STUDIES OF VISUAL ATTENTION IN PHYSICS PROBLEM SOLVING

by

ADRIAN M. MADSEN

B.S., Colorado State University, 2005

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Physics
College of Arts and Sciences

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Abstract

The work described here represents an effort to understand and influence visual attention while solving physics problems containing a diagram. Our visual system is guided by two types of processes -- top-down and bottom-up. The top-down processes are internal and determined by ones prior knowledge and goals. The bottom-up processes are external and determined by features of the visual stimuli such as color, and luminance contrast. When solving physics problems both top-down and bottom-up processes are active, but to varying degrees. The existence of two types of processes opens several interesting questions for physics education. For example, how do bottom-up processes influence problem solvers in physics? Can we leverage these processes to draw attention to relevant diagram areas and improve problem-solving? In this dissertation we discuss three studies that investigate these open questions and rely on eye movements as a primary data source. We assume that eye movements reflect a person's moment-to-moment cognitive processes, providing a window into one's thinking. In our first study, we compared the way correct and incorrect solvers viewed relevant and novice-like elements in a physics problem diagram. We found correct solvers spent more time attending to relevant areas while incorrect solvers spent more time looking at novice-like areas. In our second study, we overlaid these problems with dynamic visual cues to help students' redirect their attention. We found that in some cases these visual cues improved problem-solving performance and influenced visual attention. To determine more precisely how the perceptual salience of diagram elements influenced solvers' attention, we conducted a third study where we manipulated the perceptual salience of the diagram elements via changes in luminance contrast. These changes did not influence participants' answers or visual attention. Instead, similar to our first study, the time spent looking in various areas of the diagram was related to the correctness of an answer. These results suggest that top-down processes dominate while solving physics problems. In sum, the study of visual attention and visual cueing in particular shows that attention is an important component of physics problem-solving and can potentially be leveraged to improve student performance.

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The work described here represents an effort to understand and influence visual attention while solving physics problems containing a diagram. Our visual system is guided by two types of processes -- top-down and bottom-up. The top-down processes are internal and determined by ones prior knowledge and goals. The bottom-up processes are external and determined by features of the visual stimuli such as color, and luminance contrast. When solving physics problems both top-down and bottom-up processes are active, but to varying degrees. The existence of two types of processes opens several interesting questions for physics education. For example, how do bottom-up processes influence problem solvers in physics? Can we leverage these processes to draw attention to relevant diagram areas and improve problem-solving? In this dissertation we discuss three studies that investigate these open questions and rely on eye movements as a primary data source. We assume that eye movements reflect a person's moment-to-moment cognitive processes, providing a window into one's thinking. In our first study, we compared the way correct and incorrect solvers viewed relevant and novice-like elements in a physics problem diagram. We found correct solvers spent more time attending to relevant areas while incorrect solvers spent more time looking at novice-like areas. In our second study, we overlaid these problems with dynamic visual cues to help students' redirect their attention. We found that in some cases these visual cues improved problem-solving performance and influenced visual attention. To determine more precisely how the perceptual salience of diagram elements influenced solvers' attention, we conducted a third study where we manipulated the perceptual salience of the diagram elements via changes in luminance contrast. These changes did not influence participants' answers or visual attention. Instead, similar to our first study, the time spent looking in various areas of the diagram was related to the correctness of an answer. These results suggest that top-down processes dominate while solving physics problems. In sum, the study of visual attention and visual cueing in particular shows that attention is an important component of physics problem-solving and can potentially be leveraged to improve student performance.

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Dedication

To my parents.

Chapter 1 - Introduction and Relevant Literature

Introduction

Vision is a critically important medium of communication. Students are continuously bombarded with images on television, cell phones and during instruction. In order to understand how people learn using graphics and images, one must consider perceptual processes and how our visual system works in addition to the cognitive processes involved in learning. Each moment, our visual system takes in a large amount of visual information, though we have a limited capacity to process this information (Desimone & Duncan, 1995). Research has shown that although well-designed images can facilitate learning, poorly designed ones can increase cognitive load and reduce learning (Ayers & Paas, 2007). Therefore, it is important to study the way students learn with graphics and images.

Little work on visual attention in physics problem solving has been conducted and we often overlook the unique role of the visual system in solving problems with multiple representations, though the use of multiple representations is ubiquitous in physics learning. Two sources of information guide visual attention, one external and the other internal, referred to as *bottom-up* and *top-down* information respectively. These are discussed in detail later in this chapter. When solving problems in physics, both top-down and bottom-up processes are active, but to varying degrees depending on a variety of factors such as the visual stimuli, task, prior knowledge etc. The existence of two different guides for our visual system opens a whole body of interesting questions we can ask about visual attention in physics problem solving. For example, perceptually salient bottom-up information in diagrams and images has been found to distract learners from other important and relevant features (Hegarty, Canham, & Fabrikant, 2010; Lowe, 1999). Does this type of distraction occur in physics problem solving as well, or is visual attention in this type of problem solving primarily guided by top-down processes? Further, can we leverage bottom-up processes and use perceptually salient information in physics diagrams or animations to guide visual attention and improve physics problem solving? Additionally, does the way that bottom-up and top-down processes work together on visual attention vary with factors like ability in physics problem solving? These questions have not previously been explored in physics problem solving. In this dissertation, we discuss several studies which aim to answer these questions. All of the studies utilize eye movements as a main source of data to measure visual attention. In this chapter we begin with a brief overview of eye movements and their relationship to cognitive processing. We will then discuss previous research on visual attention in physics, learning with multiple representations, a framework for insight problem solving, and the use of visual cues. Finally we will discuss the motivations for performing this research, our research questions and the organization of the thesis.

