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Motor Affordances in Mental Rotation: When minds reflect the world and when they go beyond

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Abstract

A vivid imagination is one of the defining features of human mental life. A large body of research has shown that mental imagery is supported by some of the same cognitive systems that underlie perception and action (Decety, 1996; Kosslyn, Thompson, & Ganis, 2006). At the same time, our imaginations can go far beyond what is currently available in our physical environment; we can conjure up new worlds in art and literature, design new technologies, and conduct thought experiments that lead to major scientific discoveries. In this paper we investigate the extent to which the physical constraints and affordances of objects in the real world impinge on our ability to represent and manipulate those objects in our imagination. In particular we ask: are objects that are more difficult to physically manipulate also more difficult to mentally manipulate? Participants interacted with two wooden objects modeled after the figures from Shepard and Metzler's (1971) classic mental rotation study. One object was easy to physically rotate while the other was difficult to rotate. They then completed a mirror-image mental rotation task consisting of images of the manipulated objects. Participants were slower to solve the mental rotation task for trials consisting of images of the hard-to-rotate object, but only when they used a motor strategy in the task.

Keywords: Mental representation; Mental imagery; mental rotation; motor affordances

Background

The capacity to vividly imagine scenes, events, and actions is one of the hallmarks of human mental life, and researchers have been investigating the nature of mental imagery for the better part of four decades (Kosslyn, Ganis, & Thompson, 2001; Shepard & Metzler, 1971). A great deal of research has suggested that mental imagery is supported by some of the same cognitive systems that underlie perception and action; brain areas known to process visual information are also engaged during imagined visual activity (Kosslyn, Ganis, & Thompson, 2001; Kosslyn, Thompson, & Ganis, 2006; O'Craven & Kanwisher, 2000; Winawer, Huk, & Boroditsky, under review) and brain areas responsible for planning and executing motor movements are also activated during imagined motor movements (e.g. Decety, 1996; Jeannerod & Frak, 1999; Porro et al., 1996). It seems that the imagination is intimately tied to the processes that mediate our perceptual and motor interactions in the world.

At the same time, however, our imaginations often appear to go far beyond the information that is available in our

physical environment: we can conjure up new worlds in art and literature, design new technologies, and even conduct thought experiments that lead to major scientific advances. In fact, what often seems to separate our imagination from the everyday world is that mental imagery appears free from the constraints imposed by the physical environment. Indeed, people often imagine actions or events that they have never seen or never could experience themselves. We can imagine ourselves riding on a beam of light, leaping tall buildings in a single bound, or making a hook shot from half court.

On the one hand, then, mental imagery is supported by perception and action systems in the brain, but on the other hand our imaginations seem to go above and beyond our possible perceptual and motor worlds. This begs the question, to what extent do the constraints and affordances of objects in the real world impinge on our ability to represent and manipulate those objects in our imagination? Consider that you are redecorating your office and you are imagining what the room would look like if you moved a few items around. When you imagine moving the couch to the far wall, does the bulk of the couch, which constrains your physical motor interactions, automatically affect your mental imagery for the couch? Or can you just as easily imagine moving the heavy couch as the small reading lamp? Here we ask this very question: are objects that are more difficult to physically manipulate also more difficult to mentally manipulate?

We address this issue by utilizing a novel adaptation of the classic Shepard and Metzler (1971) mental rotation task. In their original study, participants were presented with images of two three-dimensional block figures and had to indicate whether the objects were identical or were mirror images of one another. Interestingly, reaction times were linearly proportional to the angular disparity between the two objects. These findings have since been replicated many times, though several researchers have argued that there are actually several possible mental strategies for solving this task (e.g. Kosslyn et al., 2001b). For example, it is possible to use a motor strategy and imagine manually rotating the objects (Kosslyn et al., 2001b; Wexler, Kosslyn, & Berthoz, 1998) or to use a visual strategy and imagine the objects rotating on their own (Kosslyn et al., 2001b). Kosslyn and colleagues (2001b) used PET imaging to demonstrate that participants were able to consciously adopt one of these strategies and flexibly switch to a different

strategy when cued by the experimenter. Critically, using a motor strategy reliably activated motor regions of the brain in addition visual areas, while using the visual strategy only activated visual areas.

