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DIANE PECHER
Erasmus University Rotterdam

THE ROLE OF MOTOR AFFORDANCES IN VISUAL WORKING MEMORY

ABSTRACT: Motor affordances are important for object knowledge. Semantic tasks on visual objects often show interactions with motor actions. Prior neuro-imaging studies suggested that motor affordances also play a role in visual working memory for objects. When participants remembered manipulable objects (e.g., hammer) greater premotor cortex activation was observed than when they remembered non-manipulable objects (e.g., polar bear). In the present study participants held object pictures in working memory while performing concurrent tasks such as articulation of nonsense syllables and performing hand movements. Although concurrent tasks did interfere with working memory performance, in none of the experiments did we find any evidence that concurrent motor tasks affected memory differently for manipulable and non-manipulable objects. I conclude that motor affordances are not used for visual working memory.

1. INTRODUCTION

Imagine that you are performing a complicated task, for example preparing a meal or fixing a bike, which involves manipulating various objects. Your performance would be very efficient if you could start preparing actions before you looked at the object. As you are stirring the sauce

you could already start planning to grab a knife with one hand and a tomato with the other hand. You might even take the future action of cutting the tomato into account so that the knife is in your dominant hand with the blade facing down. Such planning would involve working memory, in which the objects that are currently out of the field of vision are kept active. In this paper I will review research that investigated whether working memory also retains affordances for those objects.

2. GROUNDED COGNITION

Recent theories of cognition propose that the elements of thought are not words or symbols, but visual and motor images (e.g., Barsalou 1999; Glenberg 1997; Goldstone & Barsalou 1998; Pecher & Zwaan 2005; Zwaan 1999). According to this *grounded cognition* view, thinking shares resources with perception and action. When a person thinks about an object such as a tomato, earlier experiences with tomatoes are reactivated. This reinstatement of earlier activation results in a *sensory-motor simulation*. The visual system simulates seeing a tomato, the motor system simulates the acts of grasping, cutting, and eating a tomato, and the olfactory and gustatory system simulate the smell and the taste of a tomato. Thus, thinking about a tomato, the brain acts partially as if the person is actually perceiving and interacting with a tomato. Rather than an exact replica of experiences, however, these patterns are distorted and represent only partial experiences. In Barsalou's (1999) theory, simulators capture patterns of activation for a particular category of experiences. As a result, they represent a distributed pattern of experiences with a concept such as tomato. Simulation of experiences is dynamic and flexible and can even represent imaginary events.

2.1. Perception and Cognition

Research has shown that representations are organized along sensory-motor modalities and contain modality-specific information. In perception, switching modalities between trials incurs a processing cost (Spence et al. 2001). For example, participants who respond to light flashes and noise bursts respond more slowly if the previous stimulus was in a different modality than if it was in the same modality. Pecher, Zeelenberg & Barsalou (2003) showed that mental representations behave in a similar way. When participants had to verify a property for a concept, for example *red* for *tomato*, they were slower if the previous verification was for a property from a different modality, for example *loud* for *blender*, than from the same modality, for example *sparkles* for *diamond* (see also Lynott & Connell 2009; Marques 2006; Pecher et al. 2009a, 2004; Vermeulen et al. 2007). The same effect was obtained if, instead of verifying a concept-property pair, on the previous trial participants indicated the location of a perceptual stimulus such as a burst of noise or a flash of light (Dantzig et al. 2008). Other studies have shown that when language comprehenders read sentences, their mental representation of the sentence meaning is a simulation of the described experience, including visual information that was not directly stated in the sentence. For example, when participants read *The eagle was in the sky*, they were able to recognize a picture of an eagle with its wings stretched out more quickly than one with its wings folded in, whereas the reverse was found if they read *The eagle was in the nest* (Stanfield & Zwaan 2001; Zwaan et al. 2004; Zwaan & Pecher 2012; Zwaan et al. 2002). Such results point out that there is overlap in perceptual features between the mental representation of an object and the perception of that object. The effect of visual overlap was also found when there was an hour-long interval between sentence reading and picture processing (Pecher et al. 2009b). Thus, implied visual features are not only represented during online language processing, but remain more salient after longer delays. Similar effects are found even if the task contains no visual information. When participants are asked to list properties of concepts, they are more likely to name properties that are visible from an implied perspective than properties that are not visible from the implied perspective (l. Wu & Barsalou 2009). For example, *seeds* is named more frequently as a property of *half a watermelon* than as a property of *a watermelon*. Words that refer to objects with similar shapes (*banjo-tennis racket*) can prime each other in simple tasks such as lexical decision or word pronunciation (Pecher et al. 1998). Thus, perceptual features are relevant for concepts during language comprehension even when readers are not given any instructions to use visual information.