Relevant Literature

Eye Movements and Visual Attention

As educational researchers, we are interested in understanding the processes involved in learning and problem solving. To understand these we would like to measure such processes in real time without interfering with the processes themselves. There are many ways to go about this, but each has a unique set of limitations. For example, we could collect written samples of students' work which would give us insight into these processes, but much information is likely not captured on paper such as intermediate steps, divergent thought processes or affect. We could conduct well designed and executed interviews, though we recognize that any interactions with the interviewer or other students could influence the learning process. Think aloud interviews in particular address the real time aspect of understanding learning processes, but students must know what they think or feel in order to report it and also must discuss what really is rather than what they think should be. Further, they would ideally report all important information, as opposed to just a portion of their thoughts (Tuckman, 1994; Van Someren, Barnard, & Sandberg, 1994). Further, an interviewer must be careful to accurately understand and portray participants meaning before making conclusions (Johnson & Christensen, 2008). While these research methodologies have advantages and disadvantages, recording eye movements is an alternate method which has been used widely in many disciplines to capture cognitive processes in real time (Charness, Reingold, Pomplun, & Stampe, 2001; Hegarty et al., 2010; Jarodzka, Scheiter, Gerjets, & van Gog, 2010; Rayner, 1998). With this method, a series of saccades (i.e., when eyes are in motion) and fixations (i.e., when eyes are stationary at a specific spatial location) are recorded with an eye tracker. The locations, durations and order of the saccades and fixations are then analyzed to understand the participants learning or problem solving process. The connection between eye movements and cognitive processing was articulated by Just and Carpenter as the "eye mind assumption" (1980). These researchers studied eye movements during reading and explained that “the eye remains fixated on a word as long as the word is being processed. So the time it takes to process a newly fixated word is directly indicated by the gaze duration.” (Just & Carpenter, 1980) They proposed and tested a model for reading which included increased fixation durations for greater processing loads caused by accessing infrequent words, integrating information and making inferences. They found a good fit between their model and actual reading patterns. Their model assumes that one must fixate on a word to process it and that fixation duration is related to cognitive processing demands. Loftus and Mackworth (1978) studied the viewing of scenes and found that fixation durations were longer when participants viewed semantically informative areas of a scene. Similar findings are presented in (De Graef, De Troy, & d'Ydewalle, 1992; Henderson, Weeks, & Hollingworth, 1999; Underwood, Jebbett, & Roberts, 2004). This work suggests that the location and duration of fixations is directly related to the locus and difficulty of cognitive processing. So eye movements may give us insight into what visual information is being thought about currently and how difficult this information is to process, a very promising measure for learning and problem solving processes. But we also offer some limitations regarding this connection between eye movements and cognitive processing.

Our retina takes in a large amount of visual information in a single glance with the visual field produced by binocular vision containing an area of about 20,000 degrees squared (Irwin, 2004). Though we take in a large amount of visual information, we have a limited ability to perceive and process this information. This is because our brains can only process some of the information received by their retina at a given time (Desimone & Duncan, 1995) and we generally only become aware of that part of the retinal information that has been attended to and entered into working memory (Irwin & Gordon, 1998; Simons & Chabris, 1999; Treisman & Gelade, 1980). Further, there is only a small area of high visual acuity on our retina, called the fovea. Because of these limitations, we move our attention and eyes to different points in space in order to direct the fovea at specific visual information and select it for further processing. While we see the visual information most clearly at the center of gaze, where the fovea is, there exists a perceptual span around the foveal region from which information is also selected and processed (McConkie & Rayner, 1975). Irwin explains, “the size of the functional field of view depends on the nature of the task, the number of items in the visual field and whether other cognitive demands are placed on the subjects.” (Irwin, 2004) Additionally, there are individual differences in the size of the perceptual span: (Pringle, Irwin, Kramer, & Atchley, 2001) it can decrease with age (Scialfa, Thomas, & Joffe, 1994) or increase with expertise (Charness et al., 2001). An eye tracker determines the eye position (fixation location) based on the location of the fovea, though this is not the only area from which visual information is extracted and processed. Visual information from the larger perceptual span is also used in cognitive processing.

There are two types of visual attention: overt attention is associated with eye movements while covert attention is the act of mentally focusing ones attention at a point in space without moving the eyes (Hunt & Kingstone, 2003). These two types of attention are independent, but often move in tandem, with covert attention preceding overt eye movements to a new spatial location (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995). This means at some point during a fixation covert attention moves to the target location of the next saccade. It has been found that this shift in covert attention also means a shift in the locus of cognitive processing, where the information at the target location of the next saccade was in the locus of cognitive processing instead of the information in the center of the fovea. So, the loci of processing and eye position are temporarily dissociated right before every saccade (Irwin, 1992; Irwin & Andrews, 1996). This implies that for some portion of each fixation, covert attention and the associated cognitive processing are not aligned with the position of the fovea and instead are at the target position for the next saccade.

So, the location of fixations does not conclusively indicate the information currently being processed, but eye movements do still give us approximate insight into cognitive processes. Unlike interviews or written responses, eye movements do not require the participant to reflect on their thought processes and then articulate them or to interact with an interviewer. Instead, we can remotely record eye movements, the precise location and durations of which participants are likely unaware, and relate these to participants' real time cognitive processes, giving us a unique window into their thought processes. Eye movements as data do have their own limitations. For example, the use of an eye tracker often requires head stabilization, which can influence the participants' state of mind. Further, the mere act of recording eye movements could cause a participant to view a stimulus differently. But with these in mind, we present three studies of visual attention in physics problem solving which rely on eye movement data to make conclusions about problem solving with physics problems containing diagrams.