In our study, participants interacted with and physically rotated two identically shaped (but differently colored) Shepard and Metzler-like objects that were constructed out of wood. Crucially, one of the objects was easy to rotate while the other was more difficult to rotate. Participants then completed a standard mirror-image mental rotation task on the computer that consisted of images of the objects they had interacted with along with similarly shaped control objects. Following Kosslyn and colleagues (2001b), participants were given a specific strategy for carrying out the mental rotation task to ensure that all participants were engaged in the same mental task. Results indicate that people are significantly slower to mentally rotate objects that are more difficult to physically rotate when they use a motor mental rotation strategy. However, this reaction time difference goes away when participants are instructed to use a purely visual strategy for mental rotation. When participants are not given any strategy instructions their overall reaction times speed up, suggesting that the mind is free to find a more efficient way to solve these tasks when left to its own devices.

All together, these results support the idea that under certain circumstances the physical motor properties of objects may be integrated into mental imagery, constraining imaginative processes. However, these constraints may be avoided by switching mental imagery strategies, and people may search for the most efficient imagery strategy by default.

Experiment 1

While the imagination often appears free from the physical constraints of the world, mental imagery is supported by some of the same cognitive systems that support perception and action. Here we explore to what extent the constraints and affordances of objects in the real world impinge on our ability to represent and manipulate those objects in our imagination. Experiment 1 investigated whether participants would be slower to mentally rotate an object that was more difficult to physically rotate. To try to ensure that all participants were engaging in the same imagery processes, participants were given a “motor” strategy and were told to imagine grasping one of the objects and turning it until it aligned with the other object.

Methods

Participants 40 members of the Stanford community participated in this study in exchange for payment or class credit.

Physical Rotation Apparatus We constructed four Shepard and Metzler-style block figures from small wooden beams (Figure 1). The objects were approximately 15 cm tall and had small holes drilled into the center beam to allow them to

be mounted to the rotation platforms. The objects came in two distinct shapes with two instances of each shape. One instance of each shape was painted purple while the instance was painted green.

We also built two rotation platforms to control the rotation affordances of the objects. Each rotation platform consisted of a coffee can with an axle installed in the bottom and a freely rotating wooden paddle inside. The objects could be mounted on top via protruding metal rods. One device was completely filled with sand, making it difficult to rotate when an object was mounted onto it. The other platform was left empty, making it easier to rotate. Both devices were painted black and their inner workings were visually obscured from participants by wooden covers.

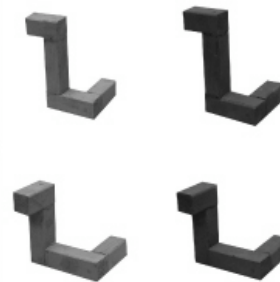


Figure 1: Images of the 4 objects built for Experiment 1.

Physical Rotation Procedure Participants received physical training with two of the Shepard and Metzler objects from the same shape class. One shape was mounted to the rotation platform filled with sand (hard-to-rotate) while the other was mounted to the empty platform (easy-to-rotate). For half of the participants, the green object was mounted to the hard-to-rotate platform while for the other participants the purple object was mounted to the hard-to-rotate platform. Half of the participants manipulated objects from one shape class while the remaining participants manipulated objects from the other shape class. The objects that participants did not manipulate would serve as control trials in the mental rotation task.

Half of the participants rotated the hard-to-rotate object first while the remaining participants rotated the easy-to-rotate object first. Participants were instructed to stand at arm’s length from the object, grasp the object by the center beam with their right hand and rotate it as far as they could clockwise and then counterclockwise. This step was then repeated for the left hand. The object was then removed from its mounting by the experimenter, rotated 90°, and remounted in a new orientation. Participants then performed the right and left-handed physical rotations in this position. This process was repeated twice more until the object had been manipulated from four different orientations. At this point the experimenter removed the apparatus and replaced it with the other rotation platform. The second object (same shape, different color) was already attached to this platform. Participants replicated the entire

physical rotation processes described above for this second object. Finally, they repeated this whole procedure again from the beginning, rotating the first object and platform followed by the second object and platform. The entire training session lasted approximately five minutes.

Mental Rotation Stimuli and Procedure The mental rotation task was conducted on a computer. Stimuli consisted of full color photos of the physical objects described above. Each object was photographed in three different orientations, with identical shapes photographed from the same angles. These orientations were chosen to allow for the unambiguous identification of each object from the digital image.

