Journal of Experimental Psychology:
Learning, Memory, and Cognition
2013, Vol. 39, No. 1, 2–13


0278-7393/12/$12.00 DOI: 10.1037/a0028642

# No Role for Motor Affordances in Visual Working Memory

Diane Pecher
Erasmus University Rotterdam

Motor affordances have been shown to play a role in visual object identification and categorization. The present study explored whether working memory is likewise supported by motor affordances. Use of motor affordances should be disrupted by motor interference, and this effect should be larger for objects that have motor affordances than for objects that do not. In 5 experiments participants performed a working memory task on photographs of manipulable and nonmanipulable objects. Concurrent motor, verbal, or visual tasks interfered with memory performance in general but did not interact with object manipulability. Thus, there was no evidence that motor affordances support visual working memory.

*Keywords:* visual working memory, motor system, premotor cortex, grounded cognition

People's ability to keep information active in their mind is commonly referred to as *working memory* or *short term memory*. Working memory supports a wide variety of activities such as mental calculations, planning a move in chess, comprehending text, driving a car, and so on. The most influential model of working memory (Baddeley, 1986, 2003; Baddeley & Hitch, 1974) assumes a limited capacity storage system that consists of several components. A *central executive* controls attention and provides a connection between working memory and long-term memory. The central executive is assisted by two *slave* systems, the *phonological loop* and the *visuospatial sketchpad*. The phonological loop stores and rehearses phonological information (the sounds of words), partly by using an articulatory rehearsal process. Evidence for the phonological storage of verbal materials comes from many studies showing effects of phonological similarity (Conrad & Hull, 1964) or articulation duration (Baddeley, Thomson, & Buchanan, 1975). The second slave system, the visuospatial sketchpad, stores and manipulates visual images and processes spatial information, which may be visual or nonvisual.

This model, with its modality specific slave systems, has some common ground with the grounded cognition framework (Wilson, 2001). The idea that articulatory and visuospatial rehearsal supports memory fits with the view that cognition is grounded in sensory-motor simulations (Barsalou, 1999). Many theories and empirical studies have suggested a central role for motor action. For example, Glenberg (1997) argued that the cognitive system has developed in order to support a person's interactions with the world. On this account, mental representations should be considered potential action patterns. Thus, the motor system may have an important role in cognition. Many studies have found evidence for activation of motor affordances when participants process object pictures (Bub, Masson, & Bukach, 2003; Ellis & Tucker, 2000; Tucker & Ellis, 1998, 2004; van Elk, Van Schie, & Bekkering, 2009; Witt, Kemmerer, Linkenauger, & Culham, 2010), words denoting objects (Bub, Masson, & Cree, 2008; Paulus, Lindemann, & Bekkering, 2009; Rueschemeyer, Lindemann, Van Rooij, Van Dam, & Bekkering, 2010), or sentences that describe objects or actions (Borghi & Riggio, 2009; Glenberg & Kaschak, 2002; Klatzky, Pellegrino, McCloskey, Doherty, 1989; Masson, Bub, & Warren, 2008; McCloskey, Klatzky, & Pellegrino, 1992; Scorolli, Borghi, & Glenberg, 2009; Scorolli & Borghi, 2007; Zwaan & Taylor, 2006). For example, Tucker and Ellis (2004) asked participants to classify pictures of objects into artifacts or natural kinds. Participants responded by squeezing a device that they held in either a full-hand grip or a precision grip (between thumb and index finger). The pictures were of objects that afforded a full-hand grip or a precision grip. Tucker and Ellis showed that responses were faster when the response grip and the object's affordance matched than when they mismatched. In addition to behavioral effects, researchers have shown activation of the premotor cortex when participants see or mentally represent objects (Chao & Martin, 2000; Creem-Regehr, Dilda, Vicchrilli, Federer, Lee, 2007; Gerlach, Law, & Paulson, 2002; Martin, Haxby, Lalonde, Wiggs, & Ungerleider, 1995; Postle, McMahon, Ashton, Meredith, & Zubicaray, 2008; Rueschemeyer, Van Rooij, Lindemann, Willems, & Bekkering, 2010). These findings suggest that mental representations of semantic information may, at least partly, consist of motor simulations.

The phonological loop in Baddeley and Hitch's (1974) model for working memory could be considered a mechanism of motor simulation of verbal materials. Some researchers have suggested an additional type of slave system that stores and maintains motor affordances. This system would be important for imitation of movements (Smyth & Pendleton, 1989) and interactions with objects (Mecklinger, Gruenewald, Weiskopf, Doeller, 2004;

This article was published Online First May 21, 2012.

This research was supported by a grant from the Netherlands Organization for Scientific Research to Diane Pecher. I am grateful to Axel Mecklinger and Christin Gruenewald for providing the materials from their studies; to Christiaan Tieman and Jeffrey de Man for technical support; and to Klaus Oberauer, Michael Masson, Aljosja Jacobs, Kalinka Timmer, Kim Melchior, Mario de Jonge, Kevin van Schie, Adinda Oerlemans, Michel Quack, and René Zeelenberg for helpful discussions, assistance, and useful comments on an earlier version of this article.

Correspondence concerning this article should be addressed to Diane Pecher, Department of Psychology T12-33, Erasmus University, Postbus 1738, 3061 DZ Rotterdam, the Netherlands. E-mail: pecher@fsw.eur.nl

Woodin & Heil, 1996). During activities such as preparing a meal or fixing a bike people often perform actions on objects, for example grasping or rotating. The role of working memory in such cases is to remember the shape and location of those objects. Whereas location information is stored and maintained by the visuospatial slave system, this type of information needs to be distinguished from body configuration information as would be needed for actions on objects such as grasping (Smyth & Pendleton, 1989; Woodin & Heil, 1996). As the research by Tucker and Ellis (1998, 2004; see also Bub et al., 2003) showed, visual perception of objects results in activation of their affordances. These affordances are then developed into motor plans, and these must be kept active in memory until the action can be executed. This could be done by the third slave system, which performs these motor simulations.

Note that this proposal contrasts with working memory models proposed by Meyer and Kieras (1997) and Schneider (1999), who both also argued for a motor component. In Meyer and Kieras' model, however, the motor systems for ocular, vocal, and manual responses are viewed as peripheral systems that execute task related responses but have no role in working memory maintenance. Similarly, Schneider proposed that visual-spatial information in working memory activates motor programs, but these motor programs are not part of working memory itself.

Other researchers have suggested that working memory is not a separate system or set of systems but rather the result of activations in long-term memory (Cowan, 1988, 1999; Hazy, Frank, & O'Reilly, 2006; Oberauer, 2002; Postle, 2006). Cowan (1998, 1999) proposed a hierarchical model of working memory, in which a subset of information in long-term memory is activated and a subset of the activated information is attended to. Hazy et al. (2006) likewise proposed that working memory should not be viewed as a separate store but as a controlled activation mechanism that activates information in long-term memory. In their view, long-term memory is distributed throughout the cortex. I do not discuss these and similar models in detail here but only mention that in these models, any long-term memory component, information type, or subsystem could potentially contribute to working memory performance. Therefore, these models are consistent with the idea that motor simulations are part of working memory, although they do not necessarily predict a role for motor simulations, because that depends on the specifics of long-term memory.

Research shows that movements can be maintained in working memory and are supported by a nonspatial motor system. Smyth and Pendleton (1989) showed that working memory span for sequences of hand configurations was decreased by a concurrent task that changed the hand configuration (squeezing a tube) but was not affected by a spatial tapping task. Similarly, Rossi-Arnaud, Cortese, and Cestari (2004) showed that working memory for ballet moves was decreased by a concurrent arm movement task but not by visual interference. The relation between working memory for movements and action performance was further investigated by Woodin and Heil (1996), who showed that *spatial* aspects of rowing were disrupted more by a spatial working memory load than by a body configuration memory load, while the *configuration* aspects of rowing showed the opposite pattern. Thus, these results indicate that working memory for movements is not supported by the visuospatial sketchpad but, rather, suggest the involvement of the motor system in working memory for movements. Moreover, spatial and configural information might be maintained by separate mechanisms.

