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# Covert shifts of attention function as an implicit aid to insight

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ABSTRACT

Previous research shows that directed actions can unconsciously influence higher-order cognitive processing, helping learners to retain knowledge and guiding problem solvers to useful insights (e.g. Cook, S. W., Mitchell, Z., & Goldin-Meadow, S. (2008). Gesturing makes learning last. *Cognition, 106*, 1047–1058; Thomas, L. E., & Lleras, A. (2007). Moving eyes and moving thought: on the spatial compatibility between eye movements and cognition. *Psychonomic Bulletin and Review, 14*, 663–668). We examined whether overt physical movement is necessary for these embodied effects on cognition, or whether covert shifts of attention are sufficient to influence cognition. We asked participants to try to solve Duncker's radiation problem while occasionally directing them, via an unrelated digit-tracking task, to shift their attention (while keeping their eyes fixed) in a pattern related to the problem's solution, to move their eyes in this pattern, or to keep their eyes and their attention fixed in the center of the display. Although they reported being unaware of any relationship between the digit-tracking task and the radiation problem, participants in both the eye-movement and attention-shift groups were more likely to solve the problem than were participants who maintained fixation. Our results show that by shifting attention in a pattern compatible with a problem's solution, we can aid participants' insight even in the absence of overt physical movements.

## 1. Introduction

Accumulating evidence within the embodied cognition literature shows that the mind uses the body to accomplish cognitive goals, both through direct action and by tapping into perceptual and motor resources to represent and manipulate information (e.g. Barsalou, 1999; Glenberg, 1997; Wilson, 2002; Zwaan, 1999). Mental simulations, situated action, and bodily states underlie thought processes in perception, language comprehension, memory, social cognition, and conceptual processing (for a review, see Barsalou, 2008). Recently, researchers have begun to investigate the nature of mind–body interactions, examining the possibility that we not only use our bodies to think, but that cognitive processes can actually arise from the manner in which our bodies interact with the immediate environment and moreover, that directed actions can guide thought.

A few recent studies have established a causal link between directed action and higher-order cognition. Children who are required to gesture while undergoing instruction on a new mathematical concept are more likely to retain the knowledge they gained during instruction (Cook, Mitchell, & Goldin-Meadow, 2008). Participants attempting to solve a difficult spatial reasoning problem are more likely to succeed if they are led to occasionally move their arms in a pattern related to the problem's solution, even though they are unaware of the relationship between their movements and the problem (Thomas & Lleras, submitted for publication). Similarly, participants who move their eyes in a pattern related to a problem's solution are also more likely to succeed than participants who move their eyes in patterns unrelated to the solution (Grant & Spivey, 2003; Thomas & Lleras, 2007). These results show that by directing people's actions, we can influence how they

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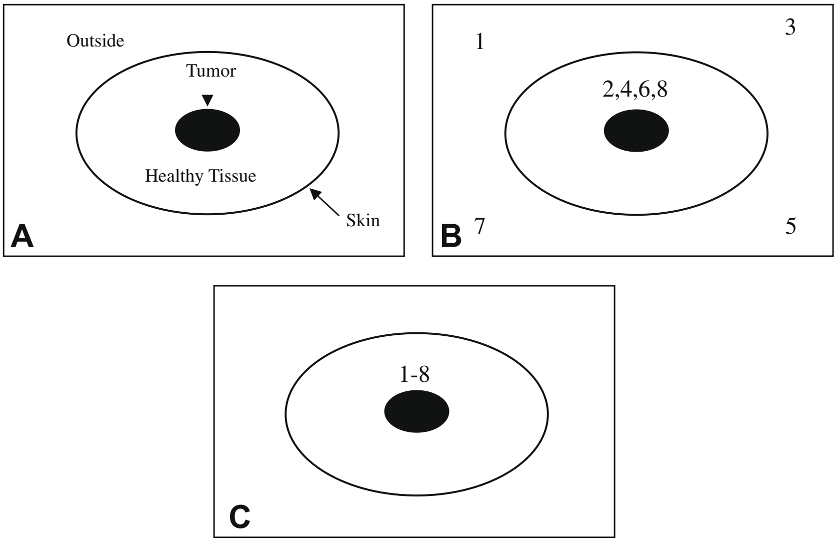

**Fig. 1.** Diagram of Duncker's radiation problem. Panel B shows the letter/digit sequence locations for the eye-movement and attention-shift groups. Participants in the eye-movement group tracked these items via overt eye-movements while participants in the attention-shift group maintained a central fixation and tracked the items via covert movements of attention only. Panel C shows the sequence for the tumor-fixation and no-eye-movement groups.

think, but the boundaries of this causal link between action and higher-order cognition are still unclear. Are overt, physical actions necessary for us to obtain embodied effects on problem solving, or are covert processes sufficient? What is it about body movements that guide cognitive processes?