2.2. *Action and Cognition*

A major role for cognition is to support people's actions in the world (Glenberg 1997). The potential actions that a person can perform on an object are referred to as affordances. Affordances thus provide important information to the observer about the potential actions that can be performed with objects (Glenberg & Kaschak 2002). For example, a cup affords grasping, lifting, and tilting, allowing the user to drink from it. Such motor affordances are proposed to be central to conceptual knowledge (Borghi 2005; Glenberg 1997). There are two sources for the activation of affordances. First, perception of an object activates its affordances; when a person perceives the physical characteristics of an object, such as its shape and size, the object's affordances are automatically activated. Second, memory of previous interactions with objects may be retrieved on a later occasion and affect behavior. Glenberg (1997) argues that the combination of these two sources forms the mental concept of an object. Masson, Bub & Breuer (2011) showed that both visible affordances (the object's orientation) and affordances from memory (the orientation that would be needed to use the object in its conventional way) affected a grasp response. These results suggest that affordances are activated by both perceptual information and knowledge of the object's function (Lindemann et al. 2006). Moreover, studies have found that affordances are activated by words and sentences that refer to manipulable objects or actions (Aravena et al. 2010; Borghi & Riggio 2009; Glover et al. 2004; Klatzky et al. 1989; Bub et al. 2008; Rueschemeyer et al. 2010b; Taylor & Zwaan 2008; Zwaan & Taylor 2006), indicating that direct visual information is not even necessary to activate affordances.

3. AFFORDANCES AND VISUAL WORKING MEMORY

The question is whether motor affordances also support working memory, or short term memory, for objects. As illustrated at the beginning of this paper, in many situations performance will be better if affordances are kept active in working memory. Working memory might recruit the motor system to maintain such affordances. If the motor system is thus part of working memory, it might also be used in contexts where there is no need for an action plan. Affordances might be activated anyway, and they provide useful information about objects, so using that information might improve memory performance. Several studies have suggested that object affordances are activated automatically when someone sees an object, even if the object is depicted on a computer screen and there is no intention to perform an action with that object (Bub et al. 2008; Bub & Masson 2010; Olivier & Velay 2009; Taylor & Zwaan 2010) although several other studies suggest that the task or context plays a role (Borghi et al. 2012; Bub et al. 2003; Ellis & Tucker 2000; Girardi et al. 2010; Pellicano et al. 2010; Rueschemeyer et al. 2010a; Tipper et al. 2006). Tucker and Ellis (2004) found that semantic categorizations were faster and more accurate when the response grip required for categorization was compatible with the object affordance than when it was incompatible. Masson (2011) showed that hand responses were affected by the orientation of a task-irrelevant object's handle but also by the object's function. This result indicates that the source of such automatically activated affordances is a combination of visual and semantic information. On the other hand, some studies have questioned whether such effects are caused by activation of affordances, or might be due to more abstract correspondences between visual stimuli and the manual response. For example, effects that show facilitation when an object affords a grip with the same hand as used for responding compared to when it affords a grip with the opposite hand might also be explained by abstract spatial codes (Cho & Proctor 2010, 2011; Iani et al. 2011; Pellicano et al. 2010; Proctor & Miles 2014). Thus, there is some debate on whether affordances are activated automatically. If they are, however, working memory might use them to maintain objects.

Research has indicated that the motor system is recruited by working memory when the task requires motor information. When participants have to keep actions in memory, the motor system seems to be involved (Rossi-Arnaud et al. 2004; but see Helstrup 2001). Concurrent motor tasks interfere with working memory for actions, especially when they focus on the same aspect of actions (Smyth et al. 1988; Smyth & Pendleton 1989; Woodin & Heil 1996). A role of the motor system in working memory has also been suggested by neuro-imaging studies that obtained activation of the premotor cortex during visual working memory tasks (Haxby et al. 1994; Owen et al. 1996, 1999; Smith 2000). However, most of these results might be due to response planning during the retention interval, because tasks typically require tapping or pointing to spatial locations as a response (Postle 2006). Nonetheless, these findings might also indicate that the motor system was recruited for memory maintenance. Postle & D'Esposito (1999) did not observe any differences in the fMRI bold response between spatial and object working memory, suggesting that the same processes underlie memory for these different types of information.

