity condition compared to the low complexity condition, $F(1,22) = 24.859$, $p < .0001$. Actions were generated in only 55% of the trials in the low complexity condition, but were generated in 75% of the trials in the high complexity condition.

The effect of complexity on performance in the mental rotation task was examined using a one variable (complexity: low, high) repeated measures ANOVA on accuracy. Accuracy was better in the low complexity condition compared to the high complexity condition $F(1,22) = 44.414$, $p < .0001$. The effect of complexity is different for action generation and mental rotation. While increase in complexity resulted in increase in action generation, increase in complexity decreased performance in the mental rotation task.

What is the relationship between the generation of actions and performance in the mental rotation task? Figure 4 shows a plot of all the participants in terms of the accuracy and action generation averaged across the complexity conditions. We performed correlation analysis with the action generation and mental rotation accuracy and there was a close to significant negative correlation ($R = -0.3914$, $p = 0.0648$) between them. The result indicates that the increase in action generation is associated with decrease in mental rotation performance. As can be seen in Figure 4, there is a large cluster of points corresponding to participants who used hands in a large percentage of trials, but their performance in the mental rotation task show a fair amount of variability. In addition, there are a small number of participants who used hands in a smaller percentage of trials and whose accuracy is fairly high.

Insert Figure 4 about here

To quantify the potential individual differences across participants, we performed a cluster analysis using *k*-means (two means in our case) clustering. The clustering analysis was performed using MATLAB. The results showed two clusters, with one cluster containing six participants who used hands 16.1% of the time and whose performance was 79.2%. These six participants used their hands very little but performed very well in the mental rotation task. The other cluster contained the remaining seventeen participants who used their hands in a high percentage of trials (82.7%) but their accuracy was not as high as the other group (63.1%). We also computed the variability in accuracy for the participants in the two clusters separately. The cluster containing those participants who used hands less had less variability in terms of accuracy (SD = 10%, range = 69%-94%) compared to the other cluster containing participants whose hands usage was high (SD = 17.5%, range = 31%-94%).

To further understand the relationship between mental rotation, action generation and complexity, we divided the participants into groups based on the clustering analysis into a high-action generation group (*N*=17) and a low-action generation group (*N*=6). The hands usage results as a function of task complexity for the low- and high-action groups are shown in Figure 5.

Insert Figure 5 about here

A 2 between (action: high-action-group, low-action-group) x 2 within (complexity: low, high) ANOVA was performed on the percentage of trials in which hands were used by the participants. As expected, there was a significant main effect of action, $F(1,21) = 112.096$, $p < .001$ and complexity, $F(1,21) = 13.54$, $p < .05$. Actions (hands) were used in only 55% of the trials in the low complexity condition, but were used 75% of the trials in the high complexity condition. More importantly, there was a significant interaction effect of action with complexity, $F(1,21) = 5.958$, $p < .05$. The effect of complexity was much larger for the high-action group, which used hands in 96% of trials in the high complexity condition, compared to only 70% in the low complexity condition. The effect of complexity on use of hands was much smaller for the low-action-group, with 18.8% of trials in the high complexity condition and 13.5% of trials in the low complexity condition.

The accuracy results are shown in Figure 6, for both the high-action and the low-action- groups. The accuracy for the high-action-group (only trials with use of hands) and the low-action-group (only trials without the use of hands) were taken for further statistical analysis. A 2 between (action: high-action-group, low-action-group) x 2 within (complexity: low, high) ANOVA was performed on the accuracy values from all the participants. There was a significant main effect for action, with performance in the low-action-group (0.812) significantly better than performance in the high-action-group (0.604), $F(1,21) = 6.322$, $p < .05$. Similarly there was a significant main effect for complexity, with performance in the low complexity condition (0.781) significantly better than performance in the high complexity condition (0.536), $F(1,21) = 20.576$, $p < .01$. The interaction between action and complexity was not significant.

Insert Figure 6 about here

The results indicate that in spite of the fact that the majority of the participants used their hands, their performance was significantly lower than those participants who did not use their hands. Even in the high complexity condition, where hands were used on almost all the trials (the high-action group), the performance was lower compared to those who used hands less. These results show that *not all* complementary actions generated during a task lead to better performance – some may actually interfere with the task.

Experiment 2

Since our results did not show an accuracy effect for the complementary actions (in contrast to the literature on such actions), we conducted two more experiments to examine the effect of actions on accuracy. Two task conditions were used with two groups of participants. In one condition, we curtailed all hand (and head) movements (action-curtailed condition). In the other condition (action-enforced condition), participants were required to use their hands in some way.

If actions do contribute to the task, then the accuracy would be lower for the first task, and higher for the second. We also wanted to see how performance in the mental rotation task differed as a function of volition, given that actions were generated involuntarily in Experiment 1, and voluntarily through instructions in Experiment 2.

Method

Participants

Twenty eight student volunteers with normal or corrected-to-normal vision from the University of Allahabad. None had laboratory experience with mental imagery. They were randomly assigned to one of the groups, action-curtailed or action-required.

Apparatus and Stimuli: Same as in Experiment 1.

