Do Perceptually Salient Elements In Physics Problems Influence Students' Eye Movements and Answer Choices?

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Abstract. Several reasons have been proposed to explain students' incorrect answers to conceptual physics problems. Heckler [3] proposed with a perceptual basis: plausible and salient "eye catching" features in a problem capture students' attention. Once students attend to these perceptually salient features, less salient albeit thematically relevant features are not considered and students answer the problem incorrectly based on the salient features. To test this hypothesis we recorded eye movements of introductory physics students on 15 conceptual problems with diagrams. Each diagram contained areas consistent with documented novice-like answers and other areas consistent with the scientifically correct answer. We manipulated the luminance contrast of the diagrams to produce three versions of each diagram, which differed by the area with the highest level of perceptual salience. We found no effect of the salience on the correctness of students' answers. We also discuss how the salience manipulations influence eye movements.

Keywords: problem solving, visual attention, perceptual salience, eye movements
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INTRODUCTION

Prior research has investigated how students answer simple conceptual questions about how the world works [e.g. 1]. Interestingly, studies have found consistent patterns of wrong answers to many of these. Several cognitive top-down explanations have been provided, including misconceptions formed through interactions with the natural world or misapplication of conceptual resources [2].

Recently Heckler [3] has suggested an intriguing alternate explanation for these wrong answer patterns. He proposes the most perceptually salient and plausibly relevant features in a problem capture visual attention through perceptual processes and less salient, albeit relevant features have little opportunity to be considered. Then students' answer based on the most perceptually salient elements, as they haven't considered other less salient elements. Perceptual salience is based on the physical characteristics of the stimuli and is highest when contrast in color, orientation, intensity, or motion is greatest [4]. Salient features are assumed to automatically capture visual attention through primitive visual mechanisms. Heckler provides student response patterns as evidence for his explanation but does not present eye movement data needed to observe these perceptual processes.

We previously investigated visual attention while solving introductory physics problems with diagrams by recording eye movements [5]. We assume that eye movements reflect information processed in working memory. Just [6] provides evidence for this assumption in the case of engagement with a goal-directed task requiring visual information to be encoded and utilized, which occurred in this study. We found that correct and incorrect solvers spent similar amounts of time viewing perceptually salient elements in a problem diagram, though the salience of these elements was not manipulated and the most perceptually salient elements overlapped the "novice-like" areas of the diagram in some cases. In the current study, we build on this previous work by manipulating the perceptual salience of diagram elements to explore two possible hypotheses based on the role of perceptual salience.

One hypothesis is that initially, salient elements in the problem diagram capture learner's attention via automatic perceptual processes. If these salient areas are relevant to the problem solution and plausible, students activate certain reasoning resources based on these elements. For instance, if the novice-like area is the most perceptually salient, participants' will activate resources consistent with a novice-like conception and answer incorrectly. Conversely, if the expert-like areas are most perceptually salient, the participant will activate scientifically correct resources and answer correctly. When the novice-like and expert-like areas are equally salient, participants will answer either correctly or incorrectly in equal proportions.

An alternative hypothesis is that automatic visual processes driven by perceptual salience play a major role in guiding attention only initially when viewing a problem. Carmi and Itti [7] studied the effects of saliency as a function of viewing time and found that their salience model best predicted the first six to seven fixations when viewing a scene. For the average viewer, this is about the first two seconds of viewing. This suggests that automatic visual processes are more dominant in the first two seconds of viewing, and after this, top-down processes become more dominant and can disengage the learner's attention from the perceptually salient area(s) to other areas of the problem consistent with the learner's top-down conceptions. Ultimately, the perceptual salience of novice-like and expert-like areas will not influence the participants' answer choices. Rather, it is the knowledge that learners already possess (correct or incorrect) that influences their answer choices.