On every trial, one of these twelve images appeared in the left half of the display, subtending approximately between 12-15 cm by 12-15 cm depending on the orientation, angle and shape. Either the same image or a mirror-reflected version of the image appeared in the right half of the display. The image on the right could be rotated 0°, 60°, 120°, 180°, 240°, or 300° clockwise in the picture plane. Every possible trial based on the combination of these images was used exactly once in this experiment. Since there were 4 objects, 3 orientations, 2 response types (same or mirror-reversed), and 6 rotation angles, this yielded 144 unique trials. The order of trials was randomized across participants.

Participants had to press one button if the images on the screen depicted the exact same object and a different button if they were mirror-reversed images of one another. Feedback was given after each trial in the form of a high tone or low tone for correct versus incorrect responses, respectively. All participants completed five practice trials before running through the experimental trials. Practice trials were similar to the experimental trials but consisted of grayscale images of the objects.

Following Kosslyn (2001b), Participants were given a motor strategy to use for responding in the task: *Please use the following strategy to accomplish this task: Imagine that you are grasping one of the objects with your hand and turning it until it aligns with the other object.*

Results

The data from 8 individuals were removed prior to analysis because they either failed to complete the entire experiment or they had error rates in excess of 20%. The remaining 32 participants had a mean accuracy of 93% and represent a fully counterbalanced set of data.

To ensure that our rotation platform manipulation really made one object significantly harder to rotate than the other, we asked participants at the end of the experiment to rate how difficult it was to physically rotate each object on a scale from 1 (*extremely easy to rotate*) to 10 (*extremely difficult to rotate*). Participants rated the object that was attached to the sand-filled rotation platform ($M=6.5$, $SD=1.87$) as significantly harder to physically rotate than the object attached to the empty rotation platform ($M=2.2$,

$SD=1.45$), $t(29)=9.19$, $p < 0.001$. Two participants failed to respond to this question.

On the mental rotation task, mirror-reversed response trials were treated as distractors and were not considered in this analysis. We removed incorrect trials as well as correct trials where the RT was greater than two standard deviations slower than the mean RT across all trials for all participants. Because mental rotations of 240° and 300° clockwise are equivalent to rotations of 120° and 60° counterclockwise, we collapsed the 240° and 300° trials into the same bin as 120° and 60° trials, respectively.

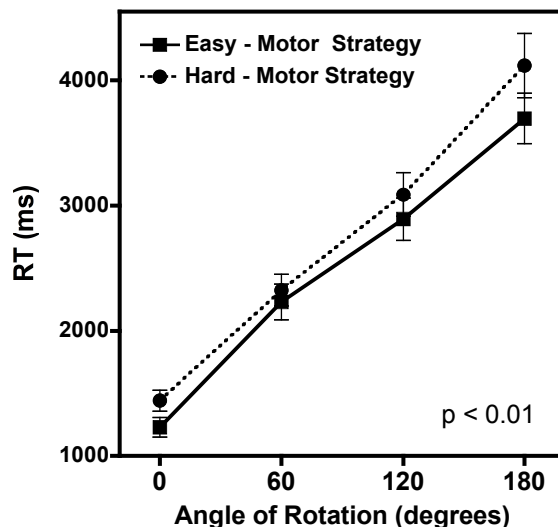


Figure 2: RTs by angle of rotation for experimental trials in Experiment 1. Error bars on all graphs represent standard error of the mean.

There were two trial types: *Experimental* trials were those where the image on the screen depicted an object that had been physically manipulated, while *Control* trials were those where the image on the screen depicted an object that had not been physically manipulated. Experimental trials were divided into *Easy* and *Hard* trials based on whether the object on the screen had been attached to the easy or hard-to-rotate platform for a given participant (rotation difficulty).