Recently, researchers have suggested an additional role for the motor system in maintenance of *visual* information in working memory. The idea that motor simulation is part of visual working memory is based on brain imaging studies that showed activation in the ventral premotor cortex during visual working memory tasks (Linden, 2007; Mecklinger et al., 2004; Owen, Evans, & Petrides, 1996). Of particular interest is a study by Mecklinger et al. (2004). In their study, participants kept pictures of objects in memory while their brains were being scanned. The researchers found larger BOLD signal responses in the ventral premotor cortex when the stimuli depicted manipulable objects (*comb, scissors*) than when they depicted nonmanipulable objects (*chimney, traffic light*). People frequently perform actions with manipulable objects but not with nonmanipulable objects. The motor simulations of such actions with manipulable objects can be maintained in working memory, supporting performance, whereas this is unlikely to play a role when participants keep nonmanipulable objects in memory. Therefore, differential activation in the ventral premotor cortex between the two types of objects seems to suggest that motor simulations support visual working memory for objects.

Activation of the ventral premotor cortex during working memory for manipulable objects is consistent with similar findings in semantic memory tasks as reviewed above. In order to broaden the scope of this finding the present study investigated the role of motor simulation for visual working memory more directly by using interference tasks. Interference is a very common method to investigate working memory. Generally speaking, if a researcher wishes to know whether a certain type of function supports working memory, he or she has participants perform a working memory task and, at the same time, another task that uses that particular system. Interaction between the concurrent task and working memory performance provides evidence that the same function supports the two tasks. Using this interference methodology, researchers have obtained evidence that working memory for verbal materials is supported by subvocal articulation (e.g., Baddeley et al., 1975). In a similar way have researchers investigated visuospatial working memory (Baddeley, 1986; Dean, Dewhurst, & Whittaker, 2008; Hale, Myerson, Rhee, Weiss, & Abrams, 1996; Quinn & McConnell, 1996) and working memory for movements (Rossi-Arnaud et al., 2004; Smyth, Pearson, & Pendleton, 1988; Smyth & Pendleton, 1989; Woodin & Heil, 1996).

In the present series of experiments, participants performed a visual working memory task on photographs of manipulable and nonmanipulable objects. They viewed one or more briefly presented items that had to be maintained in working memory for a few seconds. Following the maintenance period, the test item was presented, and participants indicated whether the item was a *target* (same as study item) or *distracter* (different from study item). The first experiment mimicked that of Mecklinger et al. (2004) as closely as possible, with one exception. In their study, a test trial was either the same picture (old) or the mirror image of that picture (new). Mecklinger et al. used a large number of different pictures for the working memory task. Consequently, on most trials participants studied a picture that they had not seen before. At test they needed to distinguish the targets, which they now had seen, from the distracters (the mirror image of the study picture), which they had not seen before. It has often been noted (e.g., Greene, 1996) that both long-term and working memory may contribute to performance in working memory tasks. Presumably, when participants studied a picture they stored information both in working memory and in long-term memory. Therefore, during test, either type of information could be used to distinguish targets and distracters. To eliminate contributions from long-term memory, most working memory studies use a small set of items (e.g., digits, letters, visual matrices) that are repeated many times. This way proactive interference will greatly impair long-term memory retrieval so that performance critically depends on keeping the current information in working memory. Therefore, in the present study only a small set of pictures was used. Before the experiment proper, participants were familiarized with all items so that participants could not distinguish between targets and distracters on the basis of information from long-term memory.

During some blocks of the experiment, participants performed concurrent tasks. One of the concurrent tasks was a motor task that required changing the configuration of the hand and thus was expected to interfere with motor patterns for grasping or manipulating objects but did not involve a visual or spatial component. A second concurrent task was a verbal interference task, which should prevent participants from adopting a verbal labeling strategy. If motor affordances support working memory, a concurrent motor task should interfere more with memory for manipulable objects than nonmanipulable objects, because manipulable objects have more motor affordances than nonmanipulable objects. It is possible that participants coded the photographs by verbal label or that they would resort to such verbal labeling when the use of affordances was disrupted. If participants used a verbal strategy, motor task interference might show up more strongly when there is also a concurrent verbal task than when there is no concurrent verbal task.

To investigate whether the concurrent motor task did interfere with activation of affordances, a pilot experiment was conducted. In the motor interference task participants made a fist with both hands; stretched their fingers one by one (but simultaneously for both hands), starting with their thumbs, until their hands were completely opened; and then made two fists again. This task was designed to interfere maximally with motor actions for grasping objects. Using both hands for the motor task caused full overlap between real and mental action in terms of effectors involved. None of the movements in the motor task was congruent with a grasping action, however, and therefore could not be used to support the mental action. In fact, it would have been impossible to actually grasp any of the objects while simultaneously performing the motor task.

In the pilot experiment, participants performed two tasks on photographs of objects. Both tasks were performed with and without motor interference. One task, grip decision, critically depended on activation of motor affordances. In this task, participants decided whether the object shown in the photograph should be grasped with a precision grip (between thumb and index finger) or with a power grip (using the whole hand). The other task, animacy decision, should rely less on affordances. In this task participants decided whether the photograph showed an animal or not. To reduce the likelihood that affordances would still play a role in this task, all nonanimal photographs showed objects that were very low in manipulability.

## Pilot Experiment

### Method

**Participants.** Twenty-six students at the Erasmus University Rotterdam participated for course credit.

**Materials.** Two sets of 100 pictures each were used. The pictures were color photographs of objects against a white background. The grip decision set consisted of 50 precision grip objects (e.g., *match, pea*) and 50 power grip objects (e.g., *soda can, cucumber*). The animacy decision set consisted of 50 animals (e.g., *cow, mosquito*) and 50 nonanimals (e.g., *windmill, antenna*). For each participant, items were randomly assigned to the interference and no-interference condition with the restriction that both conditions had 25 items of each type and items were not repeated.

A regular PC and monitor were used for stimulus presentation. Two foot pedals were attached to an E-prime response box for response collection as had been done reliably in a prior study (van Dantzig, Pecher, Zeelenberg, & Barsalou, 2008). An online metronome was run at 120 beats per minute on a second PC.

**Procedure.** Participants were tested individually in a quiet room with the experimenter present. The experiment started with instructions for the motor interference task. In the motor interference task participants made a fist with both hands, stretched their fingers one by one (but simultaneously for both hands), starting with their thumbs, until their hands were completely opened, and then made two fists again. They were instructed to make one movement on each metronome beat. In the animacy decision task participants were instructed to press the right foot pedal if the photograph showed an animal and the left foot pedal if the photograph showed a nonanimal. In the grip decision task participants were instructed to press the right foot pedal if the object was usually grasped between thumb and index finger and left foot pedal if the object was usually grasped with the full hand. A trial consisted of presentation of a photograph until the participant responded by pressing a foot pedal. If the response was incorrect, error feedback was displayed for 1,000 ms. Between trials was a 1,000-ms interval.

Each task consisted of two blocks of 50 trials, followed by a self-paced break. The first four trials of each block were treated as practice trials. During one block the participant performed the concurrent motor task; during the other block the participant performed no concurrent task. The order of tasks and blocks within tasks was counterbalanced between participants.