Top-down and Bottom-up Processes

Our visual system is guided by two sources of information, called bottom-up and top-down information. Bottom-up information is considered external and based on the physical features of visual stimuli such as color, orientation and luminance contrast. The visual processes that work on bottom-up information involve primitive brain areas early in the visual stream and tend to be very fast (Corbetta et al., 1998; Nobre et al., 2000). The influence of bottom-up information on attention is generally explained in terms of the relative *perceptual salience* of elements of the visual stimuli (Carmi & Itti, 2006; Itti & Koch, 2000; Itti et al., 1998). Perceptually salient regions of an image tend to be those with relatively greater contrast in terms of luminance, color, orientation (e.g., of lines), or motion compared to the other image elements. Perceptually salient elements are believed to automatically capture attention through primitive visual mechanisms (Boehnke & Munoz, 2008; Kustov & Robinson, 1996). Computational models of perceptual salience have been developed (Itti & Koch, 2000; Itti et al., 1998) to produce a *salience map* of a scene or diagram, using visual feature contrasts of the type described above (i.e., luminance, color, orientation, motion). Such salience maps have been found to predict significantly greater than chance where people will fixate their eyes as they view images (Parkhurst et al., 2002; Parkhurst & Neibur, 2003). Nevertheless, top-down factors, which we describe in more detail below, have been shown to have even larger effects on where people fixate in some circumstances (Einhauser et al., 2008; Foulsham & Underwood, 2007; Henderson et al., 2007). Models of the effects of saliency on eye movements generally argue that the location with highest salience is selected for attention, this location is then fixated by the eyes, and after the information at that location has been sufficiently processed, one's attention moves to the next most salient spatial location. Carmi and Itti (2006) studied the effects of saliency as a function of viewing time and found that their perceptual salience model best predicted the first six or seven fixations when viewing a scene (see also Parkhurst, Law and Niebur (2002)). For the average viewer, this is equivalent to about the first two seconds of viewing. This suggests that bottom-up processes are more dominant in the first two seconds of viewing, with top-down processes exerting a greater influence on eye movements thereafter.

However, some researchers (Foulsham & Underwood, 2007) have found that perceptual saliency, as assessed by Itti's model, did poorly in accounting for the paths that viewers' eyes took when given a search task. For instance, in Hegarty, Canham and Fabrikant's study (2010), university students viewed weather maps and were tasked to determine wind direction. The researchers found no evidence to indicate that over the full trial period participants looked at the perceptually salient areas of the weather maps based on Itti's algorithm. However, the researchers did not limit their analysis to only the first two seconds of viewing, when the effect of saliency driven bottom-up processes should be most pronounced.

Visual attention is also influenced by top-down processes, which are considered internal and based on the viewer's prior knowledge, task goals, and expectancies. Top-down effects on attention occur later in the time course of vision and tend to be mediated by higher brain areas (Sheinberg & Zelinsky, 1993; Van der Stigchel et al., 2006). Jarodzka et al. (2010) studied the visual attention of both novices and experts who viewed videos of unfamiliar fish swimming and classified the type of locomotion. The authors found that experts spent significantly more time fixating on relevant areas of the video than biology students, who had the necessary background knowledge for differentiating types of locomotion but little practice in this classification task. The authors also found that novices spent more time than experts fixating on areas irrelevant for determining locomotion. Similar studies have measured eye movements of experts when viewing art (Antes & Kristjanson, 1991) and playing chess (Charness et al., 2001), and have shown that the increased domain knowledge in these fields affects where people fixate while performing domain-relevant visual tasks. Thus, important differences in the eye movements of experts, who possess the necessary domain knowledge, versus novices, who do not possess such knowledge, can be seen by tracking their eye movements while they are carrying out domain-relevant tasks (Rosengrant, Thomson, et al., 2009; Smith et al., 2010; Tai et al., 2006).

Researchers have found that the influence of top-down processes on the allocation of attention and eye movements vary with the nature of a task. For example, Underwood et al. (2006) found that participants viewing natural images fixated more on perceptually salient objects when asked to freely view the scene, but this effect was no longer observed when the participants' were given a search task. This result has been replicated in other studies utilizing search tasks (Foulsham & Underwood, 2007; Underwood, Templeman, Lamming, & Foulsham, 2008).

The interaction between top-down and bottom-up processes is important to consider. A study by Lowe (1999) looked specifically at how the perceptual salience of elements in the visual stimuli and the level of domain knowledge interacted. He found that the written responses of low domain knowledge meteorology students who studied animated weather maps and recorded generalizations about them primarily contained information extracted from perceptually salient areas of the weather maps. Hegarty Canham, and Fabrikant (2010) also investigated how perceptual salience influenced visual attention in the context of weather maps and showed an interesting interaction between bottom-up salience and top-down knowledge in the allocation of overt visual attention. The authors recorded participants' eye movements while viewing static weather maps in which the relative salience of task-relevant and task-irrelevant information had been manipulated. They showed that before instruction, participants spent more time attending to task-irrelevant areas when they were the most perceptually salient elements on the map. However, after instruction, there was no difference in the time spent attending to task-irrelevant information regardless of its perceptually salience. Thus, while both of these studies show that novice learners are strongly influenced by areas of a diagram that are perceptually salient, the study by Hegarty, Canham and Fabrikant showed domain knowledge decreased the influence of perceptual salience on overt, visual attention processes (i.e., where learners looked).

Influence of Top-down and Bottom-up Processes in Physics Problem Solving

In physics education, a consistent pattern of wrong answers to many simple conceptual questions has been found (Heckler, 2011). There are several ways to describe the reason(s) that students answer these questions incorrectly, and these explanations differ in the way top-down or bottom-up processes are cited as contributors. For example, one perspective is that our everyday interactions with the physical world help us develop ideas about how it works without any formal instruction (Halloun & Hestenes, 1985; McDermott & Redish, 1999). These ideas can become deep-seated stable cognitive structures, called misconceptions, that interfere with the acquisition of scientifically accurate understanding (Docktor & Mestre, 2011). Other research suggests that these wrong answer patterns are a result of misapplication of conceptual resources (Hammer, 2000). These are small pieces of knowledge that a learner may activate alone or in clusters depending on context. Incorrect answers to physics questions occur when inappropriate resources or clusters of resources are applied to a given situation. Other research posits that students systematically answer problems incorrectly because they miscategorize knowledge into inappropriate ontological categories, for example thinking of force as a thing instead of an interaction (Chi, 1992). All of these above mentioned explanations for students' reasoning patterns are cognitive and top-down in nature. In other words, it is the knowledge that students possess and the ways in which they use this knowledge that results in their incorrect answers.

Heckler (2011) has suggested an intriguing alternative conjecture for why students consistently answer simple physics questions incorrectly that is bottom-up in nature. Instead of being primarily concerned with students' knowledge, he suggested that processes inherent to our visual system might be contributing to systematically incorrect answers. Heckler explains:

> I would like to consider the hypothesis that many students may simply base their response on the most salient and plausibly relevant features of a science question, even if these salient features may in fact be unrelated or contrary to the relevant scientific concept. With several competing features, the most salient one tends to automatically capture attention, with little opportunity for alternative less salient features to be considered. (pg. 251)

So, bottom-up processes inherent in students' visual system automatically direct their attention to the most perceptually salient problem elements. Then, as long as the elements suggest a plausible and relevant answer, students' base their answer choices on them. This occurs even if these elements suggest an answer choice that is contrary to the scientifically correct answer, as students have not considered other less salient elements. Heckler provided evidence for his explanation in the form of student response patterns to a set of similar questions in which areas in the problem diagram relevant to the incorrect answer were presumed to have high levels of salience, but he pointed out that eye tracking is needed to observe the allocation of attention and confirm his conjecture.

The relationship between top-down and bottom-up processes in physics problem solving will be further investigated in the research described in chapters 3 and 5.

Research on Visual Attention in Physics Education

Studies exploring cognitive processes related to physics learning or problem solving via visual attention are not common in the field of physics education research (PER), though a small set of studies have been conducted and offer interesting findings. Below we discuss work in PER that deals with differences in attention based on expertise, attention to relevant features, global versus local attention and attention to conceptual text and mathematical steps. This work is presented in chronological order.

Tai, Loehr and Brigham (2006) investigated differences in visual attention between six pre-service science teachers who varied by their ability, familiarity and confidence in chemistry, biology and physics. Their eye movements were recorded on multiple-choice questions from Virginia Standards of Learning exams in biology and chemistry and New York Regent exams in physics. They found that the higher expertise a subject had in a given domain, the fewer fixations in pre-defined zones (such as question zone, image zone, answer zone) and the fewer saccades between zones. This suggests that students with higher expertise can hold important pieces of information in working memory and coordinate those with other important features without looking back at previously attended zones. This work was done with only six subjects, so conclusions remain tentative. Rosengrant, Thomas and Mzoughi (2009) studied how nine introductory algebra based physics students (novices) and two experts in physics solved four problems containing circuit diagrams which increased in difficulty. They found experts often shifted their attention from their own written work to the circuit diagram provided, likely integrating their own solution and the circuit diagram. Novices did not show this type of integration. Experts exhibited more global attention, focusing on the whole circuit and path of the current. Novices tended to look at individual resistor components and those that could be combined with series/parallel rules for resistors. This work indicates there are important differences between physics students and experts when solving problems with circuit diagrams. Smith, Mestre and Ross (2010) investigated the visual attention of calculus based introductory physics students as they read worked examples containing conceptual textual explanations and related equations. They found that students spent a large (about 40%) portion of time reading the conceptual textual explanations and made frequent transitions between the equations and text. Interestingly, performance on conceptual post-test questions indicates low retention of the conceptual information students read. The authors suggest that this may be due to the fact that often conceptual information is not assessed in physics problem solving, that participants may not understand the role of conceptual information in problem solving or that the text was not used by the students to gain conceptual insight. Feil and Mestre (2010) investigated whether physics graduate students (experts) and introductory algebra and calculus based physics student (novices) could detect small changes to physics problems containing blocks and ramps or blocks and pulleys using a change blindness paradigm. They found that experts were more likely to notice a change if it altered the underlying physics of the situation. Novices who had stronger relevant content knowledge were also more likely to notice physics-modifying changes. Neither experts nor novices were likely to notice changes to surface features of the problems. This suggests that experts and those with strong physics understanding attend to diagram features that are important to understanding the physics in a diagram. Rosengrant, Hearrington, Alvarado and Keeble (2011) studied students attention during the lecture for a physical science course for elementary teachers. Eight students from the course volunteered to wear eye-tracking glasses for the duration of a lecture. They found students spent very little time attending to the professor and instead directed their attention to PowerPoint slides or their notes unless the professor was very animated, drew on the board or offered examples in addition to those on the PowerPoint slides. This implies that if a professor wanted students to attend to him/her, they should not also provide another distracter such as a PowerPoint slide. They also found that students located in the middle and front of the classroom tended to be more on task than those in other areas. This is preliminary work which expands beyond studying attentional processes while problem solving, learning individually or completing an assessment, to look at attention while learning physics in a classroom environment.

More recently, Docktor, Mestre, Gire and Rebello (2012) looked at how graduate physics students and introductory algebra based physics students differed in the way they viewed and interpreted kinematics graphs. The participants were tasked with selecting the region of the graph which matched a text description. The congruence between the text description and the shape of the graph was varied (e.g. the text stated the velocity was increasing and the corresponding region in the displacement vs. time had a negative slope) as well as whether the text represented a direct, derivative or integral quantity. They found that the performance of experts was higher than novices on incongruent items, though they did not find any difference in their eye movements. Experts looked at distracters, but were not fooled by them. In a related piece of work, Gire, Docktor, Rebello and Mestre (2012) investigated representational fluency of experts and novices in physics. Participants were presented with pairs of a graph, equation or text, and would indicate if the representations were consistent with each other. Experts were significantly more likely to indicate consistency correctly, indicating greater representational fluency than novices. Experts also spent less time fixating on equations and text. This implies that experts required less processing time for the information represented with equations and text, as they were more familiar with this information. It is curious that the same difference was not found on the graphical representation.

So, the work on visual attention in physics education has been increasing over the last several years with most studies focusing on differences between experts and novices and finding that various differences do exist between these groups. This is similar to the work presented in Chapter 3, though instead of looking at expertise based on experience in physics, we instead looked at differences between problem solvers based on correctness of solution. There have also been some interesting studies looking at how students learn by, for example, reading worked solutions, or how their visual attention proceeds through a lecture. The work presented in Chapters 4 and 5 is not similar to any of these previous studies in PER.

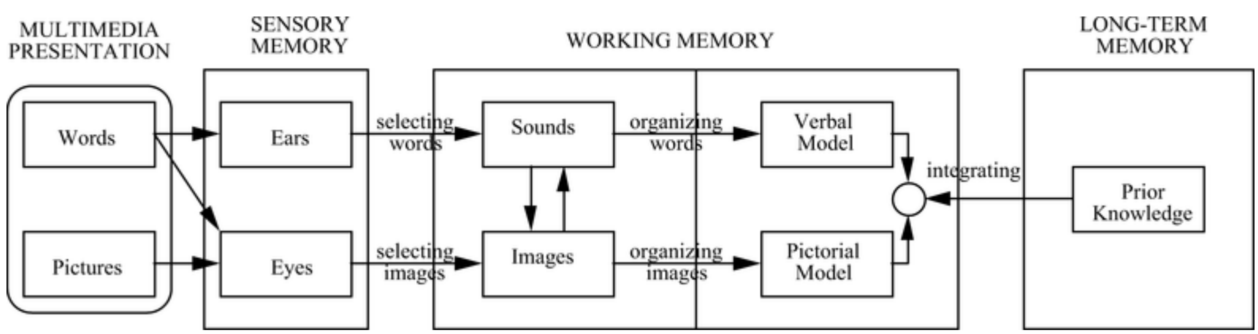
Multiple Representations and Multimedia Learning

The physics problems studied in this dissertation all contain text and a diagram or graph, making previous research on problem solving with multiple representations applicable to our work. We will briefly describe work done on multiple representations within PER as well as a theoretical model of multimedia learning relevant to our work.

Physics problem solving lends itself to the use of multiple representations to visualize problem scenarios, relationships between quantities, and express mathematical relationships. It has been found that the use and format of representations is related to performance on physics problems. Rosengrant, Heuvelen and Etkina (2009) found that students who drew free body diagrams to solve exam problems were more successful at answering the exam problems correctly. In this case, using a diagram while solving problems was helpful. Meltzer (2005) studied student performance on two very similar Newton's Third Law problems and found that the proportion of correct answers on the verbal question was higher, suggesting that students interpreted the different representations differently. Kohl and Finkelstein (2005) also found differences in performance for introductory physics students on isomorphic homework and quiz problems presented with either a mathematical, pictorial, graphical or verbal representation of the situation. Their data suggest that differences depend on prior knowledge, expectations and the particular contextual features of the problem and representation. The dependence on contextual features is of particular interest to us, as we investigated visual attention on problems with diagrams and graphs, which has given us insight into the particulars of the contextual dependence. Ibrahim and Rebello (2012) studied the strategies engineering students employed when solving problems from kinematics and work which were represented in graphical, textual and mathematical formats. The authors found that the representational format, prior knowledge and familiarity with the given topic influenced the students' problem solving approaches, but the authors did not cite the features of the representation as an important factor. This previous work motivates the study of students' visual attention when solving physics problems with multiple representations to determine precisely how the problems are viewed and interpreted to bring about these performance differences.

There has also been much work done on the use of multiple representations outside of physics. Through this work, Mayer has developed the Cognitive Theory of Multimedia Learning to describe the process of learning with words (written or spoken) and pictures (diagrams, graphs, animations, videos etc.) The problems discussed in this dissertation all include words and pictures, making this theory relevant to the work. A key tenet is the *multimedia principle* which states that under certain circumstances people learn more deeply from words and pictures than from words alone (Mayer, 2001). This tenant is informed by the way the human mind works. Mayer describes three assumptions about how the human mind works. First, the *dual channel assumption* states that the human mind contains two separate channels for processing visual/pictorial and auditory/verbal information. He goes on to specify two additional processing channels which he calls "approaches". These are the sensory modality approach, which distinguish between visually and auditorily presented information, and the presentation-mode approach, which distinguishes between stimuli presented in verbal form (written or spoken text) and non-verbal form (pictures, animation, sounds). Next, the *limited capacity assumption* asserts that each of these channels can only process a certain amount of information in working memory at a given time, approximately five to seven chunks. This implies that there is competition for attention between different pieces of incoming information. Finally, the *active processing assumption* states that humans actively create a mental representation of their experiences by attending to or selecting relevant information, organizing this information to make it coherent and integrating the information with their existing knowledge base. More specifically, selecting relevant information means choosing information from the environment and bringing it into working memory. Mayer cites examples of organization such as providing structure to the selected information in the form of process, comparison, generalization, enumeration and classification structures. Integration involves activating prior knowledge from long-term memory and bringing it into working memory to be combined with new information. Figure 1.1 presents a step-by-step diagram of Mayer's Cognitive Theory of Multimedia Learning. The first step in multimedia learning is for the multimedia information to enter sensory memory where an exact visual or auditory image is held for a very brief amount of time before selected relevant words and images enter working memory. The selected words and images enter working memory in separate channels where a mental representation of each is formed. These mental representations of sounds and images can interact, as shown by the back and forth arrows connecting these in Figure 1.1. This occurs for example by visualizing a spoken word, or internally verbalizing a written word. The sounds and images are then organized to make the representation coherent and at this point the knowledge structures are referred to as *verbal* or *pictorial models.* Now, integration occurs which involves mapping relationships among related elements in the verbal and pictorial models and combining the separate models into a single integrated mental representation. Prior knowledge from long-term memory also informs this newly integrated representation.

Figure 1.1 Schematic representation of Mayer's Cognitive Theory of Multimedia Learning (Mayer, 2001).



This theory of multimedia learning is most relevant to the work described in Chapter 4 on visual cueing. Based on Mayer's Cognitive Theory of Multimedia Learning, de Koning, Tabbers, Rikers and Paas (2009) proposed a framework for attention cueing consisting of three functions of visual cues: 1) selection of relevant information, 2) organization of information into a coherent structure and 3) integration within and across representations (referred to as the SOI framework). Since their framework deals with visual cues, they primarily discuss multimedia presented as words or pictures in animations (and not information presented auditorily). Because there is competition between which visual information is selected, visual cues are helpful because they can draw attention to relevant areas to help students' select the important information and ignore the irrelevant. Further, knowing that perceptually salient bottom-up information can automatically capture attention, selection cues should be designed to have high perceptual salience. An example is spotlighting a relevant sub-system of the heart when viewing an animation of the cardiovascular system. In line with the *limited capacity assumption,* it is important to assure ones limited cognitive resources are spent organizing and integrating important information. Organization cues assist learners in emphasizing and extracting the structure of the information, for example headings or outlines of a text help learners with text comprehension. Finally, integration cues can help relate elements within a single representation, for example, using arrows or lines to make a temporal relationship more explicit, or relate elements between representations. An example of this is integrating related information from text and a diagram. Two kinds of integration processes are important for multimedia learning and problem solving: Integrating elements (i) within a single representation that are widely spatially separated (Lowe, 1989) or (ii) across multiple representations or modalities such as coordinating graphs and pictures with text to create an operational situational mental model (Johnson-Laird, 1983) to solve the problem. Cueing learners to relate elements within a single representation is especially important if the elements they need to integrate are widely spatially separated (Lowe, 1989) or when the problem is complex and could have more than one method for solution and schema construction, imposing a high cognitive load on the learner. Cues that make implicit causal or functional relations between elements more explicit can potentially improve learning. Integration cues can be particularly helpful for learners when they must integrate textual and graphical information to create a situation model in order to solve a math or science problem (Johnson-Laird, 1983).

The SOI framework is used in our work on visual cueing described in Chapter 4. Many studies using selection, organization and integration visual cues have been conducted and are described below.

Attentional Cueing

Following from the SOI framework for visual cues described above, it may be that visual cues or signals can facilitate meaningful understanding or productive problem solving (Mautone

& Mayer, 2001; Ozcelik, Arslan-Asi, & Cagiltay, 2010). Visual cues (also called signals) were first used to aid in text comprehension by making the structure of the text more obvious. These types of signals include highlighting, underlining, headings, summaries, pointer works (e.g. first, second, third) and outlines and have been found effective at helping readers organize textual information (Loman & Mayer, 1983; Lorch & Lorch, 1996; Meyer, 1975; Rickards, Fajen, Sullivan, & Gillespie, 1997). Visual cues and signals have also been studied in multimedia environments in a wide range of disciplines. These cues varied by their function, type of visualization used, as well as their effect on comprehension and transfer. A variety of these studies are summarized below to give the reader a sense of the diversity of work done with attentional cueing and the effectiveness of visual cues. We present our work on visual cueing in Chapter 4.

We first discuss previous research where visual cues were used with static images and text or verbal explanations. Visual cues have been used to help students integrate information from these different modalities and representations. Scheiter and Eitel (2010) investigated how university students learned about the heart with text and a diagram. Important words were highlighted in the text and labeled the diagram, color-coding and deictic references were used (words or sentences that specify the referent in the diagram). They found that these signals improved understanding of the relationship between text and diagram and increased visual attention to the diagram. Kalyuga et al. (1999) studied a textual and diagrammatic representation of a "push button" circuit in which information from the text and diagram had to be integrated to understand the operation of the circuit. Color-coding was used to relate elements of the text and diagram for a group of first year trade school students. They found that participants who saw color-coding had higher comprehension scores. Similarly, Tabbers, Martens and Merrienboer (2004) studied the use of visual cues overlaid on diagrams in a lesson on instructional design. Education students viewed a set of slides with text accompanied by diagrams from which elements were highlighted in red when the student clicked on the related text. They found higher retention scores for those who saw the colored cues. Jamet, Gavota, and Quaireau (2008) investigated how visual cues could increase comprehension and transfer when spoken explanation and labeled diagrams of the brain were presented to students. When an area of the brain was mentioned in the spoken explanation, it was colored red in the diagram. The researchers found that those who saw the visual cues had higher scores on retention questions but no difference was found on transfer questions. So visual cues can help students integrate and retain information from text or spoken explanations and a static diagram.

Visual cues have also been used to assist solvers with puzzle and insight problems. Improved problem solving performance was found on a picture puzzle (picture cut up into pieces and pieces scrambled) when an expert solver's real time eye movements were shown to a novice (Velichkovsky, 1995). Grant and Spivey (2003) studied the effectiveness of visual cues on one particular insight problem called Duncker's radiation problem (Duncker, 1945). The researchers manipulated the diagram so that either the relevant or irrelevant area of the diagram pulsed or the diagram remained static. They found that those who viewed the relevant area pulsing (expanding by six pixels repeatedly) spent more time looking at the relevant area and were significantly more likely to produce a correct solution than those who saw the irrelevant area pulsing or a static diagram. They suggest that drawing attention to the critical area of a diagram can induce correct solving of an insight problem and the location of visual attention may influence cognitive processing. Thomas and Lleras (2007) conducted a follow-up study on Grant and Spivey's work (2003) to determine the existence and nature of an implicit connection between eye movements and cognition. To do this, they overlaid visual cues on the Dunker's radiation problem diagram for four seconds at the end of a 26 second free viewing period. This was repeated 20 times or until the participant answered correctly. These visual cues moved in four different patterns, one of which embodied the solution to the problem. Participants in the embodied solution group were significantly more likely to solve the problem correctly. The authors concluded that manipulating eye movements can serve as an implicit guide to influence thinking on spatial reasoning tasks. Thomas and Lleras (2009) conducted another study to determine if this effect was a result of shifts in attention or actual eye movements. The "eye-movement" group saw random digits appear in a pattern that embodied the solution and followed these digits with their eyes. The "attention-shift" group saw the same string of random digits as the eye-movement group, but was instructed to follow the digits with their attention and keep their eyes fixated at the center of the screen. The eye-movement and attention-shift groups were more likely than other groups to answer the problem correctly, though no significant difference was found between them. The results of this study suggest that the primary mechanism behind the increased correct solution rates in Thomas and Lleras' study (2007) for the embodied solution group is the shift of attention that immediately preceded the directed eye movements. Thus, directed shifts of attention have been found to influence cognitive processing on spatial insight problems and increase rates of correct solutions. This work by Grant and Spivey (2003) and Thomas and Lleras (2007) had a strong influence in the design of our study on visual cueing described in Chapter 4.

On the other hand, van Gog, Jardozka, Scheiter, Gerjets and Paas (2009) investigated how showing students the eye movements of experts could improve their problem solving ability on a problem solving task called “Frog Leap.” They found that seeing the expert eye movements did not increase problem solving ability. The authors suggest that developing cues based on the expert eye movements and not using the eye movements directly may have been more useful. So, in some cases visual cues which embody a solution or mimic expert eye movements can improve problem solving performance on puzzles and insight problems.

Visual cueing has been more recently studied in instructional animations and mixed effects on comprehension and transfer have been found. Mautone and Mayer (2001) used colored arrows in a narrated animation explaining how planes achieve lift to guide learner’s attention to relevant aspects of the animations. Additionally, they used colors to make explicit organization and relationships among components and summary icons to make the structure of the presentation more explicit. They did not find that these signals positively influenced retention or transfer. They suggest that signaling was not strong enough to be effective or this animation did not require signals. Mautone and Mayer (2007) also studied signaling with geography graphs, but in this study the signaled group saw a series of illustrations of actual rivers, river banks, boats collecting samples etc. in addition to the geography graphs which described physical situations. The authors also added visual signals to the graphs themselves by animating the order and speed in which graph elements were shown and adding colored shading and lines to the graphs. They found that those who viewed the graphs with the added illustrations and signals produced more relational statements but not more causal statements about the material at hand. Kriz and Hegarty (2007) studied the effect of signaling on comprehension of a computer animation of a flushing cistern. The signals used were arrows pointing at relevant elements during each step of the flushing process. They found no difference for the step-by-step descriptions of the system, or function and troubleshooting questions for those who saw the signals and those who did not. So, the arrow signals that accompanied the steps of the flushing cistern did not seem to help students better understand this real world system. de Koning, Tabbers, Rikers and Paas (2007) looked at how spotlight cueing on an complex animation of the cardiovascular system influenced comprehension and transfer. The spotlight cues were produced by slightly darkening all parts of the animation except the section being cued. They found participants in the cued condition were significantly more likely to answer comprehension questions about the cued system as well as other systems and transfer questions correctly. The results of this study show that visually cueing an important region in an animation can increase comprehension and transfer for that region as well as the other regions of the animation. de Koning, Tabbers, Rikers and Paas (2010) conducted a follow up study to gain more information about the cognitive processing of those viewing an animation of the cardiovascular system with spotlight visual cues and to test the effect of cueing multiple subsystems (as compared to a single subsystem looked at previously). They included a single cue condition (identical to their previous study), a multiple cue condition and no cue condition. Participants provided cued verbal retrospective reports of their thinking after studying the animation. The authors did not find the same positive effect of the cues on the comprehension or transfer test for the single cue condition and also found no positive effects on these measures for the multiple cue condition. They suspect that positioning the retrospective report before the learning tests may have influenced the null result. It was also found that cueing did affect that allocation of attention, as cued areas were fixated longer and more frequently than un-cued. The verbal reports revealed that the single and multiple cued group made statements about the cued subsystem more often than those in the no cue condition. Thus, the authors conclude that visual cues primarily influence perceptual processing and have less influence on cognitive processing when viewing animations. Boucheix and Lowe (2010) looked at how different visual cue types and synchronization of these cues affected attention and comprehension of an animated of a piano system. The experiment included an arrow cue condition, spreading color cue condition and a no cue condition. They found that the spreading cue condition had significantly higher comprehension scores than the arrow-cue condition, though no difference was found between the arrow-cue condition and the no-cue condition. They also found that the areas most relevant for understanding the piano system's functions were fixated on for longer times in the spreading color cue condition. In experiment 2, the authors investigated the effect of synchronization of the cues on comprehension and transfer. A synchronized cue is one that appears progressively as a result of user control. It was found that those in the synchronized spreading color cue condition had higher comprehension scores on a subset of the test and exhibited more fixations in the highly relevant but not perceptually salient areas of the piano system. In conclusion, these experiments show that spreading color cues can be effective at redirecting learners' attention to relevant, but not necessarily perceptually salient, areas of the piano system and this leads to higher comprehension. Further, synchronizing these cues with the user-controls instead of showing them all at once is also useful.

This is not a complete description of all studies using cues, but is meant to give the reader a sense of the types of cues and contexts that have been previously studied. Additional cueing studies include (Boucheix & Guignard, 2005; Craig, Gholson, & Driscoll, 2002; Fischer, Lowe, & Schwan, 2008; Huk & Steinke, 2007; Jeung, Chandler, & Sweller, 1997 ; Large, Beheshti, Breuleux, & Renaud, 1998; Oostendorp & Beijersbergen, 2007; Ozcelik et al., 2010; Seufert & Brünken, 2006; Tversky, Heiser, Mackenzie, Lozano, & Morrison, 2008).

In summary, many different cue types have been used with text, static images and instructional animations with varying levels of complexity, different subject matter and varying outcomes. Factors such as the time the cue is shown, the type of cue (highlighting, arrow, spotlight, spreading color), whether the cue embodies the solution or is based on expert eye movements, user control in viewing the cue, how much extra information the cue adds, whether the cue was explicitly meant to be helpful or not and the purpose of the cue (e.g. to select relevant information, make connections etc.) were varied in these studies and produced different learning outcomes.

Representational Change Theory

In our work on visual cueing described in Chapter 4, we used Representational Change Theory (Ohlsson, 1992) to help us understand how visual cues could improve students' performance on conceptual physics questions. Representational Change Theory provides a framework to understand the cognitive mechanism of solving problems – particularly problems that need insight, as opposed to merely algorithmic problems. This theory is relevant to our work on visual cues, as the problems we used required conceptual insight and are not algorithmic in nature.

Representational Change Theory explains that the way a problem is represented in a solver's mind mediates the knowledge that the solver retrieves from long-term memory. The retrieval process is based on spreading activation among concepts or pieces of knowledge in long-term memory. An impasse or block occurs when the way a problem is represented does not permit retrieval of necessary operators or possible actions. Breaking the impasse requires changing the problem representation. A new mental representation acts as a retrieval cue for relevant operators in long-term memory, extending the information available to the problem solver. Changing the mental representation can occur through elaboration, namely adding more problem information, or re-encoding, that is reinterpreting some aspect of the problem representation. Insight is achieved when the impasse is broken and the retrieved knowledge operators are sufficient to solve the problem.

According to representational change theory there are three mechanisms by which an impasse to solving a problem is broken: (i) adding information to the problem to enrich and extend the existing representation (i.e. elaboration); (ii) replacing the existing representation with a different more productive representation (i.e. re-encoding); or (iii) removing unnecessary constraints often self-imposed by the problem solver (i.e. constraint relaxation). Once the impasse is broken, the new mental representation of the problem can activate relevant concepts in long-term memory, extending the information available to the problem solver. When the relevant concept or pieces of knowledge are available to the solver, she can apply the concept to answer the question correctly.

Motivation

The studies presented in this dissertation were motivated by previous research in cognitive psychology and emerging work in physics education research on visual attention and problem solving. Much insight into student thinking has been gained by studying attention and eye movements in both of these fields, though this work has just recently begun in physics education. Visual attention can and has given us real time insight into cognitive processes that occur during physics problem solving, and eye tracking offers an exciting new tool to access what students are looking at and thinking about. For each separate research question addressed, we were motivated by studies which raised additional questions in our minds. For example, as described above, Rosengrant et al. (2009) investigated the visual attention of expert and novices in physics when solving circuit problems and found some interesting differences, but their study involved very few subjects and was limited to one type of problem. We were curious if these differences in visual attention occurred in commonly used introductory physics problems for which there is a consistent wrong answer given (these types of problems are commonly studied in misconceptions literature, for example, (McDermott, Rosenquist, & van Zee, 1987; Trowbridge & McDermott, 1980)). We were also curious if these differences in visual attention were influenced more strongly by top-down or bottom-up processes. This motivated Research Question 1.

Next, we wanted to know if we could use visual cues to influence how students thought about physics problems. Visual cues overlaid on problem diagrams and animations have been used extensively to help students focus on relevant information and relate information within and between representations (de Koning, Tabbers, Rikers, & Paas, 2009), as described above. Research Question 2 was particularly motivated by related studies of Dunckers radiation problem (Duncker, 1945) that utilized visual cues to draw participants' attention to relevant diagram areas in a pattern which embodied the solution to the problem (Grant & Spivey, 2003; Thomas & Lleras, 2007, 2009). The authors concluded that manipulating eye movements could serve as an implicit guide to influence thinking on spatial reasoning tasks. We hoped that we could find the same effect of implicit visual cues for physics problems.

Finally, Research Question 3 was motivated by work by Heckler (2011) (also described above) who proposed the intriguing alternate conjecture for why students consistently answer simple physics questions correctly which is based on the influence of bottom-up perceptual processes. We wanted to test his conjecture using eye tracking to determine if this bottom-up information was distracting students while solving physics problems and leading to incorrect answers. If it were true that perceptual salience guides students attention and reasoning on physics problems, the way the diagrams are designed could be altered and in turn problem-solving performance could presumably be improved.

Research Questions

Beyond the overarching question of exploring the role of visual attention in physics problem solving, we want to answer three specific research questions. These are as follows:

