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RESEARCH REPORT

Spatial Working Memory Is Necessary for Actions to Guide Thought

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Directed actions can play a causal role in cognition, shaping thought processes. What drives this cross-talk between action and thought? I investigated the hypothesis that representations in spatial working memory mediate interactions between directed actions and problem solving. Participants attempted to solve an insight problem while occasionally either moving their eyes in a pattern embodying the problem's solution or maintaining fixation. They simultaneously held either a spatial or verbal stimulus in working memory. Participants who moved their eyes in a pattern that embodied the solution were more likely to solve the problem, but only while also performing a verbal working memory task. Embodied guidance of insight was eliminated when participants were instead engaged in a spatial working memory task while moving their eyes, implying that loading spatial working memory prevented movement representations from influencing problem solving. These results point to spatial working memory as a mechanism driving embodied guidance of insight, suggesting that actions do not automatically influence problem solving. Instead, cross-talk between action and higher order cognition requires representations in spatial working memory.

Keywords: embodied cognition, problem solving, working memory, eye movements

The embodied cognition literature shows that we use our bodies to accomplish cognitive goals, suggesting that the sensorimotor systems we use to interact with the world ground cognitive processes (Barsalou, 1999; Glenberg & Robertson, 2000; Zwaan, 1999). Recently, researchers have advanced the notion that bodily states and situated action can also play a causal role in cognitive processing, demonstrating that the actions we perform can directly guide our thoughts. Directed actions influence performance on a wide variety of cognitive tasks such as mathematical reasoning (Cook, Mitchell, & Goldin-Meadow, 2008), language comprehension (Glenberg, Sato, & Cattaneo, 2008), and episodic memory retrieval (Casasanto & Dijkstra, 2010). The surprising potential for low-level actions to guide higher order cognition is also evident in problem solving. When people move their eyes or arms in a manner that embodies the solutions to classic insight problems—namely, the radiation and two-string problems—these actions prime the insights necessary to solve the problems (Thomas & Lleras, 2007, 2009a, 2009b). Engaging a person's action system lowers her or his threshold for experiencing thoughts that share something in common with those actions.

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Accumulating evidence backs the idea that the way we move influences how we think. By what means do actions shape the course of cognition? Prominent theories of embodied cognition suggest that concepts can directly evoke sensorimotor systems (Gallese & Lakoff, 2005) and that knowledge representations are based on such mental simulations (Barsalou, 2008). For example, we might bring a remembered item to mind by partially recreating a perceptual experience of this item (Buckner & Wheeler, 2001), use mirror neuron circuits to understand another person's mental state (e.g., Decety & Grezes, 2006; Gallese, Keysers, & Rizzolatti, 2004), or simulate acting out what is described in a written passage (e.g., Glenberg & Kaschak, 2002; Zwaan & Taylor, 2006). Likewise, when a person moves in a manner related to a problem's solution, the movement could initiate perceptual simulations consistent with this solution (e.g., Thomas & Lleras, 2007). Embodied perspectives of language comprehension and action understanding claim that simulation is an automatic process (e.g., Fischer & Zwaan, 2008; Gallese & Lakoff, 2005), but little work has directly tested this claim of automaticity or investigated exactly how a specific action can inspire a particular thought. When we move, is there a direct route from motor representations to higher level representations, or do mid-level cognitive mechanisms mediate interactions between action and thought? Representations of movement trajectories may automatically and obligatorily spread to create associations that shape the course of higher order processing. Alternatively, we may need to encode our movements into a format that can readily gain access to higher order cognition.