### Results

Reaction times (RTs) were excluded if the response was incorrect (3.7% of all RTs) or if the reaction time deviated more than three standard deviations from the participant's condition mean (2.3% of the correct RTs). The mean reaction times are presented in Table 1. Motor interference had a larger effect in the grip decision task than in the living decision task, $F(1, 27) = 8.36$, $p < .05$, partial $\eta^2 = .24$. The error rates were low and did not show such interaction ($F < 1$). Because the RTs in the grip decision task were longer than in the living decision task and because the interaction did not cross over one should be a bit cautious to interpret this interaction (Loftus, 1978; Wagenmakers, Krypotos, Criss, & Iverson, 2012). Wagenmakers et al. (2012) recommended that researchers should investigate the robustness of the effect by

Table 1
*Mean Reaction Times in Milliseconds and Standard Errors in the Pilot Experiment*

| Variable | Grip decision | | Living decision | |
|---|---|---|---|---|
| | *M* | *SE* | *M* | *SE* |
| No interference | 837 | 46 | 703 | 28 |
| Motor interference | 1,077 | 54 | 839 | 41 |
| Interference effect | 239 | | 136 | |

using a range of transformations. Following this advice analyses of the data after three transformations were performed. The proportional increase in RT due to motor interference was larger in grip decision than living decision (.31 vs. .20), $t(27) = 1.83$, $p = .078$. Analysis of logRT showed the interaction, $F(1, 27) = 3.88$, $p = .059$, but with analysis of 1/RT the interaction was no longer significant, $F(1, 27) = 2.30$, $p = .14$. Drawing conclusions based on transformed data is quite complicated, because one has to make assumption about the component processes that contribute to RT and how each of these might be affected by the manipulation. Nevertheless, the interaction effect in the present case seems to be reasonably robust. In addition to the interaction, the main effects of task and motor interference were also significant, $F(1, 27) = 37.80$, $p < .01$, partial $\eta^2 = .58$, and $F(1, 27) = 60.26$, $p < .05$, partial $\eta^2 = .69$, respectively. The main effect of motor interference indicates that participants were somewhat distracted by performing a secondary task.

Thus, the effect of the motor task was much larger in the grip decision task than in the living decision task. Since grip decision relies much more on object affordances than living decision this interaction effect indicates that the motor task interfered specifically with motor affordances.

## Experiment 1

### Method

**Participants.** Twenty-six students at the Erasmus University Rotterdam (Rotterdam, the Netherlands) participated for course credit.

**Materials.** A set of 24 pictures was used for the working memory task. The pictures were color photographs of objects against a white background. The photographs were selected from or similar to those used by Gruenewald (2002) and Mecklinger et al. (2004). Any letters or numbers on the objects were removed by digital editing. In a pilot study a larger set of photographs were rated on manipulability and object frequency on 7-point scales by a different group of participants. Twelve photographs from the current set were rated high on manipulability (*binoculars, table tennis racket, corkscrew, pliers, pepper shaker, correction fluid bottle, hand mirror, calculator, comb, iron* [*appliance*], *soup ladle, door knob*, $M = 5.4$, range = 5.1–5.9), and the other 12 were rated as low on manipulability (*parakeet, sheep, frog, bird house, chicken, painting, dog, chimney, plant, office building, road sign, emergency sign*, $M = 2.1$, range = 1.6 – 2.6).[1] The two sets of photographs did not differ in mean object frequency ratings (4.0 and 4.1).

A regular PC and monitor were used for stimulus presentation. Two foot pedals were attached to an E-prime response box for response collection. An online metronome was run at 120 beats per minute on a second PC.

**Procedure.** Participants were tested individually in a quiet room with the experimenter present. The experiment started with presentation of all photographs for 3,000 ms each in random order to familiarize the participants with all stimuli. This familiarization phase was followed by instructions for the motor interference task and the verbal interference task. The motor interference task was the same as used in the pilot experiment. In the verbal interference task participants repeated a series of four nonsense syllables (*bah-doh-ree-su*) at a pace of one syllable per metronome beat. Then the instructions for the working memory task were given. A trial in the memory task started with presentation of a photograph for 200 ms, followed by a blank screen for 5,000 ms. Then a second photograph was presented, and participants decided whether the photograph was the same or mirror image as the first photograph. They responded *same* by pressing the right foot pedal and *different* by pressing the left foot pedal. The response was followed by feedback for 500 ms. Feedback consisted of the messages "*GOED*" (*correct*) for correct responses, "*FOUT*" (*incorrect*) for incorrect responses, and "*TE LAAT*" (*too late*) for responses slower than 4,000 ms. After a 750 ms ISI the next trial started. A practice block of 48 trials was given first, followed by four blocks of 96 trials each. During a block none, only motor, only verbal, or both interfering tasks were performed. The order of interference conditions was counterbalanced between participants. In the experimental blocks each photograph was presented twice in its original orientation and twice in mirror image as the study stimulus, and each version was followed once by a target and once by a distracter. In the practice block these numbers were halved. The order of stimuli was randomized for each block and participant. After 48 trials there was a self-paced break.

### Results and Discussion

For this and all subsequent experiments the proportions of *same* responses to the test stimuli were calculated for each condition for each participant. Hits (*same* responses to targets) and false alarms (*same* responses to distracters) were used to calculate $d'$ values.[2] Hits and false alarms are shown in Table 2. Figure 1 shows the average $d'$ values for each condition. If motor affordances play a role in working memory, performance for manipulable objects should be affected more by motor interference than performance

[1] Note that the nonmanipulable list included animals, whereas the manipulable list did not. Because readers might worry that this difference could have affected the results I did a second analysis of the data from Experiments 1 and 2 after removing the data from the five animal objects and from five high manipulable objects that were matched on object frequency. The results for the remaining items still showed no interactions between object manipulability and motor interference. It should be noted, however, that removing almost half of the data has a negative effect on power. For Experiments 3–5 I could not do a similar analysis because animate and inanimate objects were mixed on most low-manipulability trials. Given these limitations, it seems that object animacy did not affect the results.

[2] A measure of memory sensitivity or strength that controls for a participant's bias to give a particular response.

Table 2
*Mean Hit and False Alarm Rates (With Standard Errors of the Mean) in Experiments 1–5*

| Variable | No verbal interference: Manipulable Hits | No verbal interference: Manipulable False alarms | No verbal interference: Nonmanipulable Hits | No verbal interference: Nonmanipulable False alarms | Verbal interference: Manipulable Hits | Verbal interference: Manipulable False alarms | Verbal interference: Nonmanipulable Hits | Verbal interference: Nonmanipulable False alarms |
|---|---|---|---|---|---|---|---|---|
| | | | | Experiment 1 | | | | |
| No motor interference | .909 (.023) | .042 (.015) | .917 (.020) | .050 (.020) | .857 (.024) | .072 (.014) | .854 (.021) | .063 (.012) |
| Motor interference | .837 (.022) | .034 (.007) | .888 (.018) | .058 (.011) | .805 (.018) | .090 (.017) | .824 (.021) | .090 (.018) |
| | | | | Experiment 2 | | | | |
| No motor interference | .933 (.014) | .130 (.020) | .936 (.014) | .122 (.022) | .886 (.028) | .226 (.033) | .893 (.021) | .189 (.023) |
| Motor interference | .880 (.027) | .213 (.032) | .888 (.017) | .210 (.032) | .865 (.018) | .306 (.033) | .865 (.019) | .228 (.032) |
| | | | | Experiment 3 | | | | |
| No motor interference | .722 (.031) | .185 (.028) | .775 (.029) | .131 (.023) | .559 (.033) | .299 (.033) | .557 (.033) | .218 (.029) |
| Motor interference | .650 (.032) | .256 (.029) | .656 (.029) | .204 (.020) | .549 (.028) | .321 (.026) | .588 (.035) | .295 (.027) |
| | | | | Experiment 4 | | | | |
| No motor interference | .806 (.030) | .146 (.017) | .859 (.023) | .095 (.019) | .606 (.030) | .303 (.035) | .625 (.031) | .319 (.030) |
| Motor interference | .756 (.026) | .232 (.030) | .809 (.028) | .252 (.033) | .585 (.025) | .380 (.035) | .612 (.030) | .397 (.037) |
| | | | | Experiment 5 | | | | |
| | No visual interference | | | | Visual interference | | | |
| No other interference | .774 (.030) | .119 (.014) | .810 (.032) | .119 (.018) | .653 (.033) | .290 (.026) | .677 (.029) | .228 (.026) |
| Motor interference | | | | | .606 (.036) | .336 (.030) | .622 (.026) | .310 (.032) |
| Verbal interference | | | | | .549 (.037) | .311 (.034) | .574 (.038) | .320 (.031) |

for nonmanipulable objects. As can be seen in the figure, however, motor interference did not have a larger effect on performance for manipulable than nonmanipulable objects ($F < 1$), nor was there a three-way interaction with verbal interference ($F < 1$). Because the ANOVA *p* values cannot be used to provide evidence in favor of the null hypothesis, I further analyzed the interaction effects between manipulability and motor interference using the Bayesian information criterion (BIC; see Masson, in press; Wagenmakers, 2007). The posterior probability favoring the null hypothesis was $p_{BIC}(H_0|D) = .83$ for the two-way interaction between manipulability and motor interference and $p_{BIC}(H_0|D) = .79$ for the three-way interaction between manipulability, motor interference, and verbal interference. BIC values between .75 and .95 should be considered positive evidence for a hypothesis (Masson, in press; Wagenmakers, 2007). Thus, there is little evidence for a role of motor affordances. Performance was better overall for nonmanipulable than manipulable objects, $F(1, 25) = 20.33$, $p < .01$, partial $\eta^2 = .45$. The interference tasks caused decreases in performance: $F(1, 25) = 24.74$, $p < .01$, partial $\eta^2 = .50$ for motor interference and $F(1, 25) = 15.74$, $p < .01$, partial $\eta^2 = .39$ for verbal interference.