3.1. *The Causal Role of Affordances*

A study by Mecklinger, Gruenewald, Weiskopf & Doeller (2004) found activation of premotor cortex in a working memory task for manipulable but not for non-manipulable objects. Since manipulable objects have affordances whereas non-manipulable objects do not, these results strongly suggest that affordances are recruited for working memory. Some caution is needed when one interprets such findings, however, because fMRI results that are mostly correlational cannot show whether activated regions are necessary to perform a task, nor do they show that a particular process was recruited (Poldrack 2008; see also Aue et al. 2009; Page 2006; 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). A similar point has been made about behavioral studies that showed effects of semantic processing of objects on motor responses. These effects might show only co-activation of affordances during or after processing semantic features of the object. Thus, even though affordances have been activated, they might not have contributed to the semantic representation of the object but might merely be a byproduct of semantic processing (Bub et al. 2008; Page 2006). Therefore, activation of a brain area that is also involved in motor tasks is not sufficient to conclude that motor simulations *support* working memory.

Evidence from interference studies, however, has indicated that language processing and learning are supported by the motor system. In these studies, a concurrent task that occupies the motor system is shown to affect cognition (Busiello et al. 2011; Casteel 2011; Dijkstra et al. 2007; McCloskey et al. 1992; Paulus et al. 2009; Witt et al. 2010). For example, Busiello et al. (2011) found reduced repetition priming for actions when participants concurrently performed a hand motor task compared to a verbal task. This finding indicates that the motor task interfered with creating a memory representation and thus suggests that mental representations for actions rely on activation of motor affordances. Casteel (2011) argued that whether action and conceptual processing interfere depends on the timing of the two processes. In particular, when the two are performed in parallel, they result in interference (see Vermeulen et al. 2008, for a similar finding in perceptual processing). Rueschemeyer et al. (2010a) showed that such interference effects occurred when participants performed intentional actions but not when they performed passive actions (i.e., when the finger was forced to move by a device). Interference effects on performance provide evidence that motor affordances contribute to comprehension because they show that when it is harder to activate motor affordances, comprehension suffers.

3.2. *Investigating the Role of Affordances in Working Memory*

3.2.1. Study 1

Interference paradigms have also been used to investigate whether the motor system and working memory performance are causally related. In our lab, we have investigated the role of the motor system for visual working memory. In the first study (Pecher 2013) photos of manipulable (e.g., *pliers*) and non-manipulable objects (e.g., *road sign*) were presented in a working memory task. Mecklinger et al. (2004) found differences in premotor cortex activation between manipulable and non-manipulable objects, and argued that because manipulable objects have affordances, the motor system was recruited to maintain these objects in memory, whereas non-manipulable objects have no affordances, and therefore the motor system would not be recruited. Because of this difference, a concurrent motor task would be expected to disrupt memory

performance more for manipulable objects than for non-manipulable objects.

In the working memory task an object was presented briefly, followed by a 5 second retention interval during which participants had to keep the object in memory. Then the test stimulus was presented, and participants indicated if the test object was the same as the study item. Only a small set of objects was presented repeatedly in the working memory task to prevent contribution from long term memory. When objects are repeated often, they all become very familiar, and subjects have to actively maintain the object in working memory in order to perform the task. The role of the motor system was investigated by having participants perform a concurrent motor task. In this task participants made a fist and then stretched their fingers one by one. A motor task like this, which keeps changing the hand configuration, should be most likely to interfere with grasping and other types of object directed actions (Smyth et al. 1988; Smyth & Pendleton 1989; Woodin & Heil 1996). Moreover, because the task is dissimilar to any interactions with any of the objects, the results would not be complicated by differences in congruency between affordances and motor task. Because the motor task would make it harder to recruit the motor system for memory, participants might change their strategies. In particular, they might use verbal encoding so that they could maintain the object in memory by repeating its name. In that case, any difference between manipulable and non-manipulable objects might disappear. To prevent a verbal strategy, participants were also instructed to repeat a series of four nonsense syllables during some blocks of the experiment. Thus, in different blocks of trials, participants performed no concurrent task, the motor task, the verbal task, or both tasks while they were doing the working memory task.

Whereas all these tasks decreased performance in general, the motor task did not affect memory for manipulable objects more than for non-manipulable objects, neither when only the motor task was performed nor when the verbal task was also performed. Such an interaction was predicted if participants had used motor affordances to maintain the objects in working memory, because motor affordances can support memory for manipulable objects more than for non-manipulable objects. Although the concurrent tasks influenced performance, the memory task might have been too easy to show the interaction between motor task and manipulability. In several follow-up experiments, the study trial showed four rather than just one object, and participants had to keep all four objects in memory during the retention interval. However, the results again did not show an interaction between motor task and manipulability. These results indicated that visual working memory does not rely on the motor system. It is possible that participants used mostly visual information to retain the objects in memory. To investigate whether removing this reliance on visual information might push participants toward using affordances, a visual interference task was used. In this task, participants saw an array of many colored blocks that changed color randomly during the retention interval. The results showed again no interaction between motor task and manipulability. In short, in five experiments Pecher (2013) did not find any evidence that a concurrent motor task had a larger effect on memory for manipulable than non-manipulable objects.

3.2.2. Study 2

In a second study, we further investigated the effect of motor interference using a different measure of working memory (Pecher et al. 2013). In the previously described study Pecher (2013) difficulty was varied by manipulating the number of items on the study trial from one to four between experiments. The effect of increasing the number of items was not just an increase in memory load, however, but also a visually more complex study trial. Moreover, the question is to what extent affordances for each object will be activated if four objects are presented simultaneously. Thus, in the easier conditions motor affordances might not have been used to keep the object in memory because the task was easy and could be performed visually, and in the difficult condition motor affordances might not have been activated because four objects with different affordances were presented at the same time. In order to exclude these potential problems, Pecher et al. (2013) used the N-back task, in which a series of items is presented individually, and participants indicate whether an item is repeated at a distance (lag) of N trials. For example, in a 2-back task the sequence might be *pliers – paperclip – pocket knife – paperclip – stock pot – pliers*. The second occurrence of paperclip would be a target repetition because it occurs two steps

from the first occurrence, but the second occurrence of pliers is farther than two steps and would not count as a target repetition. The N-back task is a popular working memory task in neuroimaging studies. An advantage of using this task is that one can easily manipulate memory load without changing the visual information or response requirements (Jaeggi et al. 2010). Moreover, when objects are presented individually there is enough opportunity for activation of motor affordances for each object. In one experiment we presented photographs of familiar manipulable and non-manipulable objects. The same concurrent motor and verbal tasks as in Pecher (2013) were used. The results showed decreased performance with increasing lag, confirming that the memory task became harder as more items needed to be maintained. As in the previous study, the concurrent tasks affected performance in general, but there was no interaction between the motor task and object manipulability. To further decrease the role of verbal rehearsal, in a second experiment we used novel objects, taken from Taylor & Zwaan (2010). The manipulable object was a smooth sphere that looked graspable, and the non-manipulable object was a spiked sphere that did not look graspable. If participants cannot use verbal labels to maintain stimuli in memory, they should rely more on other types of information. Thus, it would be more likely that affordances were used to maintain the spheres in memory. To further promote participants' reliance on affordances we varied the spheres in size only. In order to distinguish between different stimuli, participants thus needed to keep the size of the spheres in working memory. As size is strongly related to grip, support from affordances would greatly enhance working memory performance. Therefore, if there are circumstances in which affordances play a role, this should be a strong case. However, again there was no interaction between the motor task and object manipulability.

3.2.3. Study 3

A reason for this lack of support for the motor system might be that in both studies discussed so far the concurrent motor task was only interfering with affordances. That is, the motor action that was required by the task was incompatible with any potential interaction with the objects. One could argue that in such a case participants may have stopped paying attention to the motor system, because any attention to the motor system would have hurt performance. Therefore, in a third study, Quak et al. (2014) changed the concurrent motor task so that the action was congruent with one set of items and incongruent with another set of items. The concurrent task was to squeeze a rubber cylinder. Between blocks we manipulated whether the cylinder was large and held by the entire hand (power grip) or small and held between the thumb and index finger (precision grip). The objects that needed to be held in memory were non-manipulable (e.g., *wall*), manipulable with a power grip (e.g., *soda can*), or manipulable with a precision grip (e.g., *pin*). If object affordances were used for memory, memory for objects should be better if the concurrent task was congruent with the object's grip than if the concurrent task was incongruent with the object's grip. The results of this study showed that, like in the previous studies, although the concurrent task did interfere with memory performance in general, there was no difference in performance between congruent and incongruent conditions.

4. CONCLUSION

In summary, the results from these three studies do not confirm that motor affordances are used to support working memory. If participants had used motor affordances for manipulable objects we should have obtained interactions between object manipulability and motor interference, but the data did not provide any evidence for this. Because many researchers might be wary of drawing conclusions from null findings, we also performed Bayesian tests, which can be used to evaluate whether the data provide more evidence for the null or alternative hypothesis (Masson 2011; Wagenmakers 2007). These analyses showed that the data provided positive to strong evidence for the null, that is, for the absence of an interaction. This conclusion was the same under different circumstances, such as different difficulty levels, whether there was verbal interference, visual interference, for familiar and novel objects, and even when the motor task could have been helpful. Thus, the conclusion is that the motor system does not support visual working memory.

It might be argued that we simply failed to interfere enough with motor affordances to find differences between manipulable and non-

manipulable objects, or between congruent and incongruent objects. This would be inconsistent, however, with other studies that have used similar tasks, such as squeezing a rubber tube or sequentially touching the head, shoulders, and hips with both hands. In studies on working memory for actions such tasks have been shown to affect performance (Rossi-Arnaud et al. 2004; Smyth & Pendleton 1989; Smyth et al. 1988; Woodin & Heil 1996). Our tasks were similar in nature and difficulty as those used by these other studies. Therefore, it seems unlikely that they were not strong enough to cause interference in the motor system.

The absence of a role for motor affordances in visual working memory should not be taken to indicate that motor affordances play no role at all in cognition. Indeed, there are many situations in which motor affordances and cognition interact. As mentioned above, several studies have shown effects of motor interference on working memory for actions (Rossi-Arnaud et al. 2004; Smyth & Pendleton 1989; Smyth et al. 1988; Woodin & Heil 1996). These results suggest that the motor system is recruited when the task explicitly requires people to remember actions. Second, as discussed earlier, many studies have shown a role of affordances in tasks that require semantic or conceptual knowledge. This suggests that conceptual knowledge includes the actions that can be performed with an object, and is activated even under circumstances that do not require action execution. Thus, object affordances have a role in cognition, at least under circumstances that require explicit action knowledge or deeper conceptual knowledge. Visual working memory, however, might not rely so much on conceptual knowledge. In general, working memory seems to depend mostly on the modality of the items that are remembered. This is consistent with many studies showing that interference effects in working memory depend on similarity in terms of surface features rather than meaning (Baddeley 2003; Cowan 1999; Wood 2007). In the present study the stimuli were presented visually, which may have resulted in memory representations that were mostly visual.

One might think that the conclusion that visual working memory is not supported by the motor system is inconsistent with fMRI findings that showed activation of the premotor cortex during working memory maintenance of manipulable objects (Mecklinger et al. 2004). These fMRI findings might be explained by different mechanisms, however.

First, it is possible that participants in Mecklinger et al.'s study were using long-term memory to perform the task. Performance in short-term memory tasks is actually the result of both short-term and long-term memory retrieval (Hulme et al. 1991; Lewis-Peacock & Postle 2008; Shiffrin 1993; Watkins 1977). Because Mecklinger et al. presented many different study items this resulted in many trials on which both study and test item were new (i.e., presented for the first time during the experiment). Therefore, long-term familiarity alone would have been a good indicator of whether the item was a target (familiar) or a distracter (unfamiliar). To prevent long-term memory retrieval we used only a small set of items so that familiarity alone was not an indicator of whether the item had been presented N trials back. Second, their results might have been caused by just the visual presentation of the object and could have been unrelated to the memory task. Mecklinger et al. found that presentation of the same objects in a passive viewing task also activated the premotor cortex. Thus, the observed activation during the working memory task could have been simply a by-product of seeing the objects rather than an indication of support from the motor system. In contrast, by looking at actual performance, we were able to show that affordances do not contribute to memory.

Our results illustrate that interpretation of brain imaging results is quite complicated and has to be done with caution. Imaging results are often correlational, and therefore cannot tell us whether activation reflects core, necessary processing or mere by-products of processing (Aue et al. 2009; Poldrack 2008; Horn & Poldrack 2009). Moreover, because brain regions are parts of larger networks and are used by multiple processes, activity in a brain region cannot be used to conclude that a specific process was going on. In this particular case, activity in the premotor cortex during a working memory task had been interpreted as showing the involvement of affordances, but our results indicate that this was probably a logical fallacy of affirming the consequent. With the interference method used in our studies we can look at the causal relation between affordances and memory performance, and we conclude that affordances do not support visual working memory performance.

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