First we analyzed data from just the experimental trials in a 2 (rotation difficulty) X 4 (angle of rotation) repeated measures ANOVA (Figure 2). Consistent with previous studies of mental rotation, there was a significant main effect of angle of rotation, with RTs increasing with increased angle of rotation, $F(3, 93) = 102.1$, $p < 0.001$. More interestingly, there was a significant main effect of rotation difficulty, with faster responses to images of the easy-to-rotate object as compared to the hard-to-rotate object, $F(1, 31) = 8.54$, $p < 0.01$. There was no interaction between rotation difficulty and angle of rotation, $F(3, 93) = 0.77$, $p = N.S.$

We also analyzed control trials to see whether the effects of trial subtype (easy vs. hard rotation difficulty)

generalized to trials depicting objects of the same color and similar shape that participants never actually physically interacted with. Control trials were separated by color and matched to whatever colors the hard and easy objects were for each participant. In a 2 (trial type) X 2 (rotation difficulty) X 4 (angle of rotation) repeated measures ANOVA we found a significant interaction between trial type and rotation difficulty, $F(1, 31) = 11.65, p < 0.01$, suggesting that the RT effects observed for the experimental trials did not extend to the control trials. Looking just at the control trials in a 2 (color-matched rotation difficulty) X 4 (angle of rotation) ANOVA, there was a significant main effect of angle of rotation, with reaction times increasing with increased angle of rotation, $F(3, 93) = 124.40, p < 0.001$. However, there was no main effect of color-matched rotation difficulty, $F(1, 31) = 0.15, p = \text{N.S.}$ There was a marginal interaction between angle of rotation and color-matched rotation difficulty, $F(3, 93) = 2.53, p = 0.062$, though this seems to be driven by the fact that at 180° of rotation, RTs to color-matched easy trials were somewhat slower than RTs to color-matched hard trials.

Discussion

The results from Experiment 1 suggest that certain physical properties of an object may be automatically integrated into mental imagery and constrain our ability to imagine manipulating that object. Participants were significantly slower to mentally rotate an object that was more difficult to physically rotate, even though both objects were the same exact shape. Furthermore, this effect did not generalize to images of objects of similar shape that were color-matched to difficulty of rotation, suggesting that was an object-specific effect. Interestingly, there was no interaction between trial type and angle of rotation, suggesting that the cost of mentally rotating a difficult object may be fixed. This might reflect an additional processing demand that is required for preparing to interact with – or imagine interacting with – a more difficult to manipulate object.

However, it is unclear whether the specific motor affordances of an object will always and automatically influence imagined interactions with that object or whether this depends in part on the mental imagery strategy that is deployed. This issue was explored in Experiment 2.

Experiment 2

The results from Experiment 1 suggest that motor properties of objects in the world can constrain our ability to imagine manipulating them. However, people can easily imagine impossible physical feats such as lifting a car or even a mountain. How might this be possible? Perhaps people can ignore certain physical properties of objects in mental imagery by deploying a different imagery strategy. In Experiment 2, we investigated whether we could eliminate the effects of physical rotation difficulty on mental rotation speed by instructing participants used a purely visual strategy.

Methods

Participants 36 individuals from the Stanford community were recruited to participate in this study in exchange for payment or class credit.

Stimuli and Procedure The stimuli and procedure for Experiment 2 were identical to Experiment 1 with the following exception: mental rotation task instructions included a visual strategy for solving the task instead of a motor strategy. The new instructions read: *Please use the following strategy to accomplish this task: Imagine that one of the objects is rotating by itself and turning until it aligns with the other object.*

Results

The data from 6 individuals were removed prior to analysis because they had error rates in excess of 20%. The remaining 32 participants had a mean accuracy of 92% and represent a fully counterbalanced set of data. First, we analyzed data from just the experimental easy and hard trials in a 2 (rotation difficulty) X 4 (angle of rotation) repeated measures ANOVA (Figure 3). Once again there was a significant main effect of angle of rotation, with RTs increasing with increased angle of rotation, $F(3, 93) = 80.56, p < 0.001$. However, there was no main effect of rotation difficulty, $F(1, 31) = 0.002, p = \text{N.S.}$, and no interaction between rotation difficulty and angle of rotation, $F(3, 93) = 0.91, p = \text{N.S.}$

Next, we combined the data from Experiment 2 with the data from Experiment 1 to directly compare the effects of mental imagery strategy in a 2 (rotation difficulty) X 4 (angle of rotation) repeated measures ANOVA with strategy as the between-subjects variable. Overall, there was a marginal main effect of rotation difficulty, with slower RTs for trials depicting the hard-to-rotate object, $F(1, 62) = 3.81, p = 0.055$. However, this effect was entirely driven by the motor imagery strategy employed in Experiment 1, as the interaction between imagery strategy and rotation difficulty approached significance, $F(1, 62) = 3.53, p = 0.065$.