Procedure

The stimulus presentation was same as in Experiment 1. For the action-curtailed condition, participants were asked to keep their hands flat on the table, and not move once the trial started. After providing a voice response to the four choices, they could move, to type their choice into the textbox. For the action-enforced condition, participants were asked to use their hands in some way, but the way in which to use hands was left open to their choice.

Results and Discussion

Figure 7 shows the mean accuracies for both the conditions. A 2 between (action-enforced, action-curtailed) x 2 within (complexity: low, high) ANOVA was performed with the accuracy values. Similar to the first experiment, complexity had a significant effect, $F(1,26) = 26.46$, $p < .001$ with better performance in the low complexity condition (73%) compared to the high complexity condition (48%). There was no significant difference in accuracy between the action-curtailed and action-enforced conditions, unlike Experiment 1, where the use of action affected performance. These results provide further support to the view that complementary actions are not always advantageous.

Insert Figure 7 here

General Discussion

Overall, our first experiment results show that compatible actions are generated during high cognitive load conditions, but these actions do not provide a cognitive benefit in our task. Table 1 captures the accuracy results for the three conditions (Spontaneous-action, Action-enforced, Action-curtailed).

Insert Table 1 here

Note that the spontaneous actions in the table are for the high action-generation group in experiment 1. There is very little difference between the three cases. The voluntarily generated (enforced) actions have no effect compared to the spontaneous actions generated by the high action-generation group. This suggests volition does not interact with the task. The curtailment of action also has no effect on accuracy when compared with the high action-generation group. This provides more evidence that the parallel actions do not contribute to the task. However, if we compare the action-curtailed condition to the low action-generation group (considering curtailment and low generation as similar), then there is a difference in accuracy, as the low action-generation group performed much better. This suggests that, when compared with the low generation group, there was more cognitive effort for the group involved in curtailing actions.

Since the parallel actions in experiment 1 did not improve accuracy, it is unlikely that these actions are generated in a top-down fashion, triggered by the control system to specifically lower cognitive load. Such a conclusion is further strengthened by experiment 2 results, where accuracy did not improve whether actions were enforced or curtailed. This suggests a bottom-up mechanism is responsible for the generation of actions parallel to a cognitive task. We develop below a model of the bottom-up mechanism underlying these actions. Even though this model is based on the results from our current experiment, it also accounts for cases where a cognitive benefit has been reported, such as the case of epistemic actions in Tetris (Kirsh & Maglio, 1994), and the coin-counting task (Kirsh, 1995). Because the model can accommodate these cases, where actions generated in parallel to a task *do* provide cognitive benefit, the model proposes an account of the mechanism underlying prospective action control, where the short-term cost of generating actions is offset by a longer-term benefit.

Our model is based on the common coding framework, which proposes that perception, execution, and imagination of movements share a common coding in the brain (Prinz, 1992; 2005; Decety, 2002; Hommel, Müsseler, Aschersleben, & Prinz, 2001). To illustrate, going round and round can make you dizzy, but equally, watching something go round and round can also make you dizzy. Note that watching a rotating disc could also generate such dizziness, so the effect is not limited to the observation of biological motion. This effect is explained by a common coding in the brain that connects an organism’s movement (motor activation), observation of movements (perceptual activation), and imagination of movements (simulation). First clearly articulated by Prinz (1992), this common coding allows any one of these movements to automatically generate the other two movements (Prinz, 2005; Sebanz, Knoblich, & Prinz, 2005; also see Decety, 2002; Hommel et al., 2001). One central implication of common coding is a body-based ‘resonance’ – the body instantly replicates all movements it detects, generating an internal representation that is dynamic and based on body coordinates. The model postulates that all the replicated movements are not overtly executed or responded to. Most stays covert, as the overt movement is inhibited.

The basic argument for common coding is an adaptive one, where organisms are considered to be fundamentally action systems. In this view, sensory and cognitive systems evolved to support action, and they are therefore dynamically coupled to action systems in ways that help organisms act quickly and appropriately. Common coding, and the resultant replication of external movements in body coordinates, provides one form of highly efficient coupling. Since both biological and non-biological movements are equally important to the organism, and the two movements interact in unpredictable ways, it is beneficial to replicate both types of movements in body-coordinates, so that efficient responses can be generated.

In operational terms, common coding implies that there are interactions between execution, perception and imagination of movement. A large body of experiments support different types of such interactions (Brass, Bekkering, & Prinz, 2002; Welsh & Elliott, 2004; Casile & Giese, 2006; Wohlschlager, 2001; See Chandrasekharan & Osbeck, In Press, for a review). Most of the behavioral evidence for common coding is based on interference effects, where actions in one modality (say imagination) leads to a difference in reaction time or accuracy in another modality (say execution). This behavioral evidence is supported by neurophysiological experiments, including imaging (Vingerhoets, de Lange, Vandemaele, Deblaere, & Achten, 2002; Wraga, Thompson, Alpert & Kosslyn, 2003; Brass & Heyes, 2005 provides a good review), TMS (Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995) and patient studies (Fiorio, Tinazzi & Agiloti , 2006; Bosbach, Cole, Prinz, & Knoblich, 2005; Farne, Iriki & Làdavas, 2005). The most influential evidence for common coding comes from the discovery of mirror neurons (Fadiga, Fogassi, Gallese & Rizzolatti, 2000; Rizzolatti & Craighero, 2004), which showed that a set of neurons in area F5 of monkeys are activated by both execution and perception of biological movement. Recent work shows that processing, particularly prediction, of non-biological movement is based on a subset of the biological movement system (see Schubotz, 2007; Scubotz & van Cramon, 2004).

For our purposes, the important component of the common coding model is the *automatic* activation of motor representations when observing or imagining a movement. This means the motor system is activated in an ongoing fashion by perceived and imagined movements. But the control system inhibits this automatic activation of the motor system, preventing the activation from proceeding to overt action. The automatic activations move to overt actions only when the inhibition by the control system is overridden, either by intention or by other factors, such as emotional involvement. Applying this automatic activation view to our experiment, there would be activation of the motor system during both the perception and imagination stages of the rotation stimuli in our task, as experiments supporting common coding clearly show that action components are automatically activated while viewing/imagining moving stimuli, particularly mental rotation stimuli (Wohlschlager, 2001).

As soon as the action system is activated covertly by the rotation movement, the inhibition process kicks in, preventing the covert activation from moving to overt action. Now, this inhibition process could be considered as acting like a 'caretaker' to the automatic activation, constantly blocking the covert motor process from becoming an overt action. However, such a caretaker mechanism would take up processing resources. During high-processing-load tasks (as in high complexity cases in experiment 1), this 'caretaker' process would lose resources, leaving the automatically activated motor component 'orphaned'. Such a dynamic reallocation of processing resources would lead to the covert actions sliding from inhibition to overt activation during high-processing-load tasks. This would explain the generation of actions, mostly in the high complexity condition in Experiment 1. In the low complexity condition, the processing load was not high enough to overcome the caretaker mechanism. A graphic illustration of how this model explains our results is shown in Figure 8.

Insert Fig. 8 about here

This ‘orphaning’ mechanism based on cognitive load extends the common coding model beyond automatic activation and inhibition, to cognitive-load-modulated activation and inhibition. This view explains the two major questions we raised: how does the control system ‘know’ when to generate parallel actions, and, how does it ‘know’ how to generate compatible actions? Complementary actions are generated significantly in high cognitive load conditions because only in those conditions are processing resources taken away from the caretaker mechanism (which usually inhibits the automatic activation from going overt). Compatible actions are generated because automatic activation is based on the common coding between action perception and imagination, so the action pattern would follow the perceived/imagined movement pattern. In this view, there is no need for the control system to ‘know’ how to generate the compatible movement (say, which muscles to activate). Such a cognitive-load-modulated mechanism would also explain other common complementary actions, such as why people tend to make more gestures while explaining difficult concepts, and while speaking in a second language.

The orphaning model does not fully explain all our results, however. For instance, why were actions rarely activated in six participants in the first experiment (low action generation group)? Individual differences in mental rotation abilities could explain this, but this needs further investigation. In this proposal, cognitive load would be higher for individuals with low mental rotation abilities, and this would lead to more automatic action generation. This would mean that complementary action generation could be considered an indicator of when processing load is high for different individuals.

Experiment 1 shows that all complementary actions do not provide a cognitive advantage. However, reported results and everyday experience suggest that actions do have the potential for providing cognitive advantages during complex tasks and learning. In the case of the epistemic action study (Kirsh & Maglio, 1994), the exploratory actions allow participants playing Tetris to 'move' some task processing (mental rotation) to the world, by creating external task states (physical rotation of zoids) which are accessible by perception. Based on our model, how could the control system generate such epistemic actions, which do provide a cognitive benefit? In Tetris, one possibility is that imagining the rotation of zoids leads to high cognitive load, and this initiates an "orphaned" activation of rotational hand movements, similar to the high complexity case in our experimental situation. But since the hand is already executing keyboard movements to move the zoids on screen, this rotational movement is also executed on the keyboard, leading to a circular movement on the arrow keys. This results in an (initially) inadvertent rotational movement of the zoids, and a lowering of cognitive load (as the mental rotation is 'moved' outside). This lowering of cognitive load leads to the keyboard movement pattern being reinforced (see Chandrasekharan & Stewart, 2007 for more on how variations in cognitive load could drive such real-time reinforcement learning, and prospective action control; also see Braver & Cohen, 2000 on the neural mechanisms underlying such rapid associative learning involving the PFC). Over time, this movement pattern rises up to the level of consciousness, and becomes an 'intended' prospective action control strategy. Interestingly, this process presents a case of an intention getting attached to an automatic action. This model of action generation is very different from the common assumption that intention precedes action, and voluntary movement is always driven by intention.

Our experimental paradigm shows actions “breaking-out” of the participant’s control as cognitive load increases in a task. This ‘breaking-out’ parallels many real-life situations where actions are generated spontaneously, and the control system allows the actions to continue even if the actions are in conflict with the wider goals of the individual. Examples include body movements that are at odds with what is being said; actions driven by intense emotional states such as anger; environment-driven actions by people with executive function disorders (such as getting into a bus just because one comes by); and compulsive manipulation of tools by people with “alien-hand syndrome” (Assal et al, 2007).