I hypothesize that compatibilities between action and thought reflect interactions within the spatial module of working memory (e.g., Baddeley & Hitch, 1974; Brooks, 1968; Klauer & Zhao, 2004; Logie, 1995). More specifically, residual activation in spatial working memory of location and action plans that a person uses to execute movements might influence the representations she or he uses to think about the cognitive task at hand. Actions can facilitate the generation of spatially based frames of reference (Chum, Bekkering, Dodd, & Pratt, 2007; Fischer & Hoellen, 2004; Linnell, Humphreys, McIntyre, Laitnen, & Wing, 2005) and sustain spatial representations in working memory (Morsella & Krauss, 2004; Wesp, Hesse, Keutmann, & Wheaton, 2001), so if an actor encodes a specific action representation into spatial working memory, this may lead to a bias in subsequent representations in working memory that alter the way the actor conceptualizes space. For example, participants directed to move in a pattern that embodies the solution to a spatial reasoning problem may be more likely to include solution-related aspects in their spatial representation of the problem space in working memory. According to this hypothesis, activation does not obligatorily spread from motor representations to substantially bias higher order processing. Actions will only influence problem solving when representations of these actions are active in spatial working memory: If action representations fail to remain active in spatial working memory, these actions will not shape cognition.

If directed actions influence thoughts through residual activation in spatial working memory, then engaging spatial working memory resources during action programming and execution should alter the extent to which these actions guide subsequent cognition. To test this hypothesis, I asked participants to solve Duncker's (1945) radiation problem. Participants viewed the diagram in Figure 1 and were asked to figure out a way—using only lasers that destroy organic tissue when set at sufficient intensity—to destroy an inoperable stomach tumor without harming any of the surrounding healthy tissue. The target solution requires firing multiple low-intensity lasers from different outer points so that they converge at the tumor with combined intensity sufficient to destroy it. Constructing possible solutions to this problem likely engages spatial working memory to hold the possible paths that lasers could follow.

Participants directed to move their eyes in a pattern compatible with the radiation problem's solution—moving first to an outer location of the diagram, then crossing to a point near the tumor, and then crossing to a different outer location, and so forth—are more likely to solve the problem than are participants directed to maintain a central fixation (Thomas & Lleras, 2007, 2009a). However, participants directed to move their eyes in patterns unrelated to the target solution—for example, repeatedly moving between a single outer location and a single inner location—are no more likely to solve the radiation problem than participants who maintain fixation (Thomas & Lleras, 2007). Eye movements must embody the problem's solution in order to facilitate insight, but it is unclear whether such eye movements automatically bias representations that aid in problem solving regardless of working memory load. To investigate links between spatial working memory and the embodied guidance of insight, I asked participants to try to solve the radiation problem while occasionally performing a visual tracking task. At the same time, they held either a spatial or verbal stimulus in working memory. If directed actions influence thoughts via interactions in spatial working memory, participants who make directed eye movements that embody the multiple-lasers solution to the radiation problem should solve the problem more often than participants directed to fixate the tumor, but only when these movements can gain sufficient access to representation in spatial working memory. According to the hypothesis that spatial working memory representations mediate embodied guidance of thought, the facilitating influence of eye movements on problem solving should be reduced when spatial working memory resources are engaged while people perform the priming action. Success on the radiation problem should therefore be higher for participants who move their eyes while holding a verbal stimulus in working memory than for participants who move their eyes while holding a spatial stimulus in working memory.

Experiment 1

Method

Participants. The experiment was run in two parts. In Part 1, 60 Vanderbilt University undergraduates unfamiliar with the radi-

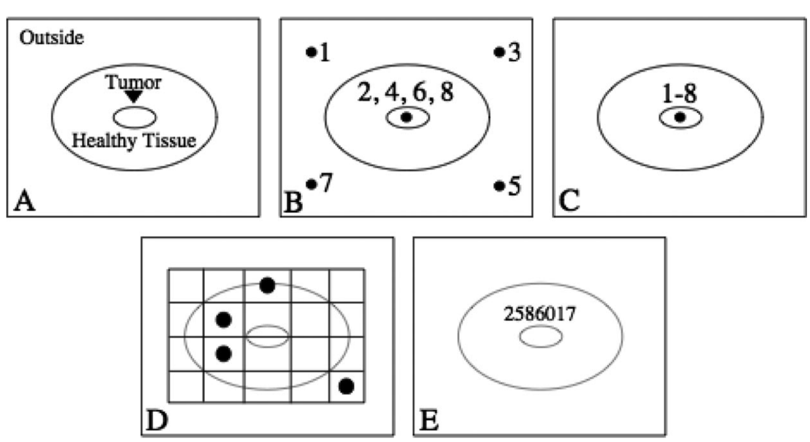

Figure 1. Diagram of the radiation problem. A: Participants viewed this diagram while listening to instructions about the problem. B: Visual tracking sequence of colored points for the embodied-solution groups in Experiment 1. C: Visual tracking sequence of colored points for the tumor-fixation groups in Experiment 1. D: Example spatial working memory stimuli. E: Example verbal working memory stimuli.

