

Influence of Visual Cues on Eye Movements and Reasoning in Physics Problems

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Visual cues overlaid on diagrams and animations can reduce cognitive load by drawing attention to relevant areas. Additionally, cues can increase speed and accuracy by causing learners to view a diagram in a pattern related to a problem's solution. We investigate the effects of visual cueing on students' eye movements and reasoning on introductory physics problems with a diagram. Students in the treatment group were shown an initial problem, and if they answered that incorrectly, they were shown a series of problems each with moving shapes cueing the correct solution. Students in the control group were also provided a series of problems, but without any visual cues. Students in both groups were asked to verbally explain their reasoning after each question, and were provided a transfer problem without cues at the end. We report on students' eye movements while answering the questions and verbal reasoning for their answers.

Introduction

To maximize learning one must ensure most of the learner's cognitive resources are spent on relevant tasks and avoid instructional environments that facilitate focusing on the irrelevant. Mayer's cognitive theory of multimedia learning (2001) explains that learning occurs when relevant information is successfully selected and organized into a coherent representation and integrated into the existing knowledge base. All of these processes occur in one's working memory. Often learners are faced with learning environments that impose a high cognitive load and max out the limited capacity of working memory. To help alleviate this problem, visual cues can be used. de Koning, Tabers, Rikers and Paas (2009) have devised a framework to describe three specific functions of cueing which include guiding learners' attention to essential information, emphasizing organization, and making the relations between elements more salient to foster their integration. There exists a large body of research which utilizes visual cues in a variety of contexts to increase learning in animations and static problems (de Koning, Tabers, Rikers & Paas, 2007, Grant & Spivey, 2003, Kriz & Hegarty, 2007, Mautone & Mayer, 2001, Ozelik, Arslan-Ari & Cagiltay, 2007).

The first function of cueing is especially interesting to us as it works to ensure that cognitive resources are spent appropriately by helping the learner focus primarily on relevant elements. This frees up working memory and allows for real learning to occur. In physics classes, students are often faced with diagrams or animations of the real world which contain elements relevant to the task at hand as well as elements which are present in the real world, but not useful for

answering the given question. To help students select the relevant and ignore the irrelevant, we study the use of dynamic visual cues overlaid on static physics problems containing a diagram.

This study builds on previous research that investigated where learners who answer questions incorrectly and correctly look when viewing physics problems containing diagrams (Madsen, Larson, Loschky & Rebello, 2012). In this study, Madsen et al. recorded eye movements of 24 individuals on six different conceptual physics problems where the necessary information to solve the problem was contained in a diagram. The problems also contained areas consistent with a novice-like response. Participants ranged from those who had only taken one high school physics course to those who had completed a Physics PhD. They found that participants who answered correctly spent a higher percentage of time looking at the relevant areas of the diagram, and those who answered incorrectly spent a higher percentage of time looking in areas of the diagram consistent with a novice-like answer. Thus, there is a significant difference in the way correct and incorrect solvers of these physics problems view the diagram. This lays the foundation for the current study, as it confirms the need for visual cues to redirect the attention of incorrect solvers from irrelevant areas of the diagram to relevant areas of the diagram.

In the current study, we use a subset of the physics problems used in Madsen et al. (2012) as well as the eye movements of those who responded correctly to design the visual cues. We aim to answer the following research questions:

1. Do dynamic visual cues patterned after experts' eye movements scaffold students' understanding of physics concepts?
2. Does students' ability to apply a given concept to a new problem improve after seeing visual cues on similar problems?
3. Do students' eye movements change on current and subsequent problems a result of seeing dynamic visual cues?

Methodology

Participants in the study were 55 individuals concurrently enrolled in an introductory algebra-based physics course. To ensure sufficient prerequisite knowledge, each completed a pre-test, which consisted of four open-ended questions gauging their understanding of speed and potential energy. The pre-tests were scored as correct or incorrect by one of the researchers. When a participant's answer was unclear, two researchers discussed the answer and agreed on a conclusion.

Participants took part in individual sessions lasting between 30 and 60 minutes. They were first given an explanation of what to expect and the eye tracker was calibrated. Next, participants were instructed to spend as much time as needed on each question and answer with a verbal explanation of their reasoning when ready. Participants in the cue condition were told that colored shapes may appear on some of the problems and when these appeared, they should follow them with their eyes.

Participants were presented with physics problems on a computer screen viewed at a distance of 24 inches using a chin and forehead rest to minimize their extraneous head movements. The resolution of the computer screen was set to 1024 x 768 pixels with a refresh rate of 85 Hz. Each physics problem subtended $33.3^\circ \times 25.5^\circ$ of visual angle. Eye movements were recorded with an EyeLink 1000 desktop mounted eye-tracking system which had an accuracy of less than 0.50° of visual angle. A nine-point calibration and validation procedure was used at the beginning of the experiment. Participants' verbal explanations and gestures were recorded with a Flip video camcorder.

The materials consisted of four sets of conceptual physics problems covering energy and kinematics, which were found to have significant differences in the way correct and incorrect solvers answered them (Madsen et al. 2012). It should be noted that these four specific problems were chosen from the six problems analyzed because they tested distinct concepts in physics. We refer to these problems as the roller coaster (Figures 1 and 2), ball (Figure 3), skier (Figure 4) and graph (Figure 5) problems

The research design is shown in Figure 6. Within each problem set, there was an “initial” problem, four “similar” problems, and a “transfer” problem. All problems were open-ended and contained a diagram with the necessary information to answer the problem. First, students answered the initial problem to demonstrate their current level of understanding. If they answered incorrectly, they saw a series of “similar” problems, which contained the same problem statement as the initial problem and tested the same concept and contained a diagram with similar surface features. When the student answered a similar problem correctly, they saw the transfer problem. This process continued until a maximum of four similar problems had been viewed by the participant, after which the participant was presented the transfer problem regardless of whether he/she answered the similar problem correctly or incorrectly. The surface features of the transfer problems were different than the initial and similar problems, though the concept tested was the same. All participants viewed the four sets of problems in the same order.

Whenever a student was ready to answer a problem, they indicated this by pressing any key on a keyboard, at which point the problem displayed on the computer would become slightly smaller in size (this was so that the student knew they had successfully pressed a key). The participants then explained their answer and reasoning to the experimenter and were able to point to areas on the computer screen if necessary. The experimenter used a pre-defined rubric to determine if the given answer and explanation were correct or incorrect. If the answer and/or reasoning were vague, the experimenter would ask for clarification. Once the experimenter had sufficient information to determine the correctness of the answer, the experiment would proceed.

Participants in the cue group saw colored shapes overlaid on the similar problems appear four seconds after the problem was initially seen. Colored shapes were used because color is known to capture one’s attention because of its high visual salience. The cues used for the roller coaster, ball, skier, and graph problems are shown in Figures 2, 3, 4 and 5 respectively. Each colored shape appeared for 500 ms at 12 different positions in the diagram for a total cueing time of six seconds. The visual cues were designed to mimic the eye movements of those who answered the same problems correctly in Madsen et al. (2012). There was a large variation in eye movements from one individual to another while viewing the diagrams in these physics problems, so the visual cues could not mimic the eye movements of correct solvers exactly. Instead, video playback of the correct solvers’ eye movements was viewed repeatedly and special attention was paid to the eye movements in and around the thematically relevant area of interest. Similarities between participants were observed, and visual cues were modeled after these patterns. Further, the cues could have remained static and simply drawn participants’ attention to the relevant areas of the problem, but we hoped by modeling the way in which correct solvers viewed the thematically relevant areas and compared elements within these areas, the cues would give the participants more insight into how to correctly answer the problems.

Results

Changes to Correct Answer on Similar Problems

Table 1 shows the number of students who answered the initial problem incorrectly and then changed to a correct answer and reasoning on a similar problem. Using a Mann-Whitney U test to compare the number of participants in the cue and no cue groups who changed to a correct answer, we found a significant difference on the roller coaster problem ($p=.002$) where six students in the cue group ($N=18$) changed to the correct answer while zero students in the no cue group ($N=14$) made this change. There were no significant differences between groups on the ball, skier, or graph problems. The particular aspects of each problem and associated cues will be further analyzed to determine where the differences in effectiveness originate.

Transfer Problem Correctness

To determine if visual cueing is useful for learning beyond the problem being cue, participants answered a transfer problem for each problem set. Figure 7 shows the percentage of participants who answered the transfer problem correctly after answering the initial problem incorrectly. We compared the cue and no cue groups performances on the transfer problems using the Mann-Whitney U test. We found that there is a nearly significant difference for the ball transfer problem ($p=.06$) and the graph transfer problem ($p=.054$). There was no difference found for the roller coaster and skier transfer problems. These results suggest the visual cues in the ball and graph problem sets positively influenced performance on the related transfer problems.

Eye Movements on Roller Coaster Problem

To further investigate the positive effect of the visual cues on the problems, we looked at the eye movements of the students. First, we investigated how well students in the cue group followed the visual cues with their eyes. To do this, we created four interest areas where the cues began and ended (around the roller coaster carts). We then counted the number of saccades each participant made between these interest areas and the total number of saccades made within the diagram during the four seconds that the cues appeared. On the roller coaster problem, 52.6% of the saccades of those in the cue group followed the cues. In the no cue group only 0.96% of the saccades were in a pattern similar to the cues (though the no cue group did not see any cues, and we did not expect their eyes to move in the pattern of the cues spontaneously).

Next we looked for a correlation between following the cues closely with the eyes and changing to the correct answer on a similar problem. We counted saccades between the same areas of interest described above for those in the cue group only. Using a one-way ANOVA, we found a significant difference in the percentage of saccades that correctly followed the cues between those who changed to a correct answer on a similar problem and those who did not ($F(1,14)=10.8$, $p=.005$). Students who answered a similar problem correctly made 85.5% of their saccades in a manner that followed the cues. Students who did not answer any of the similar problems correctly made only 46.4% of their saccades in a manner that followed the cues. This suggests a relationship between closely following the visual cues and coming to the correct answer on the roller coaster similar problems.

Eye Movements on Ball Problem

On the ball problem, we found a nearly significant difference in transfer problem performance between groups. In the cue group, 60% of students answered the transfer problem correctly while in the no cue group, 23.1% answered correctly. This suggests that seeing the visual cues positively influenced performance on the transfer problem. To further investigate this finding, we looked at the eye movements on this problem.

The visual cues used in the similar ball problems had the students compare the distances between balls at each time interval. If the visual cues influenced how students look at the transfer problem, we anticipate that the cue group would show a greater number of saccades comparing the distance between balls. In the case of the transfer problem, these would be vertical saccades within interest areas 1 and 2 (Figure 8). We found that for those in the cue group, 23.0% of their saccades were within interest areas 1 and 2. For those in the no cue group, 24.1% of their saccades were within interest areas 1 and 2. Thus, no differences were found between the way those in the cue and no cue groups look at the distances between the balls on the ball transfer problem. This suggests that this difference in performance on the transfer problem is not reflected in the participants' eye movements. We further looked at the percentage of saccades within interest areas 1 and 2 of those in each group who answered correctly versus incorrectly. We anticipated that those who answered correctly would display more saccades within the interest areas. These results are displayed in Table 2. Once again, we find no differences between the cue and no cue groups in this analysis. This suggests that the visual cues are not changing the way participants view the ball transfer problem.

Conclusion

In this study we find some evidence that viewing a physics problem overlaid with short duration visual cues can indeed help students correctly answer and reason about problems they were previously unable to. Of the four problem sets used, we found on one of these problem sets significantly more students changed to a correct answer after seeing cues. It is not enough though, to provide visual cues to help students answer a given set of problems. In looking at transfer problem performance, we found nearly significant differences on the ball and graph transfer problems with the cue group outperforming the no cue group. Thus, we find some evidence that repeatedly showing novices visual cues on related problems may help them to properly apply the factual knowledge on similar future problems viewed without cues.

We also found some differences in eye movements of those who changed to a correct answer on a similar problem and those who did not. Those who changed to a correct answer on a similar problem for the rollercoaster problem followed the visual cues more closely than those who did not change to a correct answer. Thus, there may be a relationship between how well a participant follows the visual cues with their eyes, and how helpful these cues are. This suggests that following the cues closely is related to changing to a correct answer. Further, we looked for evidence that seeing cues changes the way in which one views future problems with no cues and found no evidence for this on the ball transfer problem.

While we did find some results that point to the usefulness of cueing, we also saw no difference between cue and no cue groups in the number of similar problems answered correctly on three of the four problem sets tested. There are many reasons that the cueing may have failed. First, we have previously discussed how the cue pattern may have been too complex on these three problems. In the future, we can use simple repetitive cues as well as increase the time the cues are seen. We can also change the type of cue we are using, for example instead of moving colored shapes modeling correct solvers' eye movements, we could use lines or bars to illustrate comparisons in the diagram that correct solvers make. Additionally, there may be only certain types of problems that lend themselves to improvement through visual cueing. We have only explored four problems in this study. There are a plethora of problems that can be categorized in a variety of ways and tested in future studies. It could also be that the order in which the problems are presented influences the usefulness of the cue. The roller coaster problem was

presented first each time and was the only problem the cues were found to influence. In future studies, the order of cue problems will be randomized to balance out any order effects.

We also found differences between the cue and no cue groups on two of the four transfer problems tested. As mentioned earlier it may be that the two transfer problems that showed no difference were too difficult for this level of student, as very few students in either group answered these problems correctly. It is also possible that the researchers viewed the transfer problems as closely related to the similar problems, though the students did not view them this way, and thus were unable to apply what they gained from the cues to the transfer problems. In other words, the transfer problems, though deemed to be near transfer problems by the researchers, were perceived to be far transfer problems by the participants in our study. A problem may be perceived as near or far transfer depending upon whether the problem solver perceives the two problems to be different in surface feature or deep structure. So, it seems that although the ‘similar’ and ‘transfer’ problems were deemed to differ only in surface feature by the researchers, the participants in our study appear to have perceived them as being different in deep structure as well.

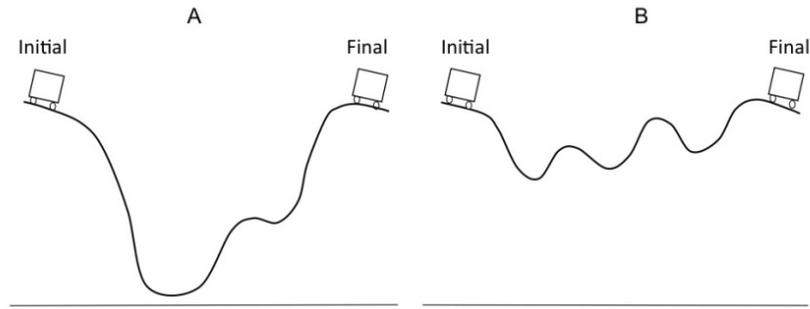
Previous studies with visual cues in several domains have also found mixed results on the effectiveness of cueing. There is much work to be done to understand the factors that lead to helpful cues. This study offers some hope that cueing can potentially serve as effective conceptual scaffolding for novice physics students, but much work is necessary to perfect this method.

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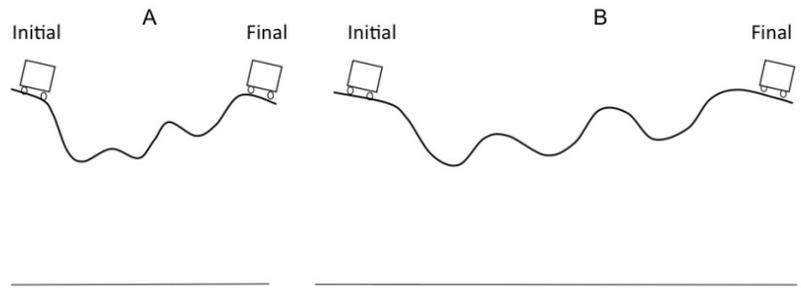
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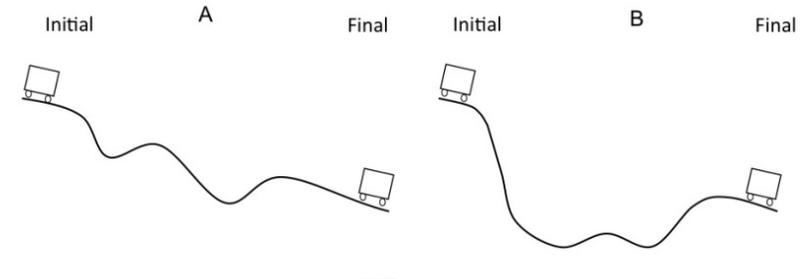


Figure 1. Example of initial problem (top), similar problem (middle), and transfer problem (bottom) used in study.

Assume frictional effects can be ignored. How does the final speed of roller coaster cart A compare to the final speed of roller coaster cart B, if the mass of the carts is the same and they both start at rest?

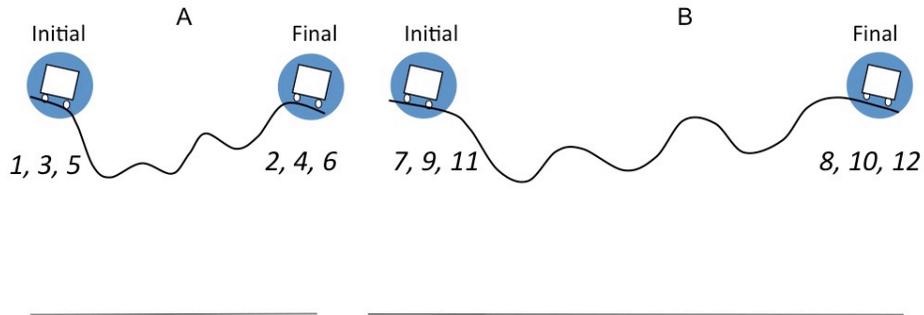


Figure 2. Problem 1 used in study. Blue circles are the visual cues overlaid on the diagram. Numbers in italics show sequence of animated cues (the numbers were not seen by study participants).

Two balls roll along the paths shown above. The position of the balls is shown at equal time intervals of one second each. When does Ball B have the same speed as Ball A?

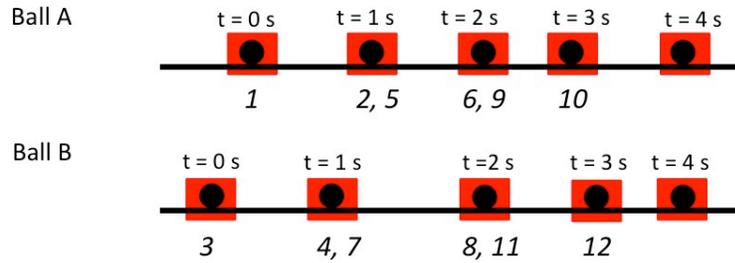


Figure 3. Problem 2 used in study. Red squares are the visual cues overlaid on the diagram. Numbers in italics show sequence of animated cues (the numbers were not seen by study participants).

Rank the changes in potential energy during the skier's descent down each slope from greatest to least.

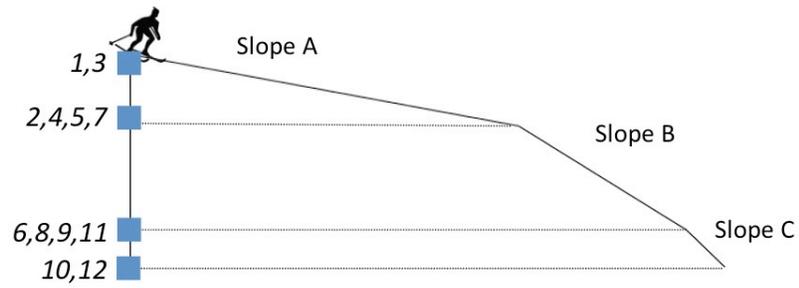


Figure 4. Problem 3 used in study. Blue squares are the visual cues overlaid on the diagram. Numbers in italics show sequence of animated cues (the numbers were not seen by study participants).

The motion of two objects is represented in the graph below.
When are the two objects moving with the same speed?

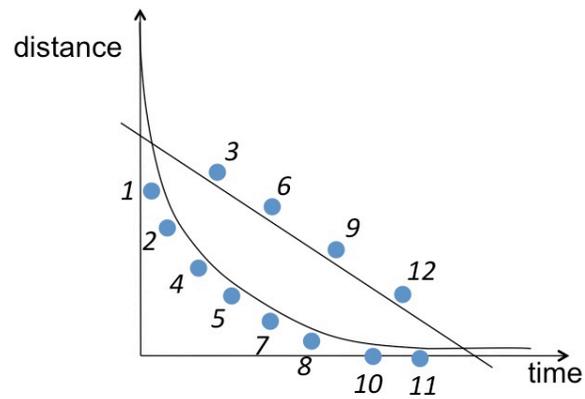


Figure 5. Problem 4 used in study. Blue dots are the visual cues overlaid on the diagram. Numbers in italics show sequence of animated cues (the numbers were not seen by study participants).

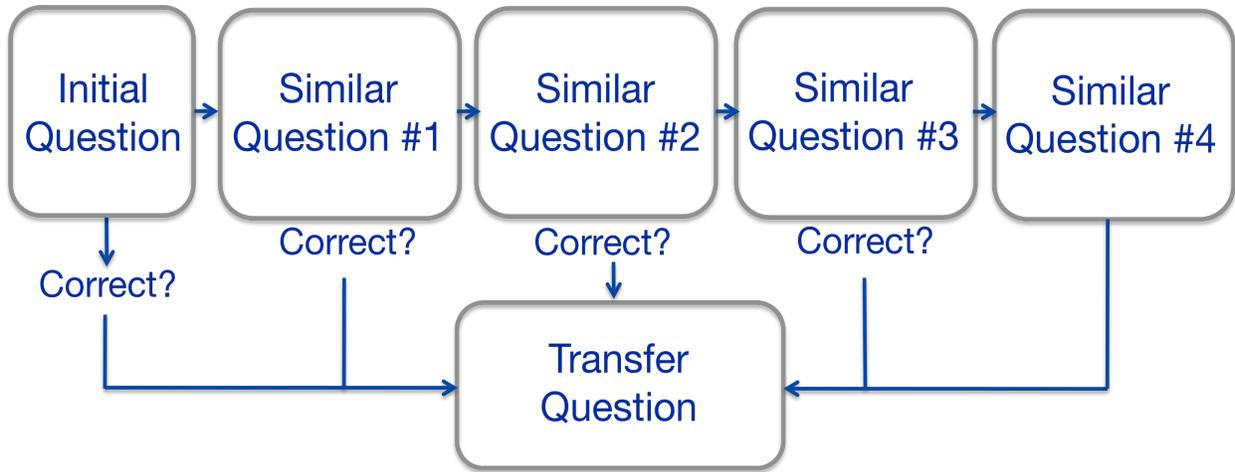


Figure 6. Flow chart showing how the initial problem, similar problems, and transfer problems were administered to students in each problem set.

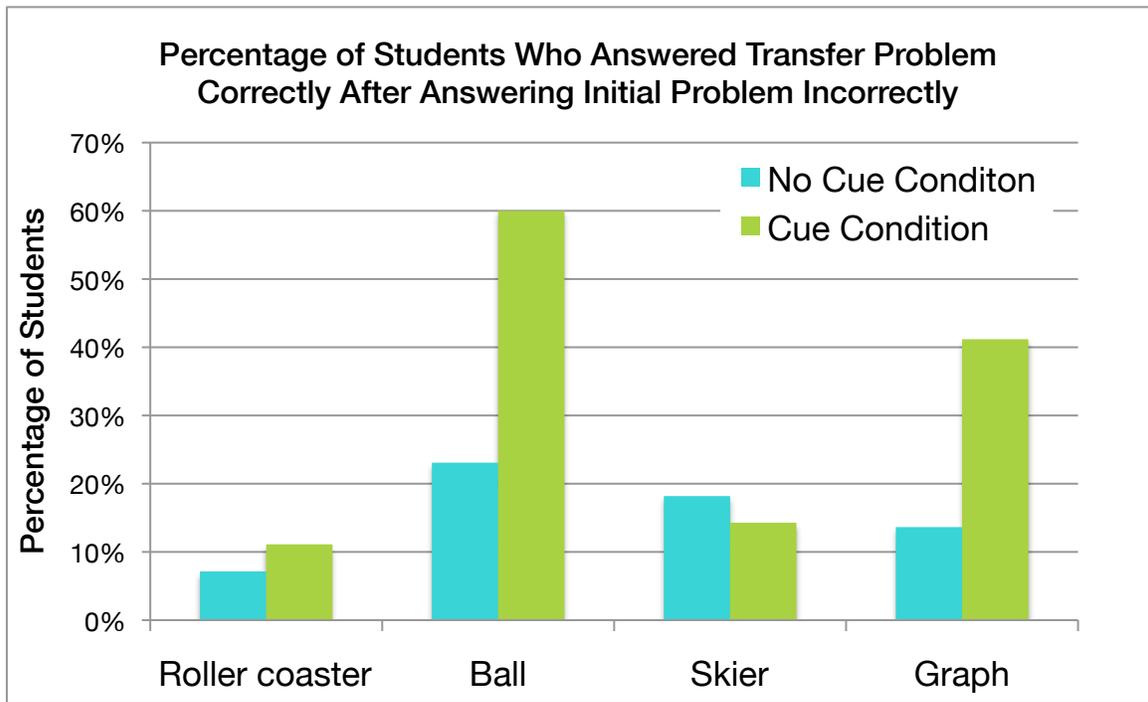


Figure 7. Percentage of students in “cue” and “no cue” conditions who answered initial problem incorrectly, but answered transfer problem correctly.

Ball A begins riding downward in an elevator at the same time Ball B is dropped from the roof of an adjacent building. The position of the balls is shown at equal time intervals of one second. When does Ball B have the same speed as Ball A?

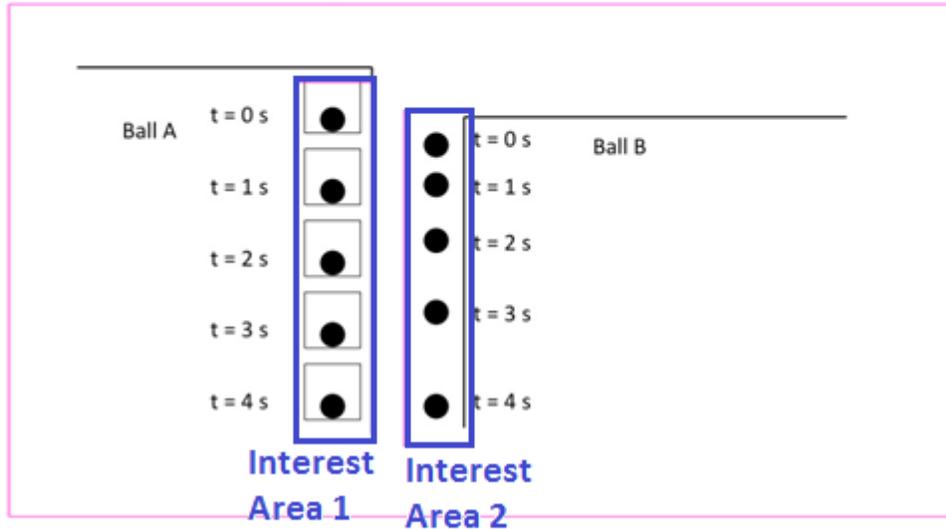


Figure 8. In the ball transfer problem the leftmost blue rectangle is interest area 1 and rightmost blue rectangle is interest area 2. These interest areas were used when analyzing eye movements.

Table 1. Number of students in cue and no cue group who answered a similar problem correctly after answering the initial problem incorrectly (* indicates a significant difference, $p < .05$).

	Rollercoaster Problem*		Ball Problem		Skier Problem		Graph Problem	
	Cue (N=18)	No Cue (N=14)	Cue (N=10)	No Cue (N=14)	Cue (N=11)	No Cue (N=7)	Cue (N=17)	No Cue (N=22)
Number Changing to Correct Answer	6	0	6	4	2	2	4	1

Table 2. Comparison of participants who answered correctly versus incorrectly in the cue and no cue groups on the ball transfer problem (Figure 8). We compared the percentage of saccades made vertically within interest area 1 or interest area 2.

		% Saccades Within Interest Areas 1 and 2
Cue	Correct Answer	18.2%
	Incorrect Answer	26.1%
No Cue	Correct Answer	17.4%
	Incorrect Answer	28.6%