Discussion

The results from Experiment 2 demonstrate that the motor affordance properties of an object do not always constrain our ability to imagine interacting with that object. When participants used a visual strategy for mental rotation, imagining the objects on the screen moving of their own accord, there was no cost for mentally rotating an object that was harder to physically rotate. This is interesting because it suggests that our mental representation of an object is intimately tied to *how* we imagine interacting with that object. However, in both Experiments 1 and 2 participants were given explicit mental rotation strategy instructions, so it is impossible to tell how participants would represent the objects without being told what to do. This issue was explored in Experiment 3.

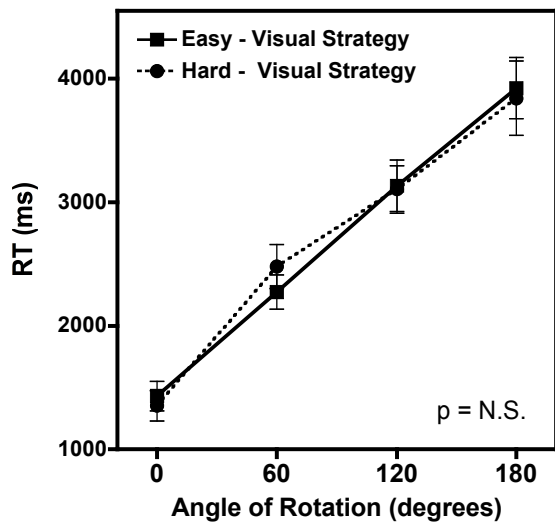


Figure 3: RTs by angle of rotation for Experiment 2

Experiment 3

Experiments 1 and 2 demonstrated that physical properties of objects in the world could constrain mental imagery for those objects, but that these constraints could be avoided by switching mental imagery strategies. However, because we provided participants with explicit strategies, it is unclear how people would represent the objects on their own without instruction. Because they had just physically interacted with these objects, it is possible that they would be biased towards using a motor strategy. However, it is also possible that they would settle on a more efficient strategy that is not constrained by the motor affordance properties of the objects. In Experiment 3, participants completed the same physical training and mental rotation task as in Experiments 1 and 2. However, they were not given any explicit strategy instructions for completing the mental rotation task in order to see how they would solve the task on their own.

Methods

Participants 38 individuals from the Stanford community were recruited to participate in this study in exchange for payment or class credit.

Stimuli and Procedure The stimuli and procedure were identical to Experiments 1 and 2 with the following exception: mental rotation task instructions did not include any explicit strategy for responding to the task.

Results

The data from 5 individuals were removed prior to analysis because they had error rates in excess of 20%. The remaining 32 participants had a mean accuracy of 91% and represent a fully counterbalanced set of data.

First we analyzed data from just the easy and hard trials in a 2 (rotation difficulty) X 4 (angle of rotation) repeated measures ANOVA (Figure 4). Once again there was a

significant main effect of angle of rotation, with RTs increasing with increased angle of rotation, $F(3, 93) = 87.20, p < 0.001$. However, there was no main effect of rotation difficulty, $F(1, 31) = 0.164, p = \text{N.S.}$, and no interaction between rotation difficulty and angle of rotation, $F(3, 93) = 1.42, p = \text{N.S.}$