Additionally, there may be an interaction between the effect of the perceptual salience on visual attention, answer choices and prior physics knowledge. Hegarty et al. [8] recorded participants' eye movements while viewing weather maps and showed that before instruction, participants spent more time attending to task-irrelevant areas when they were most salient. However, after instruction, there was no difference in the time spent attending to task-irrelevant information regardless of its perceptually salience. So, in this case the influence of perceptual salience on attention decreased with increased domain knowledge.

We propose two competing hypotheses that lead to two different patterns of students' responses for physics problems where the novice-like or expert-like areas are either differently or equally salient. Specifically we ask: How does the perceptual salience of elements in physics problem diagrams influence the eye movements and answering patterns of students?

METHOD

We conducted individual sessions with 60 students in second-semester algebra-based (GP2) and calculus-based physics (EP2). We recorded participants' eye movements on a set of 15 problems with diagrams, all previously studied in PER literature. Each had areas consistent with novice-like answers, as documented in the literature, and separate "expert-like" areas containing information needed to answer correctly. There were five problems involving graphs, five using energy conservation, one using torque, and one using Newton's 2nd Law. Further, one problem asked about the period of a pendulum, one compared voltage across parallel plate capacitors, and one compared time of flight of projectiles.

The luminance contrast of the diagrams was manipulated to alter the perceptual salience of the novice-like and expert-like elements, producing three versions of each problem: One with the novice-like area most perceptually salient, one with the expert-like area most perceptually salient and another with both areas equally salient (Fig. 1).

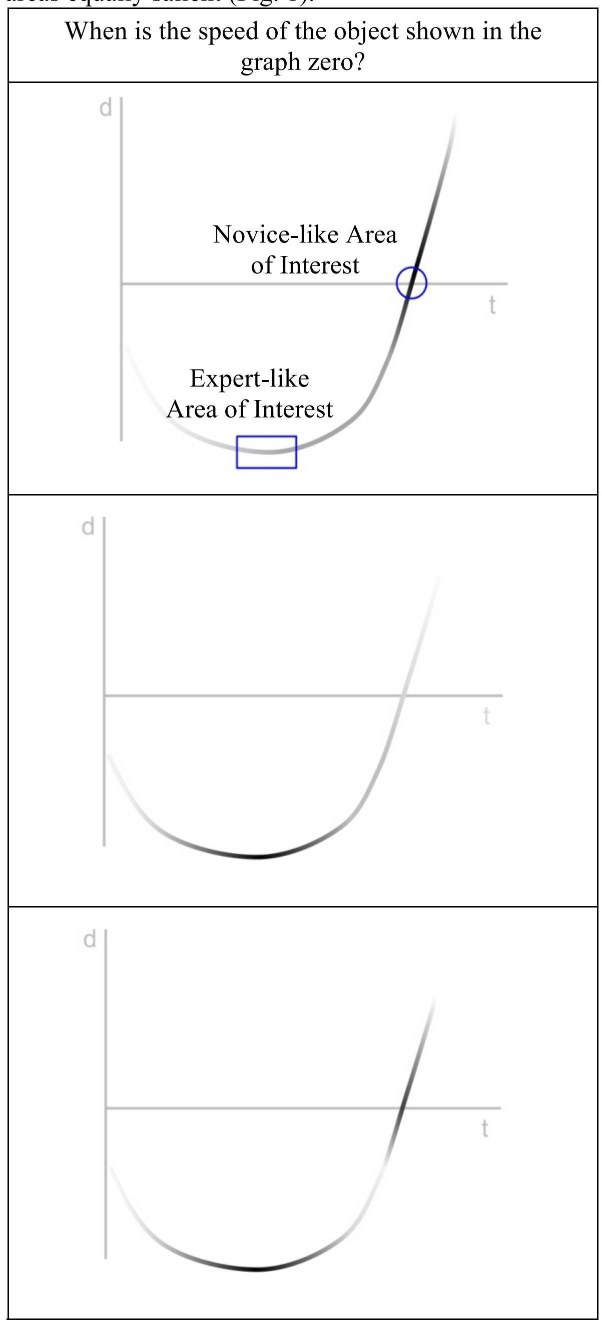

FIGURE 1. Three versions of a study problem. (Top) Novice-like area most perceptually salient. Blue shapes overlaid show expert-like and novice-like areas of interest. (Middle) Expert-like area most perceptually salient. (Bottom) Expert and novice-like areas have equal levels of salience.