Most neuropsychological work on allocation of control using stopping/switching paradigms explain such ‘break-out’ behavior as a problem in stopping or switching. This explanation works only if a full-scale detection of the non-voluntary action is assumed. For instance, patients with executive function disorders detect that an action is unintended, and that it is in conflict with their goals; they then seek to stop it, but their intention to stop does not work (such as in alien-hand syndrome), and this problem with stopping is also detected. The stopping/switching paradigms can address only situations where the detection assumption holds across monitoring, conflict and intention.

However, in cases of ‘disorders of volition’ (Sebanz & Prinz, 2006) such as paranoid schizophrenia, the problem maybe that the unintended actions are detected, but there is no sense of conflict and therefore no desire to stop / switch these actions. Instead, these actions are executed, and when asked why they executed the actions, patients explain that the actions were generated by others who are controlling the patient's system. This indicates that monitoring works well, but *no conflict or intention is detected*. This is similar to the complementary action situation. Further exploration of complementary actions would help in understanding how such unintended actions arise, and why schizophrenics consider these as generated by other people. Particularly, the way intentions get attached to such actions (as in epistemic actions) could throw light on what mechanisms allow normal populations to consider such actions as their own, and how disruptions to this mechanism leads to schizophrenics considering these actions as executed by others controlling them. More broadly, the study of complementary actions would help in isolating how breaks in the monitoring-conflict-intention link could lead to disorders of volition in general.

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References

Aron, A. R. (2008). Progress in executive function research. *Current Directions in Psychological Science, 17*, 124-129.

Assal, F., Scwartz, S., & Vuilleumier, P. (2007). Moving with or without will: Functional neural correlates of alien hand syndrome. *Annals of Neurology*, *62*, 301-306.

Bergen, B., Chang, N., & Narayan, S. (2004). Simulated Action in an Embodied Construction Grammar. In K. D. Forbus, D. Gentner & T. Regier (Eds.), *Proceedings of the 26th Annual Meeting of the Cognitive Science Society,* Hillsdale, NJ: Lawrence Erlbaum.

Bosbach, S., Cole, J., Prinz, W., & Knoblich, G. (2005). Understanding another's expectation from action: The role of peripheral sensation. *Nature Neuroscience,* 8, 1295-1297.

Brass, M. & Heyes, C. (2005). Imitation: is cognitive neuroscience solving the correspondence problem? *Trends in Cognitive Sciences*, *9*, 489-495.

Brass, M., Bekkering, H., & Prinz, W. (2002). Movement observation affects movement execution in a simple response task. *Acta Psychologica*, 106, 3-22.

Braver, T. S., & Cohen J. D. (2000). On the control of control: The role of dopamine in regulating prefrontal function and working memory. In Monsell S & Driver J (Eds.), Attention and Performance XVIII; Control of cognitive processes, pp.713-737.

Casile, A., & Giese, M. A. (2006). Non-visual motor learning influences the recognition of biological motion, *Current Biology*, *16*, 69-74.

Chandrasekharan, S., & Stewart, T. (2007). The origin of epistemic structures and proto-representations. *Adaptive Behavior, 15*, 329-353.

Chandrasekharan, S. & Osbeck, L. (In Press). Rethinking situatedness: environment structure in the time of the common code, *Theory & Psychology*.

Cooper, L.A. & Shepard, R. N. (1973). The time required to prepare for a rotated stimulus. *Memory and Cognition, 1*, 246-250.

Decety, J. (2002). Is there such a thing as a functional equivalence between imagined, observed and executed actions? In A.N. Meltzoff & W. Prinz (Eds.), *The Imitative Mind: Development, Evolution and Brain Bases* (pp. 291-310). Cambridge: Cambridge University Press.

Fadiga, L., Fogassi, L., Pavesi, G., & Rizzolatti, G. (1995). Motor facilitation during action observation: a magnetic stimulation study. *Journal of Neurophysiology, 73,* 2608–2611.

Fadiga, L., Fogassi, L., Gallese, V., & Rizzolatti, G. (2000). Visuomotor neurons: ambiguity of the discharge or 'motor' perception? *International Journal of Psychophysiology, 35*, 165-177.

Farne, A., Iriki, A., & Làdavas, E. (2005). Shaping multisensory action-space with tools: evidence from patients with cross-modal extinction. *Neuropsychologia, 43*, 238-248.

Fiorio, M., Tinazzi, M., & Agiloti. S. M. (2006). Selective impairment of hand mental rotation in patients with focal hand dystonia. *Brain*, 129, 47-54.

Frick, A., Daum, M. M., Walser, S., & Mast, F. W. (2005). Developmental changes in the interference of motor processes with mental rotation. *Proceedings of the 27th Annual Meeting of the Cognitive Science Society*. Hillsdale, NJ: Lawrence Erlbaum.