ation problem were randomly assigned to one of four experimental groups (with 15 total participants per group). In Part 2, 15 additional North Dakota State University (NDSU) undergraduates were assigned to a control group.[1] Participants received monetary compensation or course credit.

Stimuli and apparatus. Participants viewed stimuli against a black background on a color monitor displaying the radiation problem diagram, tracking points, and working memory items (see Figure 1). The spatial working memory stimuli consisted of a 5 × 4 white grid that spanned the problem diagram and filled white dots. The verbal working memory stimuli consisted of a string of seven white digits.

Procedure and design. Participants not in the control group first performed six practice trials of the working memory and visual tracking tasks. All participants then saw the problem diagram, and the experimenter read the following instructions detailing the radiation problem:

> Given a human being with an inoperable stomach tumor, and lasers which destroy organic tissue at sufficient intensity, how can one cure the person with these lasers and, at the same time, avoid harming the healthy tissue that surrounds the tumor?

Participants pressed a key on the keyboard to begin the experiment, which consisted of 20 attempt intervals. In Part 1, each interval was divided into a memory/visual tracking period and a free-viewing period. In Part 2, each interval consisted only of the free-viewing period. The problem diagram was continuously visible on the display.

Working memory and visual tracking tasks. Participants in Part 1 were assigned to one of four experimental groups that differed on the basis of the nature of the working memory task performed (spatial vs. verbal) and the pattern in which color points appeared (embodied-solution vs. tumor-fixation): embodied-solution-spatial, embodied-solution-verbal, tumor-fixation-spatial, and tumor-fixation-verbal.

Each memory/visual tracking period began with a 1-s presentation of the radiation problem alone on the display, followed by 1.5 s in which the working memory stimuli appeared superimposed over the problem diagram. Participants in the spatial memory conditions attempted to remember the random locations of four dots in a 20-square grid. Participants in the verbal memory conditions viewed a random string of seven digits displayed above the inner oval of the problem diagram.

Following presentation of the memory stimuli, participants performed an intervening visual tracking task in which they saw a series of eight red or blue points that appeared at various locations on the display for 1 s each, with a short 225-ms interval between presentation of every point. Each point had a 30% probability of being red, and the experimenter asked participants to press a key on the keyboard every time they saw a red point. The color points were small and desaturated, making them difficult to distinguish at the periphery (e.g., Abramov, Gordon, & Chan, 1991) and therefore encouraging participants to foveate each item to successfully perform the visual tracking task.

For participants in the embodied-solution conditions, the visual tracking task emphasized a triangular in-and-out pattern that crossed from the outside area, in to the tumor, and then back out to a different location of the outside area (see Figure 1B). Participants in the tumor-fixation conditions saw all eight color points appear sequentially in the center of the display (see Figure 1C).

After the final tracking point disappeared from the display, participants saw a memory probe that either did or did not match the original to-be-remembered stimuli. Mismatching memory probes were generated by randomly moving one of the four dots in the grid to an adjacent square in the spatial memory conditions and by randomly replacing one digit in the seven-digit string in the verbal memory conditions. The memory probe remained on screen until participants made a recognition response.

Free-viewing period. After each memory/visual tracking period, the problem diagram remained alone on the display for 30 s, giving participants an opportunity to think about the radiation problem.