To measure the perceptual salience of elements in a diagram, we used Saliency Toolbox [9]. This algorithm determines the relative perceptual salience of elements in a diagram based on contrasts in color, orientations and luminance and outputs a numerical value representing the degree of perceptual salience of each element. The algorithm then employs a "winner takes all" model and determines the order in which elements will be viewed. To assure the appropriate areas in each diagram were most perceptually salient, we manipulated the luminance contrast until the desired areas were the first to be viewed as predicted by the algorithm.

Additionally, we need to assure that the peak salience values in the desired areas were much greater than those values in the undesired areas. So, we manipulated the perceptual salience of the elements in the desired areas until the difference in salience values between these areas was less than 25%.

Subjects utilized a chin rest as they viewed each problem on a computer screen. Their eye movements were recorded with an EyeLink 1000 desktop mounted eye-tracking system. The problem statement and diagram appeared on different computer screens to prevent the perceptual salience of the text from interfering with the diagram. They were allowed to toggle between the text and diagram as often as needed. After they determined their answer to a problem, participants indicated their answer on a paper copy of the diagram.

ANALYSIS AND RESULTS

Correctness Of Answers

We first determined how the salience manipulation influenced the correctness of participants' answers. To this end, we conducted a repeated measures ANOVA with the three levels of salience manipulation as the independent variable and the mean correctness of the answer as the dependent variable. Each problem was coded as correct or incorrect, no partial credit was given. All 60 participants were included in this analysis. We found no main effect of salience manipulation ($F(2, 118)=1.079$, $p=.343$). This means there were no differences in the average correctness score when participants viewed problem diagrams with either the expert area most salient, the novice area most salient or both areas equally salient.

Prior knowledge may affect how the salience manipulation influences students' answers [8]. For example, students with strong content knowledge may be less influenced by the salience manipulation. To investigate this possibility, we accessed prior semester physics test scores for two different subsets of study participants; those who had taken General Physics 1 (GP1) or Engineering Physics 1 (EP1) in the previous semester. We conducted additional 3 x 2 factorial ANOVAs for these subsets of students. We took the average of the participants' previous semester physics test scores and determined the students in the top and bottom third of the average test score distribution. The top and bottom third of the test score distribution were used as two levels of the "previous semester test score" variable. In the ANOVA, the salience manipulation was used as the within-subjects variable, previous semester mean test score (top and bottom third) as a between subjects variable and mean correctness of answer on the study problems as the dependent variable. We found no main effect of salience manipulation on correctness for those who had previously taken GP1 ($F(2.28)=2.11$, $p=.141$) or EP1 ($F(2.18)=.141$, $p=.87$). This indicates that the salience manipulations had no significant effect on problem correctness for these two subsets of students. Additionally we found no interaction between salience manipulation and previous semester test scores for either the GP1 group ($F(2,28)=1.89$, $p=.17$) or EP1 group ($F(2,18)=1.26$, $p=.31$). This means that the influence of the salience manipulation on correctness of answer was not affected by their previous semester mean test scores.

We did however find a main effect of previous semester test scores on correctness for the EP1 students ($F(1,9)=5.36$, $p=.048$). This means that students who had "top third" previous semester mean test scores answered the problems in our study more correctly than those with "bottom third" previous semester mean test scores. This finding is consistent with our expectation that students with higher test scores in the previous semester have a stronger understanding of physics concepts and were more likely to answer problems in our study correctly.