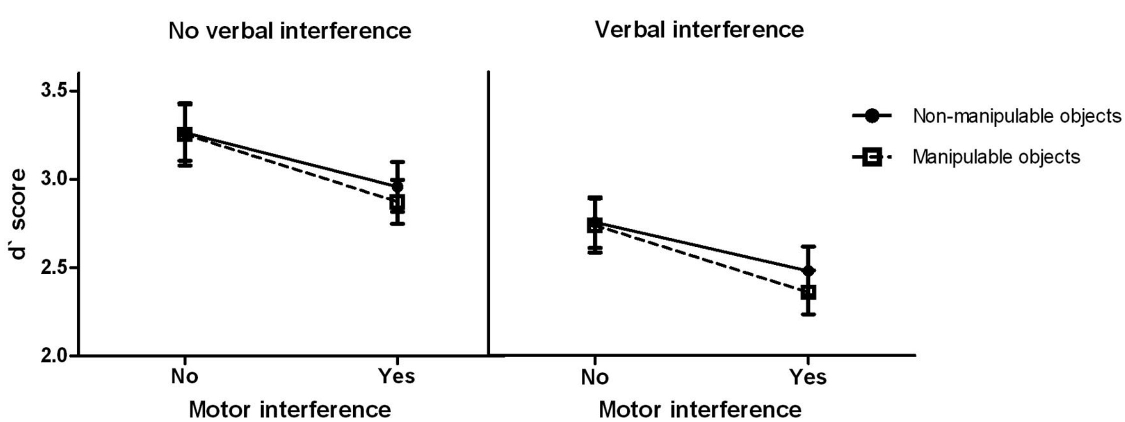


*Figure 1.* Mean *d′* scores in recognition memory for photographs of manipulable and nonmanipulable objects in Experiment 1. Participants studied one item at a time; distracters were mirrored images of the study item. Error bars represent standard error of the mean.

The design of the present experiment was very similar to the one that was used in the fMRI study that obtained premotor cortex activation for manipulable objects but not for nonmanipulable objects (Mecklinger et al., 2004). In that study participants also decided whether the test stimulus was the same or mirror image. Therefore, I expected that motor interference would affect memory for manipulable objects more than for nonmanipulable objects. It is possible, however, that participants did not pay much attention to the entire object but, rather, focused on specific visual features that would allow them to distinguish the two orientations of the photograph. Several studies have shown, however, that motor affordances play a role when participants process the identity of objects. This might be more likely when the task requires comparison of different objects so that identity is diagnostic. Therefore, in the next experiment distracters were photographs of different objects.

## Experiment 2

### Method

**Participants.** Twenty-six students at the Erasmus University Rotterdam participated for course credit. None had participated in Experiment 1.

**Materials, apparatus, and procedure.** Experiment 2 was identical to Experiment 1 except that on distracter trials a different photograph was presented. In a block each photograph was used four times as study stimulus, two times as target (*same* test stimulus), and two times as distracter (*different* stimulus). Distracters were randomly paired with study stimuli from the same manipulability condition.

### Results and Discussion

Figure 2 shows the average $d'$ values for each condition. As in Experiment 1, there was no interaction between manipulability and motor interference on $d'$ values, $F(1, 25) < 1$. The three-way interaction between manipulability, motor interference, and verbal interference also was not significant ($F < 1$). The posterior probability favoring the null hypothesis was $p_{BIC}(H_0|D) = .79$ for the two-way interaction between manipulability and motor interference and $p_{BIC}(H_0|D) = .83$ for the three-way interaction between manipulability, motor interference, and verbal interference. Thus, the present results provide positive evidence for the null hypothesis. Both types of interference affected performance overall: $F(1, 25) = 30.60$, $p < .01$, partial $\eta^2 = .55$ for motor interference and $F(1, 25) = 22.35$, $p < .01$, partial $\eta^2 = .47$ for verbal interference. These results show that the interference manipulation was quite strong. Performance was not different between manipulable and nonmanipulable objects ($F < 1$).

The concurrent motor task did not interfere more with memory for manipulable than nonmanipulable objects. Such a difference was expected to occur if participants used motor affordances to keep the photographs in working memory. A concurrent motor task occupies the motor system and therefore should make it harder to activate motor affordances for the objects in the photographs. Because manipulable and nonmanipulable objects differ in motor affordances, the effect of motor interference should have interacted with manipulability. The main effects of interference indicated that the interference manipulations were strong enough and, thus, that the experiment had enough power to detect the expected interaction. Moreover, the Bayesian analyses provided positive evidence for the absence of an interaction. It is possible, however, that the memory task was fairly easy and that participants had enough resources to compensate for the effect of motor interference. In the next experiments I therefore increased the difficulty of the memory task to investigate whether increasing task difficulty might reveal a role for motor affordances in working memory. In Experiment 3 difficulty was increased by increasing the memory load from one to four stimuli.

## Experiment 3

### Method

**Participants.** Twenty-seven students at the Erasmus University Rotterdam participated for course credit. None had participated in the previous experiments.

**Materials, apparatus, and procedure.** Experiment 3 was identical to Experiment 2 except that four photographs were shown

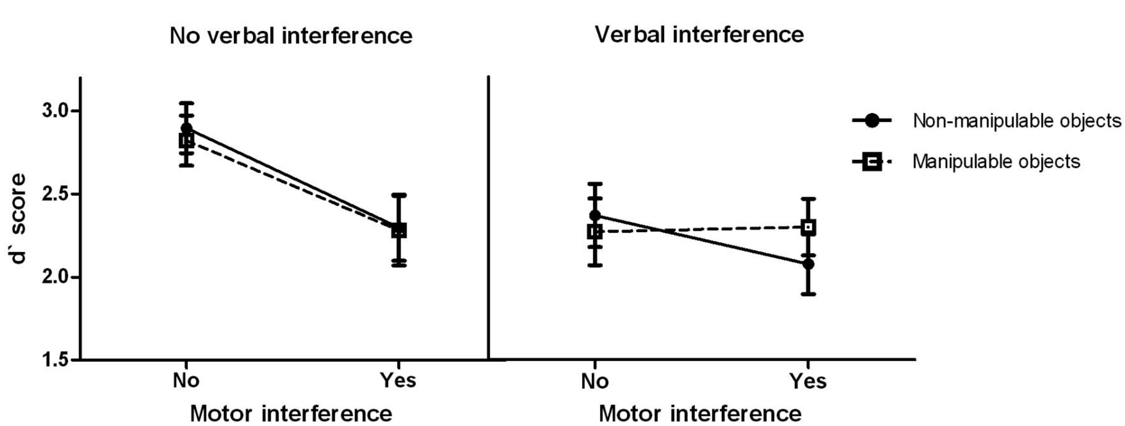


*Figure 2.* Mean $d'$ scores in recognition memory for photographs of manipulable and nonmanipulable objects in Experiment 2. Participants studied one item at a time; distracters were photographs of different objects. Error bars represent standard error of the mean.

on study trials, one in each quadrant of the computer screen, for 300 ms, followed by a retention interval of 4,500 ms. At test, only one photograph was shown, and participants decided whether the test photograph had been presented at study. On each trial, all photographs were either of manipulable or nonmanipulable objects and were selected in a semirandom way. In each block, each photograph was presented 16 times as a study item: two times as a target and two times as distracter.