Problem solution and experiment completion. At any time, a participant who wanted to venture a solution to the radiation problem could press a key to pause the current attempt interval. The experimenter then placed tracing paper over the display and asked the participant to draw her solution. If the solution was correct (i.e., showed at least two lines converging from different outer locations at the tumor), the experiment ended. If the solution was incorrect, the participant went back into the current attempt interval and was free to guess again at any time. The experiment concluded whenever a participant solved the problem, or after 20 unsuccessful attempt intervals.

Results and Discussion

Working memory and color tracking tasks. Before examining the primary question of interest regarding the relationship between working memory load and embodied guidance of insight, it is first useful to ensure that participants performed the color tracking and working memory tasks appropriately and that the spatial and verbal memory tasks were roughly equivalent in terms of the demands they placed on participants. Table 1 shows the mean accuracies and response times for the working memory and visual tracking tasks across experimental groups. I ran an analysis of variance on these data with factors of Memory Task Type (Verbal vs. Spatial) and Tracking Task Type (Embodied-Solution vs. Tumor-Fixation), the results of which are available in Table 2. As can be seen from this table, participants' speed and accuracy in the memory task was roughly equivalent regardless of whether they attempted to remember spatial or verbal material, suggesting that participants found the two memory tasks equally challenging when they performed them in conjunction with the problem-solving and tracking tasks. On the basis of difficulty alone, there is no reason to believe that one version of the memory task should have been more disruptive to problem-solving performance than another.

Although memory task type did not substantially influence memory performance, participants in the tumor-fixation groups did tend to have higher memory task accuracy than participants in either of the embodied solution groups. In addition, participants in the tumor-fixation groups were also both faster and more accurate in the color tracking task than participants in the embodied-

[1] Although participants in the control group were run separately from participants in the other groups, they were recruited from a similar pool and given identical incentives to participate.

Table 1
Memory Task Performance, Visual Tracking Task Performance, and Solution Rate as a Function of Group

Group	Memory task accuracy (%)	Memory task RT (ms)	Tracking task sccuracy (%)	Tracking task RT (ms)	Solution rate
Embodied-Solution-Verbal (Exp. 1)	77.6	2,564	93.2	798	.53
Embodied-Solution-Spatial (Exp. 1)	76.3	2,351	93.6	718	.13
Tumor-Fixation-Verbal (Exp. 1)	87.7	2,746	97.7	627	.13
Tumor-Fixation-Spatial (Exp. 1)	82.0	2,846	97.3	657	.07
Control (Exp. 1)					.20
Verbal-Hint (Exp. 2)			97.1	667	.13
Verbal-Spatial-Hint (Exp. 2)			96.3	684	.47
Verbal-No-Hint (Exp. 2)			96.6	665	.07

Note. RT = response time; Exp. = Experiment.

solution groups. These performance advantages in the visual tracking task for the tumor-fixation groups over the embodied-solution groups are not surprising—eye movements were unnecessary for participants in the former groups to track the stimuli, giving them the advantage of viewing each stimulus at the center of the display for its entire presentation time. The fact that participants in the tumor-fixation groups also had an accuracy advantage over participants in the embodied-solution groups in the memory task is similarly unsurprising, given that the programming and execution of eye movements necessary to track the color points in the latter groups may have interfered with the maintenance of information in working memory (e.g., Lawrence, Myerson, Oonk, & Abrams, 2001).

