# Research Article

## EYE MOVEMENTS AND PROBLEM SOLVING: Guiding Attention Guides Thought

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**Abstract—***Overt visual attention during diagram-based problem solving, as measured by eye movements, has been used in numerous studies to reveal critical aspects of the problem-solving process that traditional measures like solution time and accuracy cannot address. In Experiment 1, we used this methodology to show that particular fixation patterns correlate with success in solving the tumor-and-lasers radiation problem. Given this correlation between attention to a particular diagram feature and problem-solving insight, we investigated participants' cognitive sensitivity to perceptual changes in that diagram feature. In Experiment 2, we found that perceptually highlighting the critical diagram component, identified in Experiment 1, significantly increased the frequency of correct solutions. Taking a situated perspective on cognition, we suggest that environmentally controlled perceptual properties can guide attention and eye movements in ways that assist in developing problem-solving insights that dramatically improve reasoning.*

Numerous researchers since the 1970s have developed methods of recording eye movements as a "window to the mind." In particular, eye-tracking is useful for learning about the on-line process of diagram-based problem solving, which standard problem-solving measures like solution time and accuracy cannot address. Early studies showed some evidence that eye movements can correspond to inference making (Hunziker, 1970; Lenhart, 1983; Nakano, 1971). For example, Just and Carpenter (1985) found that gaze patterns across visual stimuli reflected solution strategies for mental rotation problems. More recently, eye movement patterns have been found to reflect strategic aspects of problem solving in the domains of geometric reasoning (Epelboim & Suppes, 1997), reasoning about mechanical systems (Hegarty, 1992; Hegarty & Just, 1993; Rozenblit, Spivey, & Wojslawowicz, 2002), and insight problem solving (Knoblich, Ohlsson, & Raney, 2001; see also Hodgson, Bajwa, Own, & Kennard, 2000).

As in these studies, we used eye movements in an initial study to discover the attentional and perceptual processes that accompany the solution of a well-known insight problem: Karl Duncker's (1945) radiation problem. In our second experiment, we tested for the reverse effect: how perceptual changes that elicit shifts of visual attention to critical diagram features might themselves facilitate correct inferences. Several theories of insight problem solving have proposed that directing attention to particular features of the problem is one key to generating insight. We evaluated whether a subtle perceptual change in the diagram directed attention away from unhelpful problem features and thereby facilitated insight. It is known that cognition often directs attention, but can attention sometimes direct cognition? In other words, if we led problem solvers' eyes to fodder, could we make them think?

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Insight problems are characterized as problems in which the solution cannot be logically induced. For non-insight problems, such as algebra problems, the strategy that seems the most intuitively likely to lead to a solution is typically correct; in contrast, the strategy that initially seems likely to be successful in solving an insight problem is typically incorrect, which leads to an impasse. In a process uncorrelated with participants' expectations for their own performance (Metcalfe & Wiebe, 1987), this impasse is then unpredictably overcome, leading to the solution; problem solvers often experience their discovery of the solution as an unexpected Aha! sensation (Duncker, 1945; Kaplan & Simon, 1990). What leads to the impasse is generally agreed to be inappropriate constraints applied to the problem (Ormerod, MacGregor, & Chronicle, 2002). Knoblich et al. (2001) proposed that these constraints come from the activation of knowledge elements from past experiences that are unhelpful and lead problem solvers to attempt intuitive but wrong strategies. The critical question of exactly how impasses are overcome has been a topic of recent interest (Kaplan & Simon, 1990; Knoblich, Ohlsson, Haider, & Rhenius, 1999; Ormerod et al., 2002).

Restructuring the initial misleading representation of the problem is often suggested to be the source of insight (e.g., Duncker, 1945; Mayer, 1995). Knoblich et al. (1999) have proposed constraint relaxation and chunk decomposition as mechanisms that support representational restructuring by activating knowledge in working memory that leads to revising the misleading initial representation in a way that can resolve the impasse. In more recent work, Knoblich et al. (2001) discussed the allocation of visual attention to the visual stimulus as an outcome of the representational restructuring process. But perhaps attention is more than just an outcome. Perhaps attention can itself facilitate the restructuring process.

### DUNCKER'S RADIATION PROBLEM

Duncker's radiation problem (1945), a notoriously difficult insight problem, has served as a fertile resource for psychologists investigating the nature of scientific inference making. Figure 1 depicts the diagram we used in the present study. Participants viewed this diagram while generating solutions according to the following instructions (diagram and instructions adapted from Duncker, 1945):

> 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?

The solution requires firing multiple low-intensity lasers from several angles outside the healthy tissue so that they converge at the tumor, with combined intensity sufficient to destroy it.

As shown in the figure, the diagram contained four areas of relevance to the solution. The center black oval represents the tumor and is the target for the lasers. The white area outside the center oval and within the outside oval represents the healthy tissue, which cannot be

  

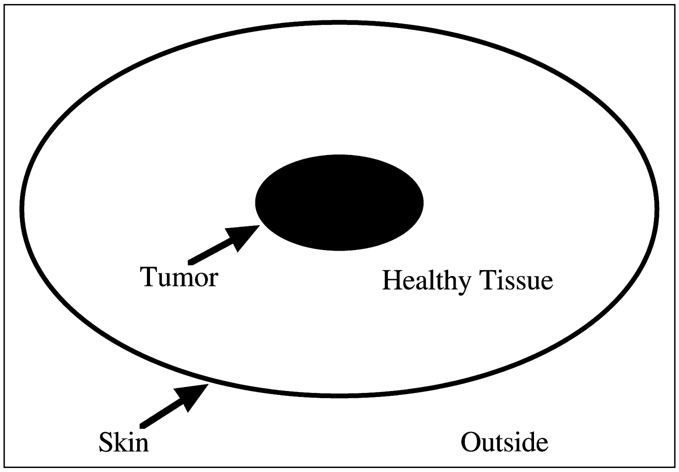


**Fig. 1.** The diagram that participants viewed while solving Duncker's (1945) radiation problem. The labels of diagram features were not shown; the features were verbally explained.

damaged. The outside black oval represents the skin that surrounds the healthy tissue through which the lasers must innocuously pass. The white area outside the outer oval represents the outside area from which multiple lasers must fire at different angles in relation to the tumor. We called these four areas, respectively, the tumor, the healthy tissue, the skin, and the outside. The lasers were not depicted in the diagram; their sources and trajectories had to be imagined by the participants.

From pilot data, we knew that participants often consider solutions that try to vary aspects of the problem that are actually invariant: the relative locations of tumor and skin, and the chemical compositions of the tumor and of the healthy tissue around it. At the same time, the activated familiar knowledge suppresses attention to the main constraints of the problem, that healthy tissue cannot be harmed and that the only tools that can be used are the lasers. Participants impose mistaken constraints that they have only one laser and that it remains at a harmfully high intensity, and thus discard lasers initially as too harmful to use. However, when explicitly instructed to relax these particular constraints, they nearly all immediately generate the solution (Weisberg & Alba, 1981). Thus, as Knoblich et al. (1999) suggested, participants have to relax these self-imposed number and intensity constraints in order to generate insight.

In the following two experiments, we considered two hypotheses: (a) Successful problem solvers direct more attention to the outer regions of the diagram and less to the tumor and healthy tissue than unsuccessful problem solvers do, because the outer regions are where the multiple laser rays must be imagined, and (b) by perceptually guiding subjects toward attending to those outer regions, it is possible to improve success rates.

## EXPERIMENT 1

### Method

Fourteen Cornell University students who were unfamiliar with Duncker's radiation problem and had normal or corrected-to-normal vision participated for course credit.

Our stimulus was the two-dimensional static diagram in Figure 1; its area equaled approximately 30° × 30° of visual angle. Participants were seated approximately 30 cm away from a vertical white marker board to which we had affixed a clear overhead transparency sheet printed with this diagram. Participants' eye movements were monitored using a lightweight ISCAN headband-mounted eyetracker, which allowed participants' heads to move naturally. Viewing was binocular, and eye position was recorded from the left eye with an accuracy of about 0.5°, sampled at 60 Hz. Eye position, verbal protocols, drawings, and solution times were recorded on a Sony Hi-8 VCR with 30-Hz frame-by-frame playback.

Participants were tested individually by the same experimenter in a laboratory with controlled lighting. The eyetracker was placed on each participant's head and was calibrated before the task began by having the participant look sequentially at a grid of eight black dots surrounding the diagram, at the inside oval of the diagram, and at one or more points along the outside oval of the diagram. After calibration of the eyetracker, which lasted approximately 5 to 8 min, the participant was allowed to move his or her head naturally.

Each participant was asked to give a verbal protocol of the solution and also to draw the solution on the diagram, using dry-erase markers, so that we could confirm the accuracy of the spoken solution (e.g., placement of laser sources at appropriate angles). The experimenter then read the problem instructions aloud and explained how the elements of the diagram correspond to the elements of the problem. During the solution attempt, the experimenter remained silent except for answering direct questions about the problem. The task ended after the participant spontaneously inferred the solution or at 10 min, whichever came first. In order to create equivalent time segments for all participants for coding eye movements immediately prior to the solution, the experimenter read one or more hints to unsuccessful participants to allow them to reach the solution. Hint 1 read, "What if you could adjust the intensity of the lasers?" Hint 2 read, "What if you had more than one laser?" The task was ended and hints were given before 10 min only if participants repeatedly stated that they could not generate any further solutions.

Solutions were scored as successful if the participants spontaneously inferred the solution before the task ended (within 10 min), or as unsuccessful if the participants failed to reach the solution in 10 min and solved the problem only with hints.

Eye movements were analyzed by coders who were blind to participants' solution times and success (intercoder reliability ranged from 90% to 100% across time). Two 900-frame time segments were coded for all participants: the 30 s after they heard the instructions (beginning time segment) and the 30 s before they stated and drew the correct solution (end time segment). This moment of insight was clearly identifiable, typically marked by an intake of breath and a comment like "Aha!" "Oh, I know," or "Okay, I have it"; the participant then simultaneously drew and explained the correct solution. Although participants may have drawn prior to this time, those drawings did not depict the correct solution.

For these two 30-s time segments, coders assigned the position of each participant's gaze during each video frame (sampled on the VCR at 30 Hz) to one of five mutually exclusive and exhaustive diagram locations: tumor, healthy tissue, skin, outside, or irrelevant (eye-position crosshairs either absent from the screen or focused on an object other than the diagram, such as the participant's hand or the marker).

### Results and Discussion

Thirty-six percent ($n = 5$) of participants solved the problem successfully; 64% ($n = 9$) were unsuccessful and required hints. We conducted analyses to compare the eye movement patterns of successful problem solvers with those of unsuccessful problem solvers. One successful participant was excluded from this analysis because of an audio recording failure. Using the coding system specified in the Method section, we calculated the proportion of time spent looking at each region of the diagram for each participant for both the beginning and the end time segments. Proportions of time spent fixating the four relevant diagram regions were normalized, and other fixations were eliminated from the analysis.

Figure 2 shows the mean proportion of time that successful and unsuccessful participants spent looking at each region of the diagram at the beginning and end of the task. For the beginning period, the first 30 s after the instructions, *t*-test comparisons indicated no significant differences between the successful and unsuccessful groups in the mean proportion of time spent looking at each region of the diagram. However, during the end period, the 30 s before inferring the solution, *t*-test comparisons of mean looking times indicated that successful participants spent significantly more time looking at the skin area of the diagram than unsuccessful participants did, $t(11) = 2.734$, $p < .02$. No significant differences between the unsuccessful and successful groups were found in the proportions of time spent looking at the tumor, healthy tissue, or outside region of the diagram. Interestingly, participants in both outcome groups spent time looking at the outside, an area of blank white space.

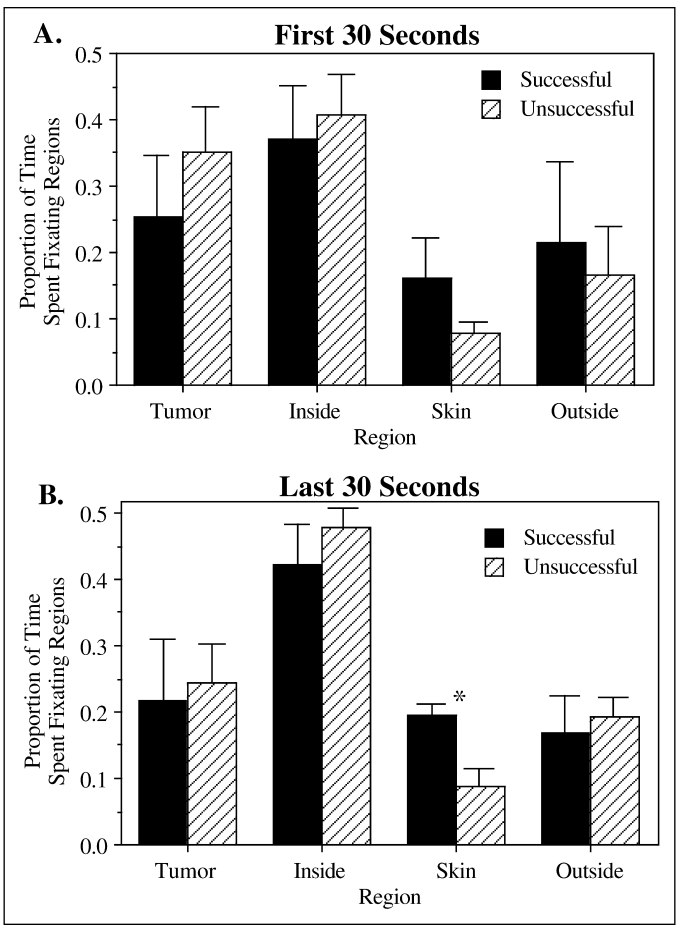


**Fig. 2.** Mean normalized proportion of looking time by area during the first 30 s of viewing (a) and the last 30 s of viewing (b) in Experiment 1. (In these graphs, the "healthy tissue" region is referred to as "inside.") The asterisk (*) indicates a significant difference between successful and unsuccessful problem solvers.

The results from Experiment 1 indicated that successful problem solvers spent a higher proportion of time looking at the skin area of the diagram than unsuccessful problem solvers did. We therefore considered this skin area to be a critical diagram feature for inferring the solution to the problem. Thus, the eye movement results in Experiment 1 provided the specific information we needed to further explore the relationship between attention and inference making. Our goal in Experiment 2 was to use this information to test the sensitivity of problem solvers to changes in the structure of the visual representation and the possibility of capitalizing on this sensitivity by manipulating attention within the diagram to facilitate the correct solution.

Previous work has demonstrated that inferences for solving Duncker's radiation problem can be facilitated with visual source analogues (viewed before seeing the radiation problem) that abstractly depict multiple pathways converging on a central location (Gick & Holyoak, 1983). Recently, this improvement in performance was shown to increase slightly when the visual source analogue is animated (Pedone, Hummel, & Holyoak, 2001). However, in the present work, instead of priming the concept of convergence by showing an animated diagram before the problem, we primed the perceptual-motor pattern that, according to Experiment 1, is correlated with inferring the correct solution, by subtly animating the tumor diagram itself. This kind of perceptual-motor priming seems analogous to a phenomenon reported by Glucksberg (1964). He found that in Duncker's wall-mounting candle problem (a functional fixedness problem), even incidental touching of the full box of tacks appeared to facilitate the insight of using the box itself as the wall mount. In our Experiment 2, we tested the hypothesis that an animated diagram that drew attention to the critical feature in the diagram (i.e., the skin) would yield a higher frequency of correct solutions than a static diagram or an animated diagram that drew attention to a noncritical diagram feature. We reasoned that increased perceptual salience of the critical diagram feature might have a bottom-up influence that would increase the likelihood of generating the correct inferences for solving the problem.

## EXPERIMENT 2

In the baseline condition of this experiment, one third of the participants faced Duncker's radiation problem represented by the static diagram from Experiment 1. In the experimental condition, another third of the participants faced the problem represented by an animated diagram that highlighted the critical feature we discovered in Experiment 1, the oval perimeter that represents the skin. In an additional control condition, the final third of participants faced the problem represented by an animated diagram that highlighted the tumor, a noncritical area according to the results from Experiment 1.

### Method

Eighty-one Cornell University undergraduates with normal or corrected-to-normal vision participated for course credit. As in Experiment 1, participants were screened for familiarity with Duncker's radiation problem.

The stimuli in this experiment were presented electronically. Participants were seated approximately 30 cm away from a Macintosh computer with a 20-in. display that depicted the tumor diagram. The computer screen was covered with a sheet of clear plastic so participants could draw on the diagram. Participants' solutions were videotaped using the apparatus described for Experiment 1, and the procedure was identical, except that eye movements were not recorded.

Participants were randomly assigned to one of three conditions: static diagram, animated-skin diagram, and animated-tumor diagram. In the static condition ($n = 27$), the diagram appeared fixed, as in Experiment 1. In the animated-skin condition ($n = 27$), the diagram's skin area subtly "pulsed," as the thickness of its outer edge increased and decreased by one pixel three times per second. In the animated-tumor condition ($n = 27$), the diagram's tumor area subtly "pulsed" in the same pattern as the skin pulsed in the animated-skin condition.

### Results and Discussion

Table 1 shows solution accuracy for the three conditions of Experiment 2 and for Experiment 1. The success rate for the static condition in Experiment 2 matched the success rate in Experiment 1, which also used a static diagram; 63% ($n = 17$) of participants in the electronically presented static condition were unsuccessful and 37% ($n = 10$) were successful. Success rates were similar when a noncritical area was highlighted, in the animated-tumor condition; 67% ($n = 18$) were unsuccessful and 33% ($n = 9$) were successful. However, when the critical area was highlighted, in the animated-skin condition, this pattern was exactly reversed: Only 33% of participants ($n = 9$) were unsuccessful and 67% ($n = 18$) were successful.

Twice as many participants spontaneously inferred the solution when the skin area was animated as when it was not (i.e., static and animated-skin conditions). Chi-square tests indicated significantly more successful solutions produced by participants in the animated-skin condition than in the static condition, $\chi^2(1, N = 54) = 4.747$, $p < .05$, and than in the animated-tumor condition, $\chi^2(1, N = 54) = 6.000$, $p < .05$. We found no significant differences between success rates in the static and animated-tumor conditions.

## GENERAL DISCUSSION

Our experiments show not only that eye movements appear to reflect cognition during diagram-based problem solving, but also that we could manipulate attention by highlighting aspects of the diagram to facilitate correct solutions. In Experiment 1, we found that while participants dealt with Duncker's radiation problem, their eye movements were nonrandom and discriminated successful from unsuccessful problem solvers. In Experiment 2, we demonstrated that a subtle increase in perceptual salience of a critical diagram component increased the frequency of correct solutions. We now review possible explanations to illuminate this striking perceptual influence on high-level cognition.

**Table 1.** *Percentage and frequency of successful and unsuccessful outcomes across experiments*

| Condition | Successful | Unsuccessful | *n* |
|---|---|---|---|
| Static (Experiment 1) | 36% (5) | 64% (9) | 14 |
| Static (Experiment 2) | 37% (10) | 63% (17) | 27 |
| Animated tumor | 33% (9) | 67% (18) | 27 |
| Animated skin | 67% (18) | 33% (9) | 27 |

Eye movements in Experiment 1 seemed to reflect task-related thought. Participants' eye movements frequently roved beyond the scope of the visual stimulus to blank areas of the screen (approximately 20% of the time participants looked at the blank white outside area); thus, fixations were not solely driven by the depicted visual stimulus. As suggested by recent eye movement work on memory and imagery (Richardson & Spivey, 2000; Spivey & Geng, 2001), it seems as though eye position may be used to coordinate spatial locations in the visual field with internally represented elements from the mental model. In addition, the successful and unsuccessful groups spent different amounts of time looking at one of the diagram areas. Compared with participants who needed hints to solve the problem, those who spontaneously solved the problem spent more time looking at the skin area in the diagram. We propose that eye movement patterns correlated with the problem-solving process (cf. Just & Carpenter, 1985).

Our results go beyond a mere correlation, however, and suggest that inducing attentional shifts to a critical diagram feature facilitated correct inference making. Visually fixating the skin was associated with correct solutions in the radiation problem (Experiment 1), and highlighting this area indeed helped people solve the problem (Experiment 2). Interestingly, highlighting a noncritical area did not harm performance; it resulted in a success rate similar to that in the static conditions. Our results demand an answer to the following question: What valuable information or looking pattern involving the skin could so dramatically induce inferences? That is, what is so critical about the critical area?

One possible explanation for our results is that the area representing the skin contains information necessary to solve the problem and that drawing attention to it helped participants recognize this information. Although one third of the participants recognized this information without the help of an animated diagram, an additional third recognized it only when we drew their attention to it via animation. What the skin area represents is the relationship between the outside and the healthy tissue and the point at which the lasers can begin to harm healthy tissue. However, if the skin area is inherently informative, one might expect it would have captured a higher percentage of looks relative to the other diagram areas than it actually did. In fact, the skin area captured the smallest percentage of looks in the unsuccessful group, and approximately the same percentage of looks as the outside area in the successful group. This is not compelling evidence that participants looked at the skin because, in and of itself, it provided them with important information. Rather, frequent fixations of the skin may have been a side effect of a particular eye movement pattern involving transitions between the tumor and the outside.

Our data point to the possibility that task-related attentional shifts between the tumor or healthy tissue and the outside could have assisted in generating problem-solving insights. It could be that animating the skin drew attention away from the tumor and healthy tissue, which are unchangeable in the context of the problem, and toward the skin and the outside, where the multiple laser rays must be imagined. Initial qualitative observations of the eye movement data from Experiment 1 suggested that eye movements of successful participants tended to reflect such attentional patterns, as there were frequent triangular in-and-out eye movement patterns from a point outside to the skin, then to the tumor, and back out to a different point outside. Such movements correspond directly to the correct solution of firing two lasers from different points outside so that the lasers converge at the tumor.

In order to quantify this pattern, we coded the number of times that successful and unsuccessful participants in Experiment 1 made a saccade (or a pair of sequential saccades) that crossed the skin region in either direction. During the first 30 s of working on the problem, the participants who were destined to solve it without hints made an average of 17 skin-crossing saccades. Later, during the 30 s immediately prior to producing the solution, those same participants made an average of 19 skin-crossing saccades. These numbers were not significantly different in a paired *t* test ($p > .4$). In contrast, participants who would eventually require hints to solve the problem made an average of 6.4 skin-crossing saccades during their first 30 s—significantly fewer than the successful participants during that period, $t(11) = 3.2$, $p < .01$. Later, after receiving hints and approaching the brink of the solution, these participants made an average of 14.4 skin-crossing saccades. The difference in skin-crossing saccades before and after the hints was significant in a paired *t* test, $t(8) = 2.55$, $p < .05$. Thus, skin-crossing saccades took place both before and during the solution phase for participants who did not need hints, but only during the solution phase for those who needed hints. We interpret these results as consistent with the possibility that, among those participants not requiring hints (in both experiments), in-and-out eye movements themselves may have served as an embodied physical mechanism that jump-started a perceptual simulation (Barsalou, 1999) of multiple incident rays, and wound up supporting the inference that multiple lasers could be fired (at low intensities) from different points outside the diagram.

We have proposed empirically informed attentional guidance as a possible way to improve reasoning in a problem-solving task that relies on a diagram. Although it may often seem that attention and eye movements are the result of cognitive processing, it may be that sometimes cognitive processing is the result of attention and eye movements. Mounting evidence in the eye movement literature is showing just how intertwined the interactions among the visual environment, attention, and mental operations are (e.g., Ballard, Hayhoe, Pook, & Rao, 1997; Glenberg, Schroeder, & Robertson, 1998; O'Regan, Deubel, Clark, & Rensink, 2000; Richardson & Spivey, 2000; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). Particularly now, as the cognitive sciences are increasingly acknowledging that cognition is an interaction between internal mental process and situated environmental constraints (e.g., Clark & Chalmers, 1998; Greeno, 1998; Spivey, Richardson, & Fitneva, in press; St. Julien, 1997; Young & McNeese, 1995), this knowledge can be applied to building representational structures and interfaces that exploit the close relationship between cognitive and sensorimotor processes.

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