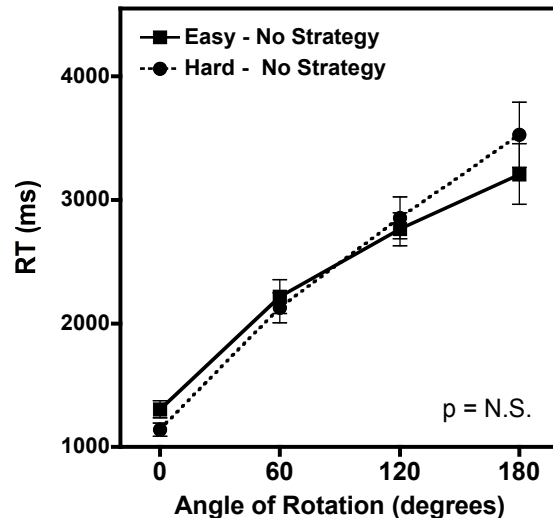


Figure 4: RTs by angle of rotation for Experiment 3

Next we compared the results of Experiment 3 to the results from Experiment 1 in a 2 (rotation difficulty) X 4 (angle of rotation) repeated measures ANOVA with strategy as the between-subjects variable. Overall, there was a main effect of rotation difficulty, with slower RTs for trials depicting the hard-to-rotate object, $F(1, 62) = 4.65, p < 0.05$. However, this effect seems to be largely driven by the motor imagery strategy employed in Experiment 1, as the interaction between experiment and rotation difficulty approached significance, $F(1, 62) = 2.33, p = 0.13$. Interestingly, there was a marginal main effect of the between-subjects experiment variable, with RTs slightly slower overall for Experiment 1, $F(1, 62) = 2.35, p = 0.13$. When we compared Experiments 2 and 3 we found a similar result, with overall RTs marginally slower for Experiment 2, $F(1, 62) = 2.63, p = 0.11$.

Discussion

The results from Experiment 2 demonstrated that the mental rotation task could be solved without representing the motor properties of the objects in imagery. The results from Experiment 3 suggest that when participants are not explicitly instructed to use a motor strategy, they do not automatically represent the motor affordances of the objects that they are mentally rotating. Moreover, there is a trend in the data that suggests that participants are faster to mentally rotate when they are not provided with any specific strategy to use. One possibility is that this simply reflects the added cognitive cost of maintaining a strategy in mind when one is provided by the experimenter. On the other hand, it could also be the case that participants are more likely to settle on

a more efficient mental rotation strategy when they are not constrained by specific task instructions. At the end of the study we asked participants to describe what strategies they used for solving the mental rotation task, and we received a startling assortment of responses. Many participants reported using a strategy that could be interpreted as either a visual or motor rotation strategy (e.g. "I rotated the image on the right to be oriented the same way the image on the left was"), but other people seemed to just compare key sub-sections of the objects (e.g. "I first focused on one corner of the first object, and then looked for the corresponding corner in the other object"), while some participants came up with even more novel strategies (e.g. "After a while, I imagined them as a sea lion with different positions"). Several people even reported using several strategies throughout the experiment. We do not have enough data at this point to analyze how well participants' reports of their strategies tracks their RT data, but it could be that participants typically search for the most efficient way to solve the task. Why and under what conditions people might adopt a given strategy is an interesting area for future research.

General Discussion

We began this research by asking a simple question: are objects that are more difficult to physically manipulate also more difficult to mentally manipulate? Our answer is a conditional *yes*, but this depends in large part on what form of mental imagery is utilized. The results from Experiment 1 suggest that when we imagine a motor interaction with an object, the properties of the object that constrain physical motor interactions also appear to constrain imagined motor interactions. However, the data from Experiment 2 suggest that this cost can be avoided simply by imagining the object moving by its own accord. Finally, we found that when left to their own devices, many participants seemed to settle on a more efficient mental rotation strategy that did not consist of representing the specific motor affordances of the objects. Taken together, these experiments demonstrate that the motor properties of objects are not automatically integrated into mental imagery for those objects, unless you are specifically imagining a motor interaction with those objects.

One interesting aspect of our findings is the fact that the cost for mentally rotating a more difficult object in Experiment 1 appears to be fixed rather interacting with angle of mental rotation. One explanation for this effect is the possibility that it takes longer to (imaginatively) prepare for a motor interaction with an object that is more difficult to manipulate relative to one that is known to be easier to manipulate. Once you have planned and started to execute the motor movement, however, the mental rotation speed for hard versus easy to rotate objects is roughly the same. It will be interesting to explore these effects in more depth in future work. For example, our participants only had a few minutes to interact with the real-world objects. Would more time spent physically interacting with these objects reduce

the cost for mentally rotating a difficult object due to increased experience planning the motor movement? Or would this extra experience cause the disparity in RT to be even greater due to a stronger representation of the motor affordances of the difficult object? Similarly, if participants in Experiment 3 were given more time to interact with the objects, might they be more likely to use a motor strategy by default even when given no explicit instructions to do so?

At the beginning of this paper we noted that while mental imagery may be supported by some of same cognitive systems that underlie perception and action, our imaginations often seem to go way beyond the constraints of the physical world to allow us to experience the impossible. All together, the experiments presented here represent a step towards understanding what specific information makes it into mental imagery under what circumstances.

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