Problem-solving task. If directed actions influence thoughts through residual activation in spatial working memory, then participants in the embodied-solution-verbal group should have a higher rate of problem-solving success than participants in the embodied-solution-spatial, tumor-fixation, or control groups. Table 1 shows each group's rate of success at the end of 20 attempt intervals, whereas Figure 2 shows the proportion of participants in each group to successfully solve the problem after each attempt interval. I analyzed these data using a Peto-Peto-Prentice survival analysis test that incorporated not only information about the number of participants who were ultimately successful in solving the problem but also information about how quickly these successful participants solved the problem. The survival analysis accounts for the limited time participants had to solve the problem (e.g., Elandt-Johnson & Johnson, 1980). This test comparing the solution rates for all five groups across attempt intervals showed these rates were significantly different from each other, $\chi^2(4, N = 75) = 14.69$, $p < .01$. Planned pairwise comparisons between groups suggested that this effect was driven by higher rates of problem-solving success in the embodied-solution-verbal group than either of the tumor-fixation groups ($\chi^2[1, N = 30] = 7.08$, $p < .01$, vs the tumor-fixation-verbal group; $\chi^2[1, N = 30] = 7.86$, $p < .01$, vs the tumor-fixation-spatial group) or the embodied-solution-spatial group, $\chi^2(1, N = 30) = 4.01$, $p < .05$, and a marginally higher rate of success in the embodied-solution-verbal group than the control group, $\chi^2(1, N = 30) = 3.69$, $p = .05$. No other pairwise comparisons approached significance (all ps $> .3$). The results of these tests not only show that participants in the embodied-solution-verbal group were more likely to solve the problem before their time was up, but also show that those who did solve the problem tended to solve it after fewer intervals than the handful of successful participants in the other conditions.

The results of Experiment 1 suggest that representations in spatial working memory mediate embodied guidance of insight in the radiation problem. Participants in both of the embodied-solution groups performed identical visual tracking tasks in which points appeared in a pattern consistent with the radiation problem's solution. The tracking task helped participants who performed a concurrent verbal memory task to solve the radiation problem more often than participants in either of the tumor-fixation groups, demonstrating the typical embodied boost to problem solving (Litchfield & Ball, 2011; Thomas & Lleras, 2007, 2009a). However, participants who performed the same tracking task while holding a spatial stimulus in working memory were no more successful in solving the problem than participants who kept their eyes fixed on the tumor or participants who were free to think about the problem without distraction. The embodied pattern did not seem to help participants in the embodied-solution-spatial group arrive at the multiple-lasers solution. Participants did not perform poorly on the radiation problem because they maintained

Table 2
ANOVA Results for Working Memory and Color Tracking Tasks Data

Dependent variable	Factor	F
Memory Task accuracy (Exp. 1)	Memory Task Type	$F(1, 58) = 0.86$
	Tracking Task Type	$F(1, 58) = 4.44^*$
	Interaction	$F(1, 58) = 0.36$
Memory Task RT (Exp. 1)	Memory Task Type	$F(1, 58) = 0.04$
	Tracking Task Type	$F(1, 58) = 1.45$
	Interaction	$F(1, 58) = 0.31$
Tracking Task accuracy (Exp. 1)	Memory Task Type	$F(1, 58) < 0.001$
	Tracking Task Type	$F(1, 58) = 14.13^*$
	Interaction	$F(1, 58) = 0.12$
Tracking Task RT (Exp. 1)	Memory Task Type	$F(1, 58) = 1.82$
	Tracking Task Type	$F(1, 58) = 38.02^*$
	Interaction	$F(1, 58) = 8.52^*$
Tracking Task accuracy (Exp. 2)	Tracking Task Type	$F(2, 41) = 0.24$
Tracking Task RT (Exp. 2)	Tracking Task Type	$F(2, 41) = 0.46$

Note. ANOVA = analysis of variance; Exp. = Experiment; RT = response time.
* $p < .05$.

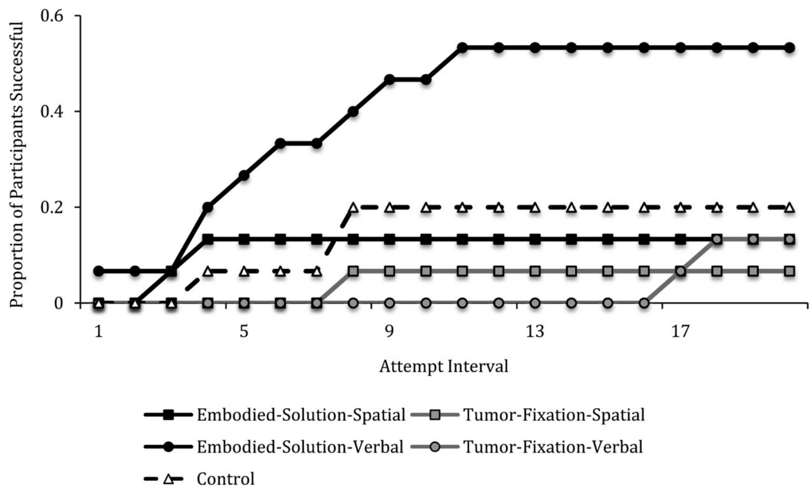

Figure 2. Proportion of participants in each group in Experiment 1 to successfully solve the radiation problem after each interval.

fixation during the tracking task or were distracted by a working memory task: Although participants in the control condition were free to devote all of their attention to solving the radiation problem without interruptions from secondary tasks or detrimental fixation of thought, these participants were no more successful than participants in the tumor-fixation groups or participants in the embodied-solution-spatial group.[2] Participants in the tumor-fixation groups were equally unlikely to solve the problem regardless of whether they performed a spatial or verbal memory task, and memory performance was approximately the same regardless of the nature of the memory stimulus. It is therefore unlikely that participants in the embodied-solution group who performed the spatial working memory task were less successful with the radiation problem simply because this task was more difficult or distracting than the verbal working memory task. Instead, the difference in problem-solving performance between the two embodied-solution groups must stem specifically from the distinction between engaging spatial versus verbal memory resources during the tracking task. Only those participants who moved their eyes in a pattern that embodies the solution—and had spatial working memory resources free while they executed these movements—experienced problem-solving facilitation.

Although the results of the first experiment support the hypothesis that spatial working memory resources must be available in order for actions to guide thought, it is unclear whether solving the radiation problem necessarily engages spatial working memory. Is this an inherently spatial problem, or could a strictly verbal hint that does not require representation in spatial working memory also prime participants to arrive at the converging lasers solution? Experiment 2 addressed this question.

Experiment 2

Method

Participants. Forty-five undergraduate volunteers from NDSU participated for course credit.

Stimuli, apparatus, procedure, and design. Participants performed in a replication of Experiment 1 in which they attempted to solve the radiation problem while periodically engaging in a color tracking task. No working memory task was required. Participants in Experiment 2 performed a tracking task in which they saw red and blue words that appeared in the center of the display instead of tracking red and blue points appearing at various locations on the screen. These color tracking words appeared with the same frequencies and timings as the color tracking points of Experiment 1.

Participants were assigned to one of three experimental groups of 15 participants each that differed on the basis of the words displayed during the color tracking task. During the tracking task, participants in the verbal-hint condition saw the words *out* and *in* alternating through four repetitions in the center of the screen. These words could provide a hint to the multiple-lasers solution—potentially suggesting lasers that start at different outer points to converge at the tumor—yet do not describe any specific spatial location within the problem diagram. Participants in the verbal-spatial-hint condition instead saw the following sequence of words: *upper left*, *center*, *upper right*, *center*, *lower right*, *center*, *lower left*, *center*. These words may also hint at the convergence solution, but do so by naming specific spatial locations, potentially drawing participants' attention to these locations in a manner that can aid insight (Thomas & Lleras, 2009a). Finally, participants in the verbal-no-hint condition saw the words *off* and *on*—words that

[2] Participants in the control condition were drawn from a different student population than the other groups tested in Experiment 1, raising the question of whether differences in cognitive abilities across populations drove these findings. However, the performance of a separate group of NDSU students receiving similar guidance was not significantly different than Vanderbilt students in the embodied-solution-verbal group ($p > .5$; see Experiment 2), nor was the performance of another group of NDSU students who completed a replication of the embodied-solution-verbal condition ($p > .5$; see General Discussion). The general similarity of performance across similar conditions for Vanderbilt versus NDSU students suggests that these populations were not substantially different in their abilities to solve the radiation problem.

are unrelated to the multiple-lasers target solution—alternating through four repetitions.