Goldin-Meadow, S. & Wagner, S. M. (2005). How our hands help us learn. *Trends in Cognitive Sciences, 9*, 234-240.

Heyes, C. M. (2005). Imitation by association. In S. Hurley & N. Chater (Eds.), *Perspectives on imitation: From cognitive neuroscience to social science* (pp. 157-174). Cambridge: MIT Press.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, 24, 849-878.

Kirsh D. (1995). Complementary Strategies: Why we use our hands when we think. In *Proceedings of the Seventeenth Annual Conference of the Cognitive Science Society*, Hillsdale, NJ: Lawrence Erlbaum.

Kirsh, D., & Maglio, P. (1994). On distinguishing epistemic from pragmatic action. *Cognitive Science*, *18*, 513-549.

Knoblich, G. & Sebanz, N. (2006). The social nature of perception and action. *Psychological Science, 15*, 99-104.

Kosslyn, S. M. (1994). *Image and Brain*. Cambridge, MA: MIT Press.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24*, 167-202.

Prinz, W. (1992). Why don't we perceive our brain states? *European Journal of Cognitive Psychology, 4*, 1-20.

Prinz, W. (2005) An ideomotor approach to imitation. In S. Hurley, N. Chater (Eds.), *Perspectives on imitation: From neuroscience to social science*, Vol. 1, pp. 141-156. Cambridge, MA: MIT Press.

Rizzolatti, G., & Craighero, L. (2004). The mirror neuron system. *Annual review of Neuroscience, 27*, 169-192.

Rolheiser, T.M., Binsted, G., & Brownell, K.J. (2006). Visuomotor representation decay: influence on motor systems. *Experimental Brain Research*, *173*, 698-707.

Schubotz, R. I., & von Cramon, D.Y. (2004). Sequences of abstract non-biological stimuli share ventral premotor coretx with action observation and imagery. *Journal of Neuroscience*, *24*, 5467-5474.

Schubotz, R. I. (2007). Prediction of external events with our motor system: towards a new framework. *Trends in Cognitive Sciences*, *11*, 211-218.

Sebanz, N., Knoblich, G., & Prinz, W. (2005). How two share a task. *Journal of Experimental Psychology: Human Perception and Performance*, *33*, 1234-1246.

Thomas, L. E., & Lleras, A. (2007). Moving eyes and moving thought: On the spatial compatibility between eye movements and cognition. *Psychonomic Bulletin & Review*, *14*, 663-668.

Vingerhoets, G., de Lange, F.P, Vandemaele, P, Deblaere, & Achten, E. (2002) Motor imagery in mental rotation: an FMRI study. *Neuroimage*, *17*, 1623-1633.

Welsh, T. N., & Elliott, D. (2004). Movement trajectories in the presence of a distracting stimulus: Evidence for a response activation model of selective reaching. *Quarterly Journal of Experimental Psychology – Section A*, *57*, 1031-1057.

Wexler M., & van Boxtel, J. J. A. (2005). Depth perception by the active observer. *Trends in Cognitive Sciences*, *9*, 431-438.

Wexler, M., Kosslyn S. M., & Berthoz, A. (1998). Motor processes in mental rotation. *Cognition*, *68*, 77-94.

Wilson, N.L., & Gibbs, R.W. (2007). Real and imagined body movement primes metaphor comprehension. *Cognitive Science*, *31*, 721-731.

Wohlschlager, A. (2001). Mental object rotation and the planning of hand movements. *Perception and Psychophysics*, *63*, 709-718.

Wraga, M., Thompson, L. M., Alpert, N. M., & Kosslyn, S. M. (2003) Implicit transfer of motor strategies in mental rotation. *Brain and Cognition*, *52*, 135-143.

Figure Legends

Figure 1: The four patterns used in Experiment 1

Figure 2: Snap shots of the rotation operations

Figure 3: The screen during the second phase

Figure 4: Scatter plot of participants in terms of their action generation and accuracy (data corresponding to low-action generation participants are indicated by the circle signs and high-action generation participants are indicated by the plus signs)

Figure 5: Use of hands within the high- and low-action- groups

Figure 6: Accuracy with High-action and Low-action-groups. Circles represent the low-action group, crosses the high-action group.

Figure 7: Accuracy with action-restricted and action-required conditions

Figure 8: Graphic illustrating the way the orphan model explains action generation in the high complexity condition.

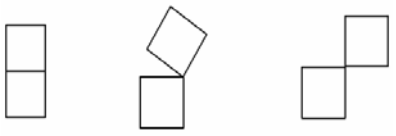
Table Legend

Table 1: Accuracy results for the three major conditions

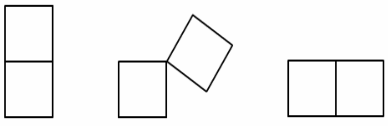
Table 1

Level	Spontaneous action	Action-enforced	Action-curtailed
Low complexity	73.6%	72.5%	73.5%
High complexity	47.2%	43.7%	52.4%