To examine these questions, we asked participants to solve a classic insight problem,[1] Karl Duncker's (1945) radiation problem, while occasionally directing them to either move their eyes or shift attention via a digit-tracking task in which they identified digits amongst letters appearing at various locations in the display. Participants viewed the diagram in Fig. 1A and read the following instructions[2]:

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?

To solve this problem, participants must choose to fire multiple low-intensity lasers from different points around the tumor such that they converge at the tumor. Although each individual laser is not strong enough to damage the healthy tissue surrounding the tumor, the combined intensity of multiple lasers meeting at the tumor is sufficient to destroy it. Grant and Spivey (2003) found that participants who spontaneously solved the radiation problem tended to move their eyes in a pattern compatible with the problem's solution immediately beforehand, hinting at a link between eye movement patterns and higher-order cognition. Thomas and Lleras (2007) tested the directionality of this link and discovered that participants who were 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 the skin to a point just above the tumor, and then again crossing the skin to a different outer location of the diagram and so forth – were two-and-a-half times more likely to solve the problem than participants who moved their eyes in other, unrelated patterns.

While these results show that directed eye movements guide insight, it is possible that physical movement of the eyes did not drive the effect. In the current paper, we examined whether we could obtain implicit effects of directed action on cognition in the absence of overt body movements, exploring the influence of directed shifts of covert attention on high-level cognition. Shifts of covert visual attention precede saccadic eye movements to locations in space (e.g. Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995), and one classic theory of attention postulates that attention movements are planned-but-unexecuted eye movements (Rizzolatti, Riggio, Dascola, & Umilta, 1987), so perhaps these sequential shifts of attention triggered insight, rather than eye movements per se.

Although much research suggests a tight coupling between eye movements and covert attention, recent evidence points to the need for a more nuanced perspective on covert attention, suggesting it is neither a sub-type nor a sub-mechanism of eye movements, but rather a separate mechanism, with distinct properties, serving its own goals. One such view posits that covert attention is the outcome of a saliency analysis of visual input, with attention located at the highest point in the saliency map of the scene (e.g. Clark, 1999; Itti & Koch, 2000; Koch & Ullman, 1985; Wolfe, 1994). This output may or may not then be supplied to saccade-generating mechanisms. According to

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[1] Insight problems are characterized by the fact that solutions seeming most obvious to naïve participants do not work, that participants cannot accurately track or predict their own performance, and that participants must often overcome an impasse in reasoning to infer the problem's solution (Metcalfe & Wiebe, 1987; Weisberg & Alba, 1981).

[2] Diagram and instructions adapted by Grant and Spivey (2003) from Duncker (1945).

another popular conception, covert attention is a mechanism responsible for resolving neural competition for representation (Desimone & Duncan, 1995) rather than an antecedent for eye movements. In addition, research on saccadic adaptation shows that the rate of gain adaptation for saccades is different than for attention movements (e.g. McFadden, Khan, & Wallman, 2002) and that adaptation of the saccadic system does not shift the locus of covert attention (Ditterich, Eggert, & Straube, 2000), suggesting the neural circuitry that computes the magnitude and target destination of attention shifts can adapt independently of the circuitry that computes shifts of the eyes. One last important difference between covert shifts of attention and eye movements is the manner in which they each cover distance. The eyes move in an analog manner, whereas research suggests that covert attention moves discretely. From a computational perspective, a shift of attention is a switch in the ascendancy of different saliency peaks (one becoming less active, one more active), with no physical movement or scanning of locations in between; from an empirical point of view, attention movements have been found to be time and distance invariant (e.g. Egeth & Yantis, 1997; Eriksen & Murphy, 1987; Henderson & Macquistan, 1993; Kwak, Dagenbach, & Egeth, 1991; Remington & Pierce, 1984; Sagi & Julesz, 1985; Sperling & Weichselgartner, 1995).