Results and Discussion

Color tracking task. Table 1 shows the mean accuracies and response times for the color word tracking task in Experiment 2, whereas Table 2 displays the results of a one-way analysis of variance comparing performance on the tracking task as a function of condition. As can be seen from these tables, participants' speed and accuracy in the tracking task was quite similar across all three groups, suggesting that any differences in problem-solving success across these groups are unlikely to be the result of differences in the level of engagement with the tracking task.

Problem-solving task. Table 1 shows each group's rate of success at the end of 20 attempt intervals. To examine the importance of spatial representations in solving the radiation problem, I again used a Peto-Peto-Prentice survival analysis test to compare problem-solving performance between the three groups across attempt intervals. These solution rates were significantly different from each other, $\chi^2(2, N = 45) = 6.62, p < .05$. Planned pairwise comparisons between groups suggested that this effect was driven by higher rates of problem-solving success in the verbal-spatial-hint group than the verbal-no-hint group, $\chi^2(1, N = 30) = 5.06, p < .05$. Participants in the verbal-spatial-hint group were also marginally more successful in solving the problem than participants in the verbal-hint group, $\chi^2(1, N = 30) = 2.93, p = .09$. However, participants in the verbal-hint group were no more likely to solve the problem than participants in the verbal-no-hint group, $\chi^2(1, N = 30) = 0.36, p > .5$.

The findings of Experiment 2 show that the explicitly spatial words participants in the verbal-spatial-hint group viewed helped them arrive at the insight necessary to solve the radiation problem. Although participants read these words, they also likely formed a spatial representation of the words' meaning. However, the less spatial language that participants in the verbal-hint group saw was no more effective in helping them produce the converging lasers solution than the series of words unrelated to the problem's solution that participants in the no-hint group viewed. These results suggest that purely verbal cues that do not indicate specific locations in space are not particularly effective in facilitating insight into the radiation problem. Instead, the findings of Experiment 2 point to the importance of spatial representations in solving this problem.

General Discussion

The results of the current experiments demonstrate that spatial working memory representations are linked to embodied guidance of thought. In Experiment 1, participants were only able to take advantage of the spatial hint inherent in the pattern of their guided eye movements when spatial working memory resources were available as they performed these actions. When participants performed the same priming actions while also holding material in spatial working memory, they were no more likely to solve the radiation problem than participants who did not move their eyes in this helpful pattern. The results of Experiment 2 emphasize the importance of spatial representations in the radiation problem—verbal hints at the problem's solution were most effective only when they contained inherently spatial material.

Why did a spatial working memory load interfere with the problem-solving benefits of the embodied tracking task in Experiment 1? Although unlikely given participants' high performance on the tracking task, it is possible that the spatial working memory task actually prevented participants from executing the pattern of priming actions the embodied-solution tracking task was designed to elicit. Eye movements, spatial attention, and spatial working memory are closely linked, with shifts of spatial attention serving as a means to maintain spatial information in working memory (e.g., Awh & Jonides, 2001). Participants in the embodied-solution-spatial group might have shifted their eyes to rehearse the locations of the dots in the memory grid during the tracking task, potentially disrupting the intended helpful pattern of eye movements. However, in a replication of the embodied-solution conditions in which eye movements were recorded, although spatial working memory load once again reduced the effectiveness of eye movements in guiding insight, the pattern of executed eye movements was similar regardless of whether participants performed a spatial or verbal working memory task.[3] Instead of preventing participants from moving their eyes in a manner that could guide insight, the maintenance and/or retrieval of the spatial memory stimuli prevented representations of these eye movements from influencing conceptualization of the radiation problem.

Participants in the spatial memory condition had to maintain representations of the to-be-remembered dots in working memory as they moved their eyes in a pattern that embodied the problem's solution. They then had to access a working memory representation of the remembered dot locations immediately after executing these movements. Engaging spatial working memory in this manner left insufficient resources available for participants to also represent the locations of their recently executed actions in spatial working memory. These actions did not help participants to arrive at the insight necessary to solve the problem because participants did not represent the actions in a format that allowed access to higher order processes. Participants who tried to remember digits across tracking eye movements contended with similar memory demands, but this load tied up verbal rather than spatial representations, leaving open a route for actions to influence spatial representations of the radiation problem. Movement representations do not automatically or obligatorily spread to trigger movement-related thoughts that influence problem solving. Instead, actions only influence higher order cognition when they can receive representation in spatial working memory. Spatial working memory was necessary for participants' eye movements to guide them toward insight.