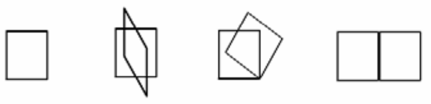
Figure 1



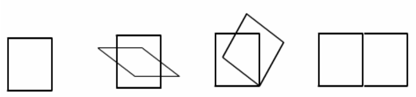
90^o Rotation



180^o Rotation



Horizontal flip followed by 90^o rotation



Vertical flip followed by 90^o rotation

Figure 2

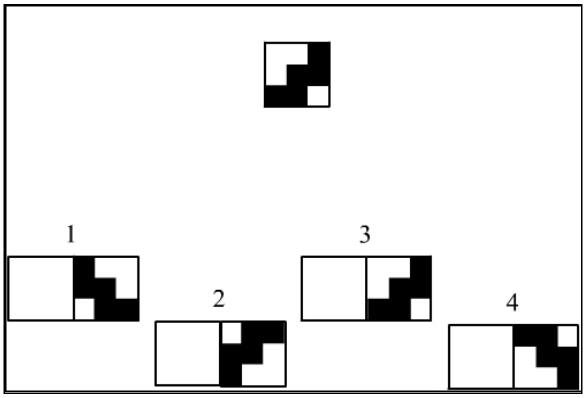
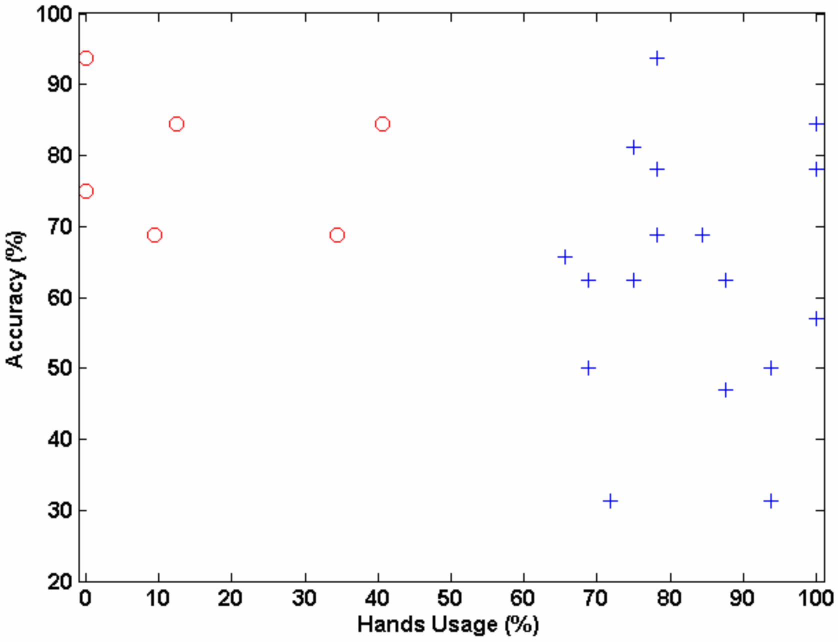


Figure 3



100
90
80
70
60
50
40
30
20
Accuracy (%)
0
10
20
30
40
50
60
70
80
90
100
Hands Usage (%)

Figure 4

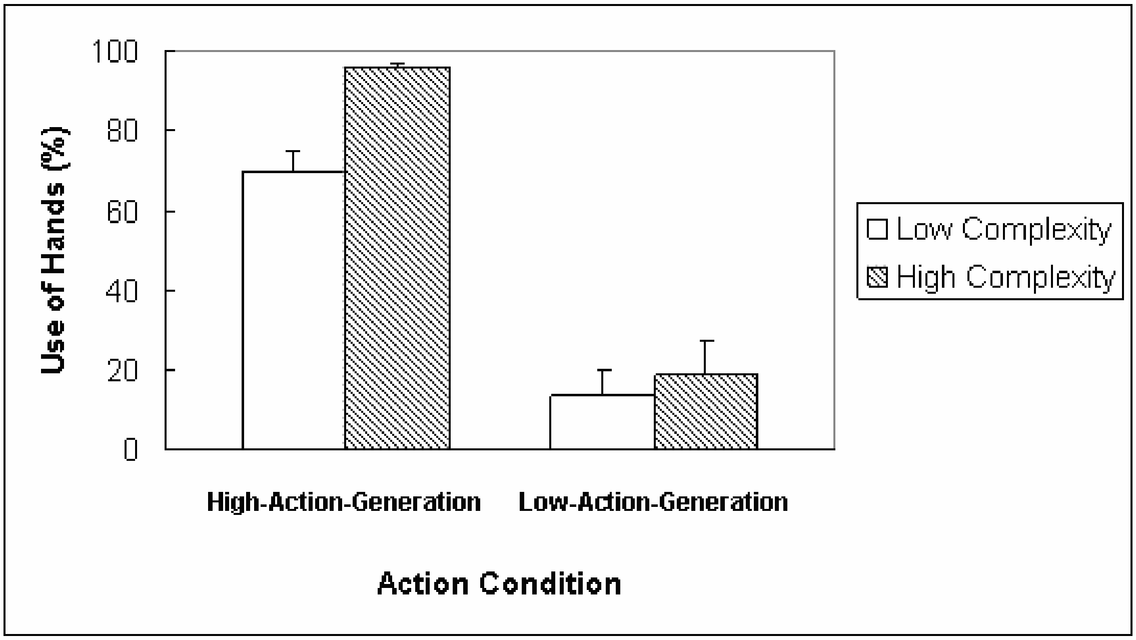

Use of Hands (%)
100
80
60
40
20
0
☐ Low Complexity
▨ High Complexity
High-Action-Generation
Low-Action-Generation
Action Condition

Figure 5

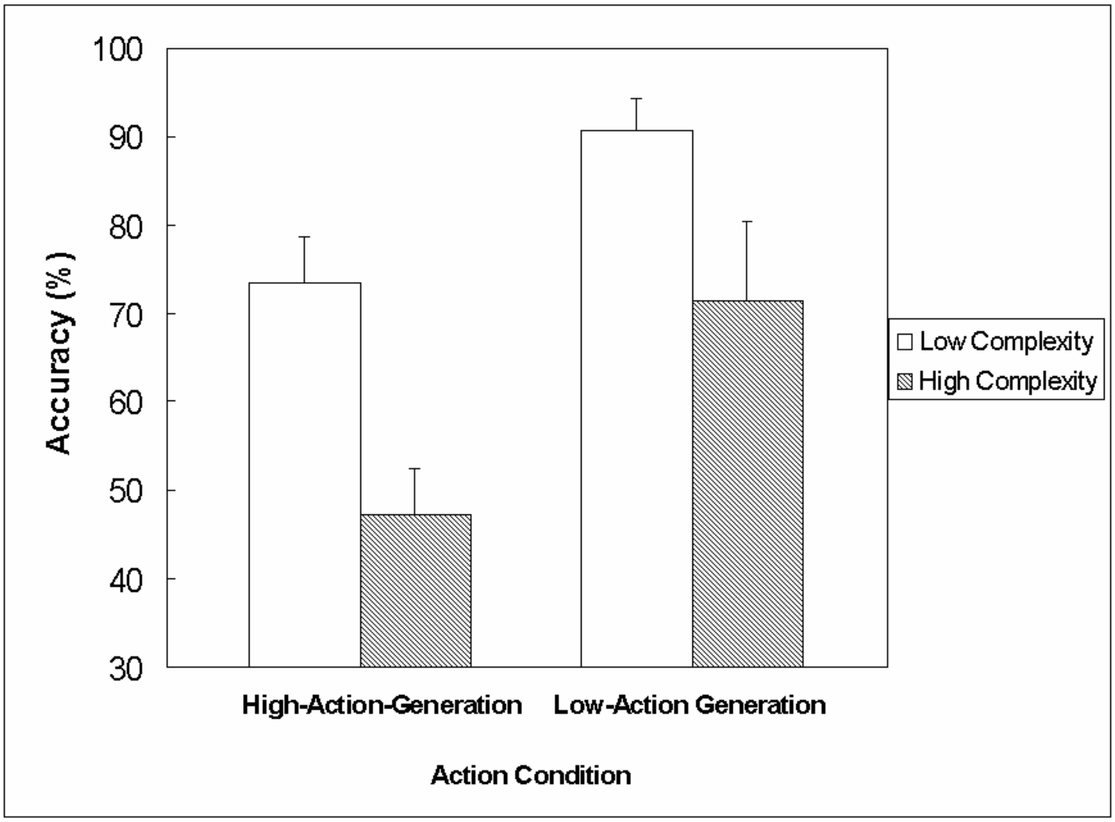

100
90
80
70
60
50
40
30
Accuracy (%)
High-Action-Generation
Low-Action Generation
Action Condition
☐ Low Complexity
▨ High Complexity

Figure 6

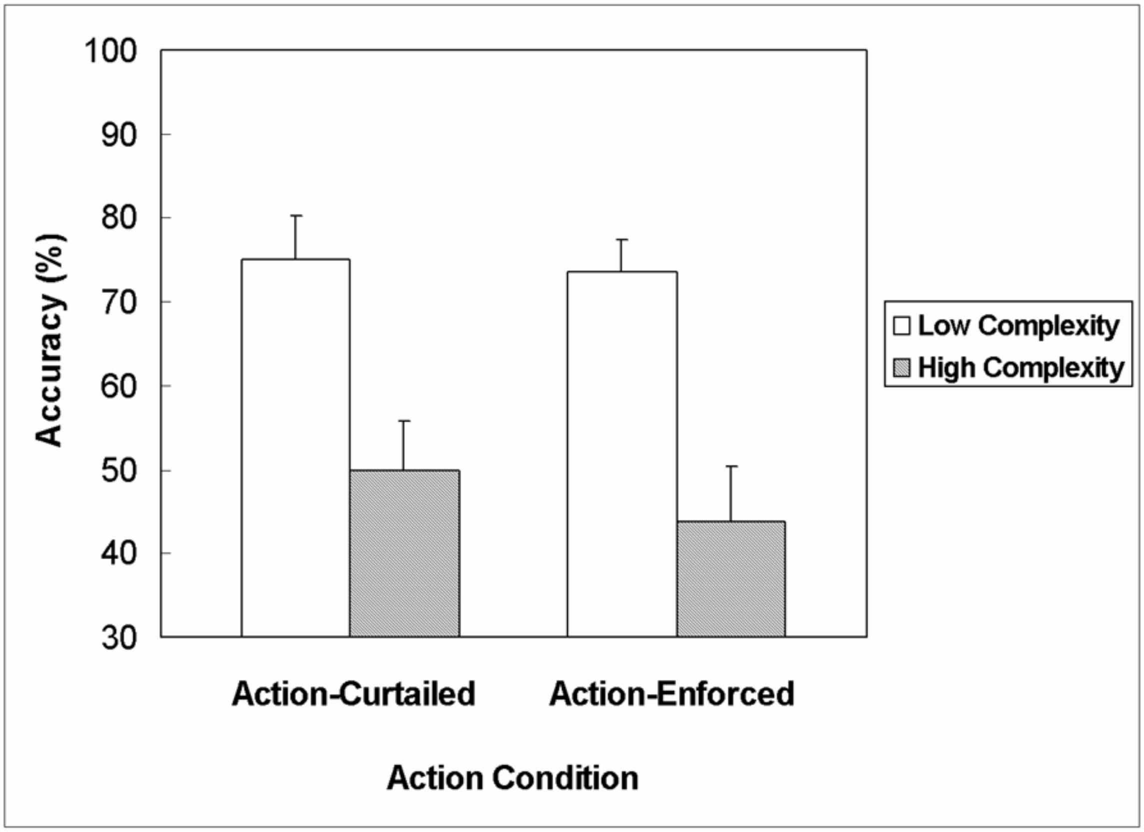

100
90
80
70
60
50
40
30
Accuracy (%)
Action-Curtailed
Action-Enforced
Action Condition
☐ Low Complexity
▨ High Complexity

Figure 7

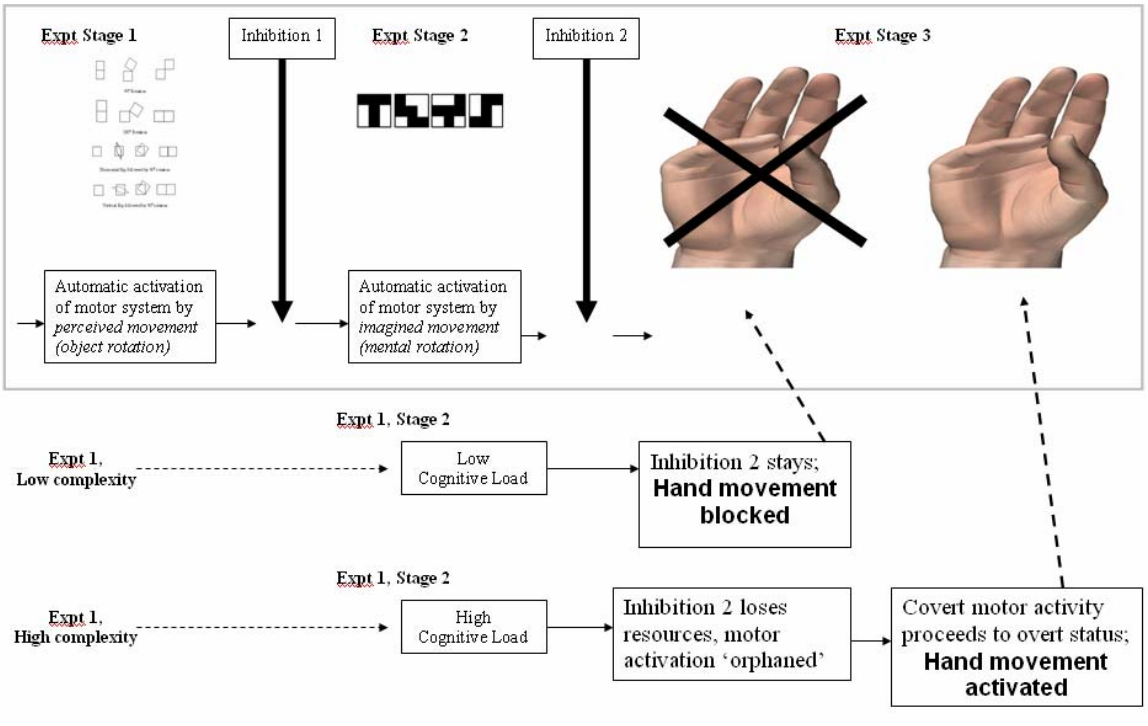

Expt Stage 1
Inhibition 1
Expt Stage 2
Inhibition 2
Expt Stage 3
Automatic activation of motor system by perceived movement (object rotation)
Automatic activation of motor system by imagined movement (mental rotation)
Expt 1, Stage 2
Expt 1, Low complexity
Low Cognitive Load
Inhibition 2 stays; Hand movement blocked
Expt 1, Stage 2
Expt 1, High complexity
High Cognitive Load
Inhibition 2 loses resources, motor activation 'orphaned'
Covert motor activity proceeds to overt status; Hand movement activated

Figure 8