## Results and Discussion

Figure 3 shows the average $d'$ values for each condition. As can be seen in Figure 3, motor interference did not have a larger effect on performance for manipulable than nonmanipulable objects, on the contrary, motor interference had a larger effect on performance for nonmanipulable objects than manipulable objects, $F(1, 26) = 5.80$, $p < .05$, partial $\eta^2 = .18$. There was no three-way interaction with verbal interference ($F < 1$). The posterior probability favoring the null hypothesis was $p_{\mathrm{BIC}}(\mathrm{H}_0|\mathrm{D}) = .26$ for the two-way interaction between manipulability and motor interference. This value indicates that there is evidence against the null hypothesis, consistent with the low $p$ value. However, the direction of the interaction was opposite from the one that was predicted. The posterior probability favoring the null hypothesis was $p_{\mathrm{BIC}}(\mathrm{H}_0|\mathrm{D}) = .80$ for the three-way interaction between manipulability, motor interference, and verbal interference. Performance was better overall for nonmanipulable than manipulable objects, $F(1, 26) = 26.03$, $p < .01$, partial $\eta^2 = .50$. The interference tasks caused decreases in performance: $F(1, 26) = 24.53$, $p < .01$, partial $\eta^2 = .49$ for motor interference and $F(1, 26) = 71.00$, $p < .01$, partial $\eta^2 = .73$ for verbal interference.

Thus, in the present experiment motor interference decreased working memory performance for nonmanipulable objects more than performance for manipulable objects. It is not clear why performance for nonmanipulable objects would be affected more by motor interference than performance for manipulable objects, but it is unlikely that this finding indicates a role of motor simulations in working memory for visual information. If participants used motor simulations to maintain information in working memory, they should have done so more for manipulable objects than for nonmanipulable objects, because manipulable objects have motor affordances, whereas nonmanipulable objects do not. Therefore, these results do not provide evidence for the use of motor simulations for visual working memory.

One might wonder what information participants used to keep items in memory. So far, there is little evidence for a role of motor affordances. It is possible that participants used verbal labels for the objects, but when such a strategy was prevented by a concurrent verbal task, there was still no evidence for motor affordances. Next, I attempted to increase the need for participants to involve the motor system during memory maintenance by decreasing their reliance on visual information. Visual working memory (i.e., memory for photographs as in the present experiments) probably relies also on visual information, and perhaps motor simulations only have a tiny role. By reducing visual information the role of motor simulation may become more pronounced. In Experiment 4 visual information was reduced by presenting object names instead of photographs.

# Experiment 4

## Method

**Participants.** Twenty-six students at the Erasmus University Rotterdam participated for course credit. None had participated in the previous experiments.

**Materials, apparatus, and procedure.** Experiment 4 was identical to Experiment 3 except that the photographs were replaced by the Dutch names[3] of the objects both during study and test. To allow participants to read the four names the study trial duration was increased to 1,500 ms.

## Results and Discussion

Figure 4 shows the average $d'$ values for each condition. As can be seen in Figure 4, motor interference did not have a larger effect on performance for manipulable than nonmanipulable object names, $F(1, 25) = 1.75$, $p = .20$. There was no three-way interaction with verbal interference, $F(1, 25) = 2.06$, $p = .16$. The posterior probability favoring the null hypothesis was $p_{\mathrm{BIC}}(\mathrm{H}_0|\mathrm{D}) = .68$ for the two-way interaction between manipulability and motor interference, and $p_{\mathrm{BIC}}(\mathrm{H}_0|\mathrm{D}) = .65$ for the three-way interaction between manipulability, motor interference, and verbal interference. These values provide weak evidence for the null hypothesis. Performance was better overall for nonmanipulable than manipulable objects, $F(1, 25) = 7.53$, $p < .05$, partial $\eta^2 = .23$. The interference tasks caused general decreases in performance: $F(1, 25) = 22.30$, $p < .01$, partial $\eta^2 = .47$ for motor interference and $F(1, 25) = 90.65$, $p < .01$, partial $\eta^2 = .78$ for verbal interference.

The interfering effect of the verbal task was very high in this experiment, consistent with the verbal nature of the stimuli. When there was concurrent verbal interference, participants might have relied more on sensory-motor representations of the objects rather than the object names. This prediction was not supported by an interaction between manipulability and motor interference on performance, however, so again there is no evidence for a role of motor simulations.

In Experiment 5 participants' reliance on visual information was reduced in a different way. During the retention interval a modified version of dynamic visual noise (Quinn & McConnell, 1996) was presented. This visual noise should interfere with maintenance of visual information in working memory (Dean et al., 2008). During the visual noise participants watched a pattern of colored squares that rapidly changed. Most of the time, 50% of the squares changed color at the same time but occasionally all squares changed color at the same time. Participants had to detect such 100% changes. An active task was used because it may cause more

[3] Manipulable objects: *handspiegel (hand mirror), kam (comb), kurkentrekker (corkscrew), pepervaatje (pepper shaker), soeplepel (soup ladle), verrekijker (binoculars), deurklink (door knob), rekenmachine (calculator), strijkijzer (iron), tafeltennisbatje (table tennis racket), knijptang (pliers), tippexflesje (correction fluid bottle).* Nonmanipulable objects: *tekkel (dog), kikker (frog), kip (chicken), wegwijzer (road sign), parkiet (parakeet), kamerplant (plant), kantoorgebouw (office building), nooduitgangbordje (emergency sign), schaap (sheep), schilderij (painting), schoorsteen (chimney), vogelhuisje (bird house).*

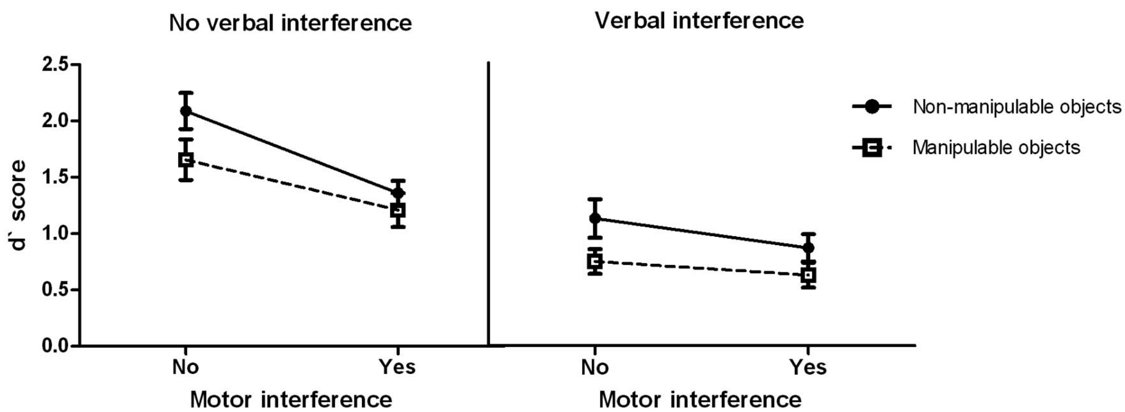


*Figure 3.* Mean $d'$ scores in recognition memory for photographs of manipulable and nonmanipulable objects in Experiment 3. Participants studied four items at a time; distracters were photographs of different objects. Error bars represent standard error of the mean.

interference than merely passive viewing of visual noise (Andrade, Kemps, Werniers, Jon, & Szmalec, 2002).

## Experiment 5

### Method

**Participants.** Twenty-eight students at the Erasmus University Rotterdam participated for course credit. None had participated in the previous experiments.