Although the current study focuses on cases in which actions prime insight, the results potentially have relevance for the embodied cognition literature more broadly. Documented relationships between sensorimotor representations and the comprehen-

[3] Two new groups of NDSU students ($N = 30$) performed in the embodied-solution-verbal and embodied-solution-spatial conditions while an EyeLink 1000 video-based eyetracker (SR Research, Ltd.) recorded their eye movements. Participants in the embodied-solution-spatial group were significantly less successful in solving the radiation problem than participants in the embodied-solution-verbal group (.47 vs. .07), $\chi^2(1, N = 30) = 5.09, p = .02$, but made approximately the same number of saccades crossing from the inner to the outer area of the problem diagram and fixated the tracking points with similar accuracy and for similar durations as participants in the other group (all ps $> .3$).

sion of language (e.g., Zwaan & Taylor, 2006), number (Lindemann, Abolafia, Girardi, & Bekkering, 2007), and time (Casasanto & Boroditsky, 2008) have led some theorists to argue that cross-talk is automatic. However, demonstrations of priming or interference between sensorimotor simulations and higher order cognition do not necessarily imply that these connections are obligatory. The current work raises the possibility that effective simulations may require working memory resources. For example, a spatial working memory load may attenuate motor resonance in language comprehension, whereas loading verbal working memory could interfere with auditory simulations (e.g., Brunyé, Ditman, Mahoney, Walters, & Taylor, 2010). Future research will be necessary to fully explore the relationship between working memory representations and sensorimotor simulations.

Although the current study sheds new light on the importance of spatial working memory resources for the embodied guidance of insight, it also speaks to the literature on the importance—or lack thereof—of executive control resources in insight problem solving. Holding information in verbal working memory did not prevent actions from facilitating problem solving, and actions can prime insight even when participants perform a backward counting task while moving (Thomas & Lleras, 2009b), suggesting that central executive/attentional control resources (e.g., Baddeley, 1992) need not be available during movement execution in order for these movements to shape subsequent thoughts. These findings are consistent with the idea that automatic restructuring resolves impasses in insight problem solving (e.g., Ash & Wiley, 2006; Ohlsson, 1992; Seifert, Meyer, Davidson, Patalano, & Yaniv, 1995). According to this view, problem solvers initially conceptualize insight problems in inappropriate ways. Automatic restructuring occurs when inappropriate connections fade, allowing new connections made through activation from a novel source—such as an external cue, or, in the case of embodied guidance, internal action representations in working memory—to break through as viable paths to a solution. Automatic restructuring does not place demands on central attentional control mechanisms, but for directed actions to drive restructuring, spatial working memory must be available to represent movement trajectories.

In sum, the results of the current study show that directed eye movements embodying the solution to a problem can guide insight, but only when spatial working memory is free as the eyes move. The embodied cognition literature shows that the ways in which we move can impact the course of subsequent processing, from visual discrimination (Casile & Giese, 2006) to cognitive control (Koch, Holland, Hengstler, & van Knippenberg, 2009). This study moves the literature forward, documenting not only another instance in which actions influence thoughts, but also pointing to a mechanism that can mediate these interactions: Our actions shape our thoughts through representations in the spatial module of working memory. The study also has implications for the best way to apply theories of embodied cognition. For example, in order to best take advantage of the potential actions have to guide thoughts in learning situations (i.e., Cook et al., 2008), researchers should be careful to keep demands on spatial working memory low as the learners move. Another implication of the current work is that individuals with the highest spatial working memory capacity may also be the most likely to experience actions guiding their thoughts; the more working memory capacity one has, the more likely an action will receive representation in spatial working memory and have access to higher order processing. Future investigations of directed actions may help tease apart the contribution of individual differences in spatial working memory to embodied effects.

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