Given these fundamental differences in the manner in which the eyes move versus the way that attention shifts, it becomes less clear whether or how behavioral effects driven by eye movements will translate to movements of attention. Directed eye movements in Thomas and Lleras (2007) covered area in an analog fashion; participants essentially drew the solution vectors with their eyes as they performed the tracking task. Since attention shifts do not involve a continuous movement across space, they are missing a perhaps crucial vector component (the movement vector itself) that may be necessary for an embodied triggering of insight in the radiation problem. Thus, examining whether covert shifts of attention aid high-level spatial cognition in a similar manner to eye movements will help us constrain the type of mental representations underlying this embodied effect, helping us to answer the question: is the insight of multiple converging lasers triggered by the representation of the movement (itself a physical embodiment of the lasers in the problem), or is it driven by the positional relationship representing separate points outside the body in alternating relation with the tumor, irrespective of movement?

We answered this question by assigning participants to one of four groups differing solely in the pattern in which they moved their eyes or shifted their attention during the tracking task. Participants in the eye-movement group made skin-crossing saccades to several locations during the tracking task, emphasizing an in-and-out pattern that embodies the multiple converging lasers solution to the radiation problem. Participants in the attention-shift group were presented with the exact same stimuli in the exact same sequence as participants in the eye-movement group, but we instructed these participants to track the items covertly, attending to each stimulus as it appeared while keeping their eyes stationary at the center of the display. Participants in the tumor-fixation group viewed all tracking items at the center of the display; they did not need to make skin-crossing saccades or shift their attention to perform the tracking task. Likewise, participants in the no-eye-movement group also viewed all tracking items at the center of the display, but in addition, we instructed these participants to keep their eyes fixated at the center throughout the entire experiment, even during non-tracking periods. We compared the rates of problem-solving success between these four groups to determine the impact of shifts of covert attention on higher-order cognition.

## 2. Methods

### 2.1. Participants

Ninety-two undergraduate students unfamiliar with the radiation problem participated in one experimental session for course credit or monetary compensation.

### 2.2. Stimuli and apparatus

The stimuli were a diagram of the radiation problem (Fig. 1) and a random selection of letters and digits. We presented stimuli on a 21 in. monitor with resolution of $800 \times 600$ pixels. An EyeLink II video-based eyetracker (SR Research Ltd., Mississagua, Ontario, Canada) with a temporal resolution of 500 Hz and a spatial resolution of $0.1^\circ$ recorded eye movements. It classified an eye movement as a saccade when its distance exceeded $0.2^\circ$ and its velocity reached $30^\circ/s$, or when its distance exceeded $0.2^\circ$ and its acceleration reached $9500^\circ/s^2$.

During the experiment, participants' heads were stabilized by a chinrest 42 cm from the display monitor. At this viewing distance, the outer oval within the problem space subtended approximately 29° of visual angle horizontally and 18° vertically. Individual letters and digits subtended approximately 3° horizontally and 7° vertically. The drift correction dot presented at the start of each trial subtended 1°. Participants made their responses via keys on a game pad interfaced with the EyeLink software.

### 2.3. Procedure

The experimenter fitted participants with the eyetracker and ran a calibration procedure. Participants then saw a display of the problem diagram with written instructions detailing the radiation problem and the letter/digit-tracking task that the experimenter read aloud. Following the instructions, participants pressed a game pad key to begin the experiment.

#### 2.3.1. Free-viewing period

We divided the experiment into 20 30 s intervals. Each interval consisted of a 26 s free-viewing period and a 4 s tracking task. Before each interval, participants performed a drift correction procedure. Following successful drift correction, the problem diagram appeared alone on the display for 26 s. During this period, participants in the eye-movement, attention-shift, and tumor-fixation groups were free to move their eyes or fixate anywhere within the display, while we instructed participants in the no-eye-movement group to keep their eyes fixated in the center of the display.

#### 2.3.2. Tracking task

Following the free-viewing period, a random string of eight letters and digits appeared at various locations on the display at a rate of 500 ms/item. We asked participants to press the game pad key under their right index finger whenever a digit appeared and measured their digit detection reaction times. Because the letters and digits were large, participants did not need to foveate items to perform this task. We recorded participants' eye movements throughout the entire experiment.

The four experimental groups differed based on the pattern in which letters and digits appeared during the tracking task and on the instructions they received. Fig. 1 illustrates the differences between groups. For each group, the sequence of locations at which the tracking items appeared was the same for every interval.

The tracking task for the eye-movement group emphasized triangular in-and-out eye movements that crossed from the outside area, over the skin to the tumor, and then back out to a different location of the outside area. We told participants in the eye-movement group to follow the tracking items with their eyes. The letter/digit sequence appeared, in order, over the following locations: upper left corner, center, upper right corner, center, lower right corner, center, lower left corner, center (see Fig. 1B).

Participants in the attention-shift group were presented with the exact same sequence of items in the exact same locations as participants in the eye-movement group, but we asked these participants to keep their eyes fixated in the center of the display during the tracking task and to track the items only via shifts of visual attention. The experimenter monitored eye movements during the tracking task; if a participant moved her eyes during the tracking task, the experimenter reminded her to try to maintain a central fixation.

Participants in the tumor-fixation and no-eye-movement groups performed a tracking task in which all eight items appeared sequentially in the center of the display (see Fig. 1C).

#### 2.3.3. Problem solution and experiment completion

In addition to performing the letter/digit-tracking task, participants also attempted to solve the radiation problem. They were free to pause the experiment and guess the problem's solution at any time. When a participant believed she had solved the problem, she pressed a game pad key under her left index finger, pausing the current interval. The experimenter placed tracing paper over the display and asked the participant to draw her solution on the paper. If the solution was correct (i.e. showed at least two lines from different outer locations crossing the skin to converge at the tumor), the experiment ended. If the solution was incorrect, the participant restarted the current interval and was free to guess again at any time. The experiment concluded whenever a participant solved the problem, or after 10 min at the task (i.e. 20 tracking sequences), whichever happened first.

After the experiment ended, participants completed a short post-test questionnaire that asked whether they saw a relationship between the radiation problem and the digit-tracking task.

## 3. Results

### 3.1. Tracking task

We evaluated the performance of each participant on the digit-tracking task. Table 1 shows the mean digit identification accuracies and reaction times for each of the experimental groups. Although a one-way ANOVA showed no effect of group on digit identification accuracy ($F(3,88) = 2.3$, $MSE = 87.35$, $p = 0.08$), there was a significant effect of group on reaction time ($F(3,88) = 11.12$, $MSE = 5221.90$, $p < 0.001$). A Tukey planned comparison confirmed that RTs for the tumor-fixation group were significantly faster than RTs for the eye-movement group ($p < 0.01$) and the attention-shift group ($p < 0.01$) and that RTs for the no-eye-movement group were also significantly faster than RTs for either of these groups ($p = 0.02$ vs. eye-movement group; $p = 0.05$ vs. attention-shift group). This RT advantage for the tumor-fixation and no-eye-movement groups was to be expected given that participants in these groups did not have to move their eyes or their attention in order to track the stimuli and therefore had the advantage of viewing each stimulus at fixation for its entire presentation time.

In order to determine the effectiveness of our instructions in eliciting the desired eye movements/attention shifts, we counted the number of skin-crossing saccades participants made during the tracking task. Fig. 2A shows the average number of skin-crossing saccades participants in each of the four groups made during the tracking intervals. The effect of group was significant in a one-way ANOVA ($F(3,88) = 279.94$, $MSE = 0.54$, $p < 0.001$). A Tukey planned

**Table 1**
Tracking task performance, skin-crossing saccades, and solution rate as a function of group.

| Group | Tracking task accuracy (%) | Tracking task RT (ms) | Skin-crossing saccades during free-viewing period | Skin-crossing saccades during tracking task | Solution rate |
|---|---|---|---|---|---|
| Eye-movement | 92 | 545 | 8.99 | 5.4 | 0.39 |
| Attention-shift | 90 | 536 | 6.58 | 0.5 | 0.30 |
| Tumor-fixation | 96 | 438 | 9.18 | 0.2 | 0.13 |
| No-eye-movement | 90 | 480 | 1.63 | 0.3 | 0.09 |

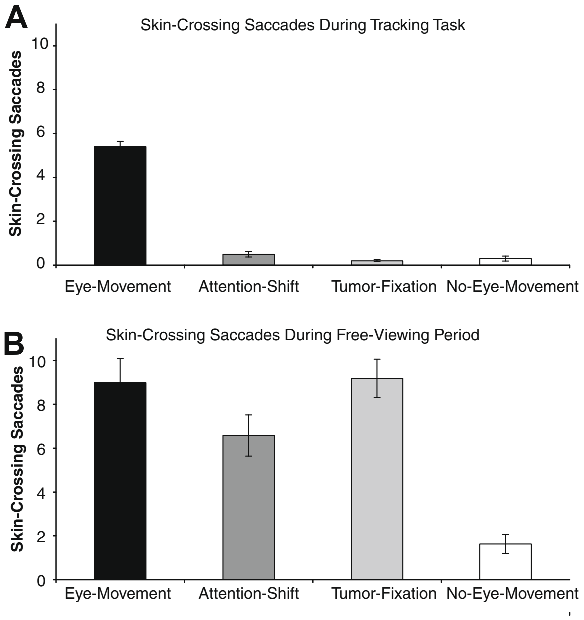

**Fig. 2.** Mean number of skin-crossing saccades for each of the four groups. Panel A shows the mean number of skin-crossing saccades during the 4 s tracking task and Panel B shows the mean number of skin-crossing saccades during the 26 s free-viewing periods.

comparison showed that participants in the eye-movement group made more skin-crossing saccades during the tracking task than did participants in the attention-shift group, the tumor-fixation group, and the no-eye-movement group (all $p$-values < 0.01); all other pairwise comparisons were non-significant. These results confirmed that participants in the eye-movement group did in fact track items via saccades, that participants in the attention-shift group maintained fixation during the tracking task (tracking the same items via movements of attention), and that participants in the tumor-fixation and no-eye-movement groups also maintained fixation during the tracking task.

We also examined whether there were any differences between the average number of skin-crossing saccades participants in each of the groups made during the free-viewing period, as shown in Fig. 2B. A one-way ANOVA showed a significant effect of group on free-viewing saccades ($F(3,88) = 16.32$, $MSE = 17.44$, $p < 0.001$). As expected based on our instructions, participants in the no-eye-movement group made fewer skin-crossing saccades during the free-viewing period than did participants in any of the other groups (all $p$-values < 0.01); all other pairwise comparisons were non-significant.

### 3.2. Problem-solving task

We were primarily interested in whether participants' pattern of eye and attention movements during the tracking task influenced their chances of successfully solving the radiation problem. Table 1 shows each group's rate of problem-solving success at the end of the 10 min period, while Fig. 3 shows the proportion of participants in each group to successfully solve the problem after each 30 s interval. A log-rank test for equality of survivor functions comparing the solution rates for all four groups showed these rates were significantly different ($\chi^2(3, N = 92) = 8.39$, $p = 0.04$). Planned pairwise comparisons between groups suggested that this effect was driven by significant differences in solution rates between the eye-movement and tumor-fixation groups ($\chi^2(1, N = 46) = 4.16$, $p = 0.04$), between the eye-movement and no-eye-movement groups ($\chi^2(1, N = 46) = 6.06$, $p = 0.01$), and between the attention-shift and no-eye-movement groups ($\chi^2(1, N = 46) = 3.63$, $p = 0.05$); no other pairwise comparisons were statistically significant (all $p > 0.14$). However, a comparison of solution rates for the attention-shift group versus the tumor-fixation and no-eye-movement groups combined was also significant ($\chi^2(1, N = 69) = 4.54$, $p = 0.03$).

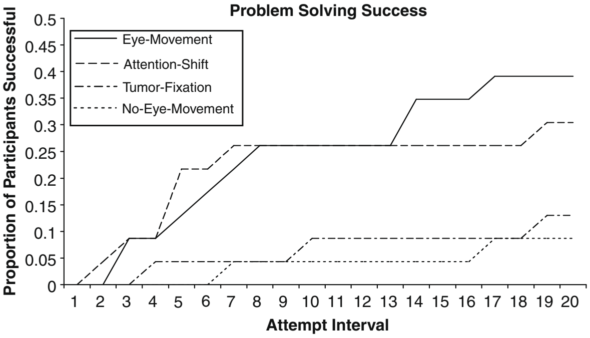

**Fig. 3.** Proportion of participants in each group to successfully solve the radiation problem after each interval.

A check of the post-test questionnaires participants completed showed that none of the participants reported seeing a relationship between the tracking task and the radiation problem.

## 4. Discussion

Our results demonstrate that covert shifts of attention can act as an aid to insight; participants who kept their eyes fixated on a central location but were directed to shift their attention in a pattern consistent with the solution to the radiation problem were more likely to solve the problem than were participants who kept both their eyes and their attention fixed in the center of the problem diagram. In addition, our results replicate the findings of Thomas and Lleras (2007); once again, participants who made directed eye movements (and the necessary accompanying shifts of attention) embodying the solution to the radiation problem were more successful than participants who did not move their eyes or shift attention in this helpful pattern. In fact, the lack of a significant difference between problem-solving success rates in our eye movement and attention-shift conditions suggests that the boost in success of participants in the eye-movement group was largely driven not by the physical eye movements, but rather by the shifts of attention which preceded them.

Moreover, we found that the influence of directed movements on cognitive processing occurs outside of participants' conscious awareness. To the extent that our post-test questionnaire accurately captured participants' perceptions of the relationship between the tracking and problem-solving tasks, our results suggest that movements of the eyes and shifts of attention implicitly guided participants toward the insight necessary to solve the problem. Additional support for the claim that our manipulations influenced participants implicitly can be found in our eye movement data for the free-viewing periods. With the exception of participants in the no-eye-movement group, who were explicitly instructed not to move their eyes, there were no significant differences in the number of spontaneous skin-crossing saccades between groups. Had participants in the eye-movement or attention-shift groups been aware that the pattern in which stimuli appeared during the tracking task was related to the radiation problem's solution, we might have expected them to move their eyes in this pattern and make more skin-crossing saccades during the free-viewing period than participants in the tumor-fixation group. In light of the substantial difference between skin-crossing saccades during the free-viewing period for the tumor-fixation and no-eye-movement groups, coupled with the lack of difference between these groups' solution rates, we can in fact conclude that spontaneously produced skin-crossing saccades did not have much of an influence on problem-solving success; it was the particular pattern in which the eyes or attention shifted during the short tracking periods that facilitated insight.

We have demonstrated that overt physical movements are not necessary for participants to experience the benefits of embodied guidance during problem solving: directed covert shifts of attention were equally as effective as overt directed eye movements in facilitating insight. This is surprising in light of the fact that attention does not move in an analog fashion (e.g. Egeth & Yantis, 1997; LaBerge, Carlson, Williams, & Bunney, 1997); participants did not "draw" the solution vectors as they shifted attention in the same way that they did when they moved their eyes, and yet these discrete shifts still helped participants to arrive at the multiple converging vectors solution. From this, we can conclude that directional movement vectors are not the underlying force behind eye movements' embodied guidance of insight. Instead, our results suggest that the mechanism driving our effects is the alternating relationship between the central tumor in the diagram and the multiple outer locations. As long as participants shift attentional focus in an alternating manner from the inner tumor to separate outer points, there is no need for actual in-and-out movements that enact the path of the lasers, nor does there seem to be a need for internally representing such movements. This finding is also consistent with the observation that movement vectors may be confusing cues to problem solvers; in the embodied-solution group, there are as many "outgoing" movement vectors as there are "ingoing" ones, and it is not clear how thinking of lasers shooting out of the tumor towards the outside would improve solution rates to the problem. In contrast, representing the positional relation "in–out–in–out–in–out" with a constant value for the "in" location and a varying value for the "out" location may lend itself to analogous thoughts of a constant location of interest surrounded by various outer locations. Consistent with this idea, we found that participants rarely drew solutions that used the same outer locations as those referenced in the tracking task as the starting point for the lasers' trajectories; they also tended to draw more or fewer converging lasers than the four suggested by the tracking task. If the movements themselves had influenced participants, we may have expected a greater degree of similarity between drawn solutions and the outer locations from the tracking task. Instead, the pattern of drawn solutions suggests guided movements of the eyes and shifts of attention influence thoughts at a more conceptual, less physical/procedural level.

In addition to demonstrating that an attentional mechanism divorced from physical movements underlies eye-movements' embodied effects on problem solving, this work also raises two intriguing possibilities. First, if shifts of attention in the absence of physical movements are sufficient to aid insight in problem solving, perhaps even passive perception of another person's movements – movements seemingly unrelated to the task at hand – can also help participants find solutions to complex spatial problems. In future work, we plan to take advantage of the tight coupling of perception and action systems (e.g. Hommel, Müsseler, Aschersleben, & Prinz, 2001; Sebanz, Knoblich, & Prinz, 2003) to directly test whether we can guide participants' insights by having them observe others' actions. Second, and more generally, our results broaden our understanding of the nature of human thought: higher-order cognition is not an isolated module in the mind. In our experiments, we have found cross talk between cognitive, attention, and action systems that is spatial in nature. Perhaps cross talk can be expected between modules along other types of representational and topological compatibilities (e.g. Boroditsky & Ramscar, 2002; Cohen Kadosh, Sagiv, Linden, Robertson, Elinger, & Henik, 2005). In sum, our results show that discrete shifts of visual attention can explain embodied effects on problem solving previously connected only to physical actions and, more broadly, that cross talk between seemingly independent modules of the mind can shape human thought.

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