**Materials, apparatus, and procedure.** Experiment 5 was identical to Experiment 3, with the exception of the interference tasks. During one block participants performed no interfering task, during one block they performed only the visual interfering task, during one block they performed both visual and verbal interfering tasks, and during one block they performed both visual and motor interfering tasks. As the visual interfering task a matrix of 18 × 22 squares, each approximately 1 $cm^2$, in six different colors (from a set of 13 colors) was presented during the 4,500-ms interval between study and test stimuli. The distribution of colors was random with the restriction that there were 66 squares of each color. Every 150 ms, 50% of the squares randomly changed color. Participants watched the matrices in order to detect an occasional 100% change (i.e., all squares changed color at once). This happened randomly on 12 of the 96 trials in a block. Participants pressed the space bar when they noticed the 100% change.

### Results and Discussion

Figure 5 shows the average $d'$ values for each condition. As can be seen in Figure 5, the effect of the different types of interference was similar on performance for manipulable and nonmanipulable object photographs; this was confirmed by the absence of an interaction effect ($F < 1$). Performance was better overall for nonmanipulable than manipulable objects, $F(1, 27) = 5.89$, $p < .05$, partial $\eta^2 = .18$. The interference tasks caused general decreases in performance, $F(3, 81) = 75.27$, $p < .01$, partial $\eta^2 = .74$. Follow-up analyses showed that visual interference decreased performance compared with the no interference condition, $F(1, 27) = 68.07$, $p < .01$, partial $\eta^2 = .72$. The combination of visual

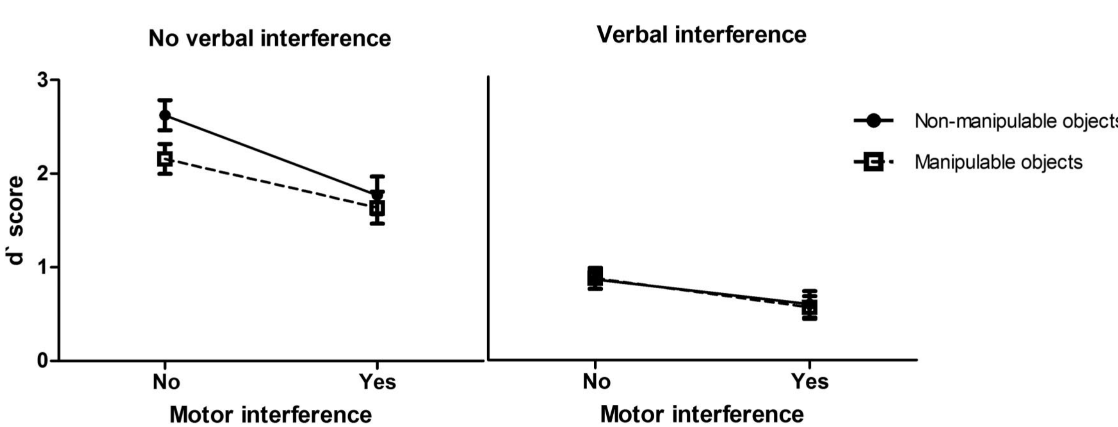


*Figure 4.* Mean $d'$ scores in recognition memory for names of manipulable and nonmanipulable objects in Experiment 4. Participants studied four items at a time; distracters were names of different objects. Error bars represent standard error of the mean.

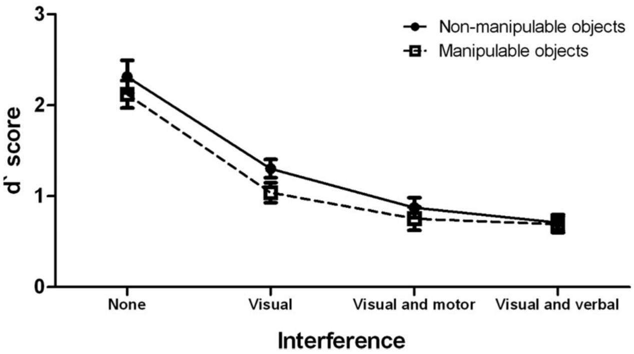


*Figure 5.* Mean $d'$ scores in recognition memory for photographs of manipulable and nonmanipulable objects in Experiment 5. Participants studied four items at a time; distracters were photographs of different objects. Error bars represent standard error of the mean.

and verbal interference resulted in worse performance than visual interference alone, $F(1, 27) = 20.78$, $p < .01$, partial $\eta^2 = .44$, and the combination of visual and motor interference also resulted in worse performance than visual interference alone, $F(1, 27) = 12.33$, $p < .01$, partial $\eta^2 = .31$. None of these effects interacted significantly with manipulability. The posterior probability favoring the null hypothesis was $p_{BIC}(H_0|D) = .83$ for the two-way interaction between manipulability and motor interference. Thus, the Bayesian analysis again provided positive evidence that there was no interaction between manipulability and motor interference.

As in the previous experiments, the interference tasks caused general decreases in performance, but there was no evidence that motor interference had a larger effect on working memory for manipulable than nonmanipulable objects. Thus, as in the previous experiments, there was no evidence that motor simulations play a role in visual working memory.

## General Discussion

In five experiments I tested the idea that the motor system is recruited for visual working memory. Previous fMRI findings (Mecklinger et al., 2004) suggested that visual objects activated a motor program which was then used to maintain the object representation in working memory. Such a mechanism should be disrupted by concurrent motor activity. Therefore, working memory performance should decrease as a result of an interfering motor task, and this effect should be larger for manipulable than nonmanipulable objects. Contrary to this prediction, however, motor interference did not affect memory for manipulable and nonmanipulable objects differently. Increasing the difficulty of the memory task did not change the pattern of results, nor did reducing the availability of visual information. Therefore, these experiments indicate that the motor system is not involved in visual working memory.

In all experiments memory performance was decreased by the concurrent tasks, whether they were motor, verbal, or visual. This finding provides a manipulation check by showing that the tasks were interfering enough to disrupt performance to a significant degree. None of the experiments had conditions in which the reliance on verbal information was manipulated. Thus, there were no conditions within experiments that were expected to differ in how much they would be affected by verbal interference. Therefore, the effect of verbal interference may have occurred because it interfered with articulatory rehearsal or because it interfered with central processing. Likewise, Experiment 5 did not have conditions that were expected to differ in terms of visual processing. The potential reliance on motor affordances was manipulated, however, and the concurrent motor task did not interact with manipulability. This suggests that the observed interference due to the concurrent motor task was general and points to a central attentional bottleneck (e.g., Pashler & Johnston, 1998) as the locus of interference rather than the involvement of the motor system by the memory task.

Although the findings provide evidence that the motor system is not involved in visual working memory, an alternative explanation might be that the concurrent motor task did not interfere with the motor system. This is not very likely, however, because the motor task involved a sequence of six different movements with both hands, which should disrupt processing of hand related actions. The pilot experiment showed that the motor task caused much more interference in a grip decision task than a living decision task, arguably because grip decision relies more on object affordances than living decision. In addition, researchers investigating working memory for movements rather than visual information did obtain interference from comparable interfering motor tasks. For example, when participants were instructed to sequentially tap the top of their head, their shoulders, and their hips with both hands, their performance in a concurrent working memory task for movements decreased (Rossi-Arnaud et al., 2004; Smyth et al., 1988; Woodin & Heil, 1996). Similar interference effects were obtained when participants repeatedly squeezed a rubber tube (Smyth & Pendleton, 1989). The motor interference tasks in these studies were comparable or even slightly easier to the one used in the present study in terms of difficulty. Thus, the motor interference task in the present study would have affected working memory for action.

Another explanation for the present findings might be that manipulable objects do not rely on motor affordances. However, as discussed in the introduction, many other studies have shown that affordances play a role in object processing. In particular, motor interference tasks also interfere with semantic processing of object information, even when the concurrent task is irrelevant for the semantic task. Paulus et al. (2009) showed interference from a hand task (squeezing a ball with the hands) on learning the function of novel objects but no such interference from a foot task (squeezing a ball with the feet). Witt et al. (2010) showed that squeezing a ball in one hand interfered with picture naming if the object on the picture afforded grasping with the occupied hand (e.g., if the handle pointed toward the squeezing hand). Moreover, imaging studies have shown that activation in the ventral premotor cortex during attention for objects overlaps considerably with activation due to hand movement execution (Schubotz & von Cramon, 2003), which indicates that if object processing and motor actions share processing resources, this overlap should be greatest for hand actions. Thus, these findings all support the idea that any support from the motor system in the present working memory task should have been affected by the concurrent motor task. The absence of motor interference therefore suggests that visual working memory is not supported by the motor system.