Overall, we find salience manipulations used in this study do not influence the correctness of students' answers when considering all participants. Additionally, we find the same null result for the subsets of participants previously enrolled in GP1 and EP1. We also find that for these subsets of students, the salience manipulation does not interact with previous semester physics test scores.

Dwell Time In Areas Of Interest

We are also interested in determining how the salience manipulation influenced students' eye movements. To this end, we defined areas of interest (AOI) around the expert and novice-like areas of each problem diagram. The expert areas of interest (EXAOI) are those portions of the diagram that one needs to attend to in order to answer the problem correctly. The novice-like areas of interest (NVAOI) are the portions of the diagram consistent with the most common incorrect answer for each problem as documented in the literature. For example in Fig. 1, to answer correctly, one needs to find the area where the slope of the line is zero, which is where the speed of the object is zero (Expert-like area of interest). The most common incorrect answer for this problem is the point where the line crosses the x-axis and the distance is zero (Novice-like area of interest). The eye tracker used had an average error of 0.5 degrees of visual angle, so the AOIs were defined to be 0.5 degrees of visual angle from the edge of the desired region.

It has been shown that perceptual salience has the strongest effect during the first two seconds of viewing [5]. So, we determined the percentage of time in the first two seconds each participant fixated in each AOI for each salience manipulation. We wanted to compare eye movements across problems, so it was also necessary to take the area of each AOI into account. To do this, we divided the fixation time in the AOI as percentage of two seconds by the percentage of area (in pixels). This produced a new dependent variable, percentage of total fixation time divided by the percentage of total area, which we will call PTPA.

We conducted a 2 x 3 x 15 factorial ANOVA to compare the PTPA for the expert and novice-like AOIs for the expert and novice salience manipulations by problem. We found a three-way interaction between AOI type, salience manipulation and problem ($F(28,1814)=1.52$, $p=.04$). This indicates that the PTPA is influenced by a combination of salience manipulation, AOI type and problem. To determine precisely how these three factors influenced PTPA, we completed pair wise comparisons for each AOI type, manipulation and problem. We found a significant difference in PTPA on the problem pictures in Fig. 1 in the NVAOI, where participants had higher PTPA on diagrams with the novice-like salience manipulation compared to diagrams with the expert-like salience manipulations ($p=.005$). Overall, the eye movement analysis indicates that salience manipulation did not significantly influence the PTPA in either the EXAOI or NVAOI, except in one instance.

CONCLUSIONS AND FUTURE WORK

We found that manipulation of perceptual salience via luminance contrast of expert and novice elements in a physics problem diagram did not influence the average correctness of students' answers. Additionally, when we factored in previous semester physics test grades, we still found no effect of this type of salience manipulation on correctness of answer. This result aligns with the hypothesis that, when viewing a diagram in a physics problem, even through perceptual salience may influence attention initially, top down cognitive processes relying on prior knowledge (correct or incorrect) exert a large influence on attention and ultimately determine how a student answers the problem.

We did not find a significant effect of our salience manipulation on the percentage of fixation time divided by percentage of area (PTPA) for either the expert or novice AOIs. This seems to indicate that attention was not drawn to perceptually salient portions of the diagram in the first two seconds of viewing. This finding is curious, as it contradicts results of previous studies [8], that people first fixate on the most salient points as they view images. It may be that this effect occurred at a much shorter timescale than the two seconds used in our analysis so we did not capture the initial influence of perceptually salient regions on attention. To further investigate this issue, we will compare PTPA in the EXAOI and NVAOI for even shorter time scales. Additionally, it may be that participants did not fixate precisely in the areas of interest we outlined, but the perceptual salience of these areas shifted their eye movements closer to the salience points. To study this further, we will compare the distances between the most salient point in a given manipulation and the participants' eye movements.

It should be noted that only the luminance contrast of the images was manipulated. High perceptual salience can be achieved through relatively greater contrast in color, orientation, intensity, motion etc., though these were not investigated in this study.

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