This conclusion indicates that earlier findings that showed activation of the ventral premotor cortex during visual working memory for manipulable objects (Mecklinger et al., 2004) may be the result of processes other than working memory maintenance. As Mecklinger et al. (2004) also showed premotor activation for manipulable objects during passive viewing and during semantic tasks, it is likely that the premotor activation was related to semantic memory rather than working memory processes. Studies showing motor interference during semantic tasks on manipulable objects further support this idea. Thus, motor affordances seem to play an important role in processing semantic representations but not in working memory for objects.

The discrepancy between previous fMRI data and the present results provide a good illustration of the problems with reverse inferencing (Aue, Lavelle, & Cacioppo, 2009; Page, 2006; Poldrack, 2008) and the correlational nature of fMRI research (Van Horn & Poldrack, 2009). When researchers observe brain activation in overlapping areas between two tasks, they tend to conclude that the tasks must share a functional component. Such a conclusion is only valid, however, if brain regions are involved in only one particular function, and we know this is not the case. When researchers still draw conclusions about function from activation in certain brain areas, they are committing the logical fallacy of affirming the consequent. Moreover, instead of being the cause of behavior, activation of a brain area might just as likely be the result or a mere side-effect of behavior (Mahon & Caramazza, 2008). Therefore, activation of a brain area that is also involved in motor tasks is not sufficient to conclude that motor simulations *support* working memory.

In Baddeley's working memory model (Baddeley, 1986, 2003; Baddeley & Hitch, 1974) there is a clear separation between working memory and long-term memory. Visual working memory, such as used in the tasks in the present study, is most likely supported by the visuospatial sketchpad in which the visual properties of the to be remembered stimuli are maintained. This explanation is consistent with the idea that semantic information, such as an object's affordances, does not play a role in visual working memory. The present results are also consistent with some alternative models of working memory. For example, Schneider (1999) proposed a model of working memory in which object information is kept in a visual-spatial workspace. This information includes shape and location of the object and can be used to activate a spatial motor program. In his model, however, the motor program is external to working memory. The present data are consistent with Schneider's model and might also explain why researchers have found activation of the ventral premotor cortex during working memory tasks. Because the motor program is not part of working memory itself, motor interference should not affect working memory performance in tasks that do not require participants to perform actions with the objects. At the same time, however, participants may still activate such motor programs because shape and location information are available.

To conclude, the present study did not find any evidence for a role of motor affordances in visual working memory. These results cast doubt on the involvement of the motor system in visual working memory. They also demonstrate that researchers should use caution before drawing conclusions about cognitive mechanisms from correlational neuroimaging data.

## References


Andrade, J., Kemps, E., Werniers, Y., Jon, M., & Szmalec, A. (2002). Insensitivity of visual short-term memory to irrelevant visual information. *Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 55,* 753–774. doi:10.1080/02724980143000541

Aue, T., Lavelle, L. A., & Cacioppo, J. T. (2009). Great expectations: What can fMRI research tell us about psychological phenomena? *International Journal of Psychophysiology, 73,* 10–16. doi:10.1016/j.ijpsycho.2008.12.017

Baddeley, A. D. (1986). *Working memory.* New York, NY: Oxford University Press.

Baddeley, A. D. (2003). Working memory: Looking back and looking forward. *Nature Reviews Neuroscience, 4,* 829–839. doi:10.1038/nrn1201

Baddeley, A. D., & Hitch, G. (1974). Working memory. *Psychology of Learning and Motivation: Advances in Research and Theory, 8,* 47–89.

Baddeley, A. D., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning & Verbal Behavior, 14,* 575–589. doi:10.1016/S0022-5371(75)80045-4

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences, 22,* 577–609.

Borghi, A. M., & Riggio, L. (2009). Sentence comprehension and simulation of object temporary, canonical and stable affordances. *Brain Research, 1253,* 117–128. doi:10.1016/j.brainres.2008.11.064

Bub, D. N., Masson, M. E. J., & Bukach, C. M. (2003). Gesturing and naming: The use of functional knowledge in object identification. *Psychological Science, 14,* 467–472. doi:10.1111/1467-9280.02455

Bub, D. N., Masson, M. E. J., & Cree, G. S. (2008). Evocation of functional and volumetric gestural knowledge by objects and words. *Cognition, 106,* 27–58. doi:10.1016/j.cognition.2006.12.010

Chao, L. L., & Martin, A. (2000). Representation of manipulable man-made objects in the dorsal stream. *NeuroImage, 12,* 478–484. doi:10.1006/nimg.2000.0635

Conrad, R., & Hull, A. J. (1964). Information, acoustic confusion and memory span. *British Journal of Psychology, 55,* 429–432. doi:10.1111/j.2044-8295.1964.tb00928.x

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychological Bulletin, 104,* 163–191. doi:10.1037/0033-2909.104.2.163

Cowan, N. (1999). An embedded processes model of working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 62–101). Cambridge, England: Cambridge University Press.

Creem-Regehr, S. H., Dilda, V., Vicchrilli, A. E., Federer, F., & Lee, J. N. (2007). The influence of complex action knowledge on representations of novel graspable objects: Evidence from functional magnetic resonance imaging. *Journal of the International Neuropsychological Society, 13,* 1009–1020. doi:10.1017/S1355617707071093

Dean, G. M., Dewhurst, S. A., & Whittaker, A. (2008). Dynamic visual noise interferes with storage in visual working memory. *Experimental Psychology, 55,* 283–289. doi:10.1027/1618-3169.55.4.283

Ellis, R., & Tucker, M. (2000). Micro-affordance: The potentiation of components of action by seen objects. *British Journal of Psychology, 91,* 451–471. doi:10.1348/000712600161934

Gerlach, C., Law, I., & Paulson, O. B. (2002). When action turns into words. activation of motor-based knowledge during categorization of manipulable objects. *Journal of Cognitive Neuroscience, 14,* 1230–1239. doi:10.1162/089892902760807221

Glenberg, A. M. (1997). What memory is for. *Behavioral and Brain Sciences, 20,* 1–19.

Glenberg, A. M., & Kaschak, M. P. (2002). Grounding language in action. *Psychonomic Bulletin & Review, 9,* 558–565. doi:10.3758/BF03196313

Greene, R. L. (1996). The influence of experimental design: The example of the Brown-Peterson paradigm. *Canadian Journal of Experimental Psychology, 50,* 240–242. doi:10.1037/1196-1961.50.2.240

Gruenewald, C. (2002). *Die rolle motorischer schemata bei der objektpräsentation: Untersuchungen mit funktioneller magnetresonanztomographie* [The role of motor schemata for object representation: fMRI studies] (Doctoral dissertation). Max-Planck-Institut für neuropsychologische Forschung, Leipzig, Germany.

Hale, S., Myerson, J., Rhee, S. H., Weiss, C. S., & Abrams, R. A. (1996). Selective interference with the maintenance of location information in working memory. *Neuropsychology, 10,* 228–240. doi:10.1037/0894-4105.10.2.228

Hazy, T. E., Frank, M. J., & O'Reilly, R. C. (2006). Banishing the homunculus: Making working memory work. *Neuroscience, 139,* 105–118. doi:10.1016/j.neuroscience.2005.04.067

Klatzky, R. L., Pellegrino, J. W., McCloskey, B. P., & Doherty, S. (1989). Can you squeeze a tomato? The role of motor representations in semantic sensibility judgments. *Journal of Memory and Language, 28,* 56–77. doi:10.1016/0749-596X(89)90028-4

Linden, D. E. J. (2007). The working memory networks of the human brain. *Neuroscientist, 13,* 257–267. doi:10.1177/1073858406298480

Loftus, G. R. (1978). On interpretation of interactions. *Memory & Cognition, 6,* 312–319. doi:10.3758/BF03197461

Mahon, B. Z., & Caramazza, A. (2008). A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content. *Journal of Physiology Paris, 102,* 59–70. doi:10.1016/j.jphysparis.2008.03.004

Martin, A., Haxby, J. V., Lalonde, F. M., Wiggs, C. L., & Ungerleider, L. G. (1995). Discrete cortical regions associated with knowledge of color and knowledge of action. *Science, 270,* 102–105. doi:10.1126/science.270.5233.102

Masson, M. E. J. (in press). A tutorial on a practical Bayesian alternative to null-hypothesis significance testing. *Behavior Research Methods.*

Masson, M. E. J., Bub, D. N., & Warren, C. M. (2008). Kicking calculators: Contribution of embodied representations to sentence comprehension. *Journal of Memory and Language, 59,* 256–265. doi:10.1016/j.jml.2008.05.003

McCloskey, B. P., Klatzky, R. L., & Pellegrino, J. W. (1992). Rubbing your stomach while tapping your fingers: Interference between motor planning and semantic judgments. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 948–961. doi:10.1037/0096-1523.18.4.948

Mecklinger, A., Gruenewald, C., Weiskopf, N., & Doeller, C. F. (2004). Motor affordance and its role for visual working memory: Evidence from fMRI studies. *Experimental Psychology, 51,* 258–269. doi:10.1027/1618-3169.51.4.258

Meyer, D. E., & Kieras, D. E. (1997). *Precis to a practical unified theory of cognition and action: Some lessons from EPIC computational models of human multiple-task performance* (EPIC Tech. Rep. No. 8, TR-97/ONR-EPIC-8). Ann Arbor, MI: University of Michigan, Psychology Department.

Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28,* 411–421. doi:10.1037/0278-7393.28.3.411

Owen, A. M., Evans, A. C., & Petrides, M. (1996). Evidence for a two-stage model of spatial working memory processing within the lateral frontal cortex: A positron emission tomography study. *Cerebral Cortex, 6,* 31–38. doi:10.1093/cercor/6.1.31

Page, M. P. A. (2006). What can't functional neuroimaging tell the cognitive psychologist? *Cortex, 42,* 428–443. doi:10.1016/S0010-9452(08)70375-7

Pashler, H., & Johnston, J. C. (1998). Attentional limitations in dual-task performance. In H. Pashler (Ed.), *Attention* (pp. 155–189). Hove, England: Psychology Press/Erlbaum.

Paulus, M., Lindemann, O., & Bekkering, H. (2009). Motor simulation in verbal knowledge acquisition. *Quarterly Journal of Experimental Psychology, 62,* 2298–2305. doi:10.1080/17470210903108405

Poldrack, R. A. (2008). The role of fMRI in cognitive neuroscience: Where do we stand? *Current Opinion in Neurobiology, 18,* 223–227. doi:10.1016/j.conb.2008.07.006

Postle, B. R. (2006). Working memory as an emergent property of the mind and brain. *Neuroscience, 139,* 23–38. doi:10.1016/j.neuroscience.2005.06.005

Postle, N., McMahon, K. L., Ashton, R., Meredith, M., & de Zubicaray, G. I. (2008). Action word meaning representations in cytoarchitectonically defined primary and premotor cortices. *NeuroImage, 43,* 634–644. doi:10.1016/j.neuroimage.2008.08.006

Quinn, J. G., & McConnell, J. (1996). Irrelevant pictures in visual working memory. *Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 49,* 200–215. doi:10.1080/713755613

Rossi-Arnaud, C., Cortese, A., & Cestari, V. (2004). Memory span for movement configurations: The effects of concurrent verbal, motor and visual interference. *Cahiers de Psychologie Cognitive/Current Psychology of Cognition, 22,* 335–349.

Rueschemeyer, S., Lindemann, O., Van Rooij, D., Van Dam, W., & Bekkering, H. (2010). Effects of intentional motor actions on embodied language processing. *Experimental Psychology, 57,* 260–266. doi:10.1027/1618-3169/a000031

Rueschemeyer, S., Van Rooij, D., Lindemann, O., Willems, R. M., & Bekkering, H. (2010). The function of words: Distinct neural correlates for words denoting differently manipulable objects. *Journal of Cognitive Neuroscience, 22,* 1844–1851. doi:10.1162/jocn.2009.21310

Schneider, W. X. (1999). Visual-spatial working memory, attention, and scene representation: A neuro-cognitive theory. *Psychological Research, 62,* 220–236. doi:10.1007/s004260050052

Schubotz, R. I., & von Cramon, D. Y. (2003). Functional–anatomical concepts of human premotor cortex: Evidence from fMRI and PET studies. *NeuroImage, 20,* S120–S131. doi:10.1016/j.neuroimage.2003.09.014

Scorolli, C., & Borghi, A. M. (2007). Sentence comprehension and action: Effector specific modulation of the motor system. *Brain Research, 1130,* 119–124. doi:10.1016/j.brainres.2006.10.033

Scorolli, C., Borghi, A. M., & Glenberg, A. M. (2009). Language-induced motor activity in bi-manual object lifting. *Experimental Brain Research, 193,* 43–53. doi:10.1007/s00221-008-1593-4

Smyth, M. M., Pearson, N. A., & Pendleton, L. R. (1988). Movement and working memory: Patterns and positions in space. *Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 40,* 497–514. doi:10.1080/02724988843000041

Smyth, M. M., & Pendleton, L. R. (1989). Working memory for movements. *Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 41,* 235–250. doi:10.1080/14640748908402363

Tucker, M., & Ellis, R. (1998). On the relations between seen objects and components of potential actions. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 830–846. doi:10.1037/0096-1523.24.3.830

Tucker, M., & Ellis, R. (2004). Action priming by briefly presented objects. *Acta Psychologica, 116,* 185–203. doi:10.1016/j.actpsy.2004.01.004

van Dantzig, S., Pecher, D., Zeelenberg, R., & Barsalou, L. W. (2008). Perceptual processing affects conceptual processing. *Cognitive Science, 32,* 579–590. doi:10.1080/03640210802035365

van Elk, M., Van Schie, H. T., & Bekkering, H. (2009). Action semantic knowledge about objects is supported by functional motor activation. *Journal of Experimental Psychology: Human Perception and Performance, 35,* 1118–1128. doi:10.1037/a0015024

Van Horn, J. D., & Poldrack, R. A. (2009). Functional MRI at the crossroads. *International Journal of Psychophysiology, 73,* 3–9. doi:10.1016/j.ijpsycho.2008.11.003

Wagenmakers, E.-J. (2007). A practical solution to the pervasive problems of p values. *Psychonomic Bulletin & Review, 14,* 779–804. doi:10.3758/BF03194105

Wagenmakers, E.-J., Krypotos, A.-M., Criss, A. H., & Iverson, G. (2012). On the interpretation of removable interactions: A survey of the field 33 years after Loftus. *Memory & Cognition, 40,* 145–160. doi:10.3758/s13421-011-0158-0

Wilson, M. (2001). The case for sensorimotor coding in working memory. *Psychonomic Bulletin & Review, 8,* 44–57. doi:10.3758/BF03196138

Witt, J. K., Kemmerer, D., Linkenauger, S. A., & Culham, J. (2010). A functional role for motor simulation in identifying tools. *Psychological Science, 21,* 1215–1219. doi:10.1177/0956797610378307

Woodin, M. E., & Heil, J. (1996). Skilled motor performance and working memory in rowers: Body patterns and spatial positions. *Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 49,* 357–378. doi:10.1080/713755629

Zwaan, R. A., & Taylor, L. J. (2006). Seeing, acting, understanding: Motor resonance in language comprehension. *Journal of Experimental Psychology: General, 135,* 1–11. doi:10.1037/0096-3445.135.1.1

Received August 31, 2011
Revision received April 5, 2012
Accepted April 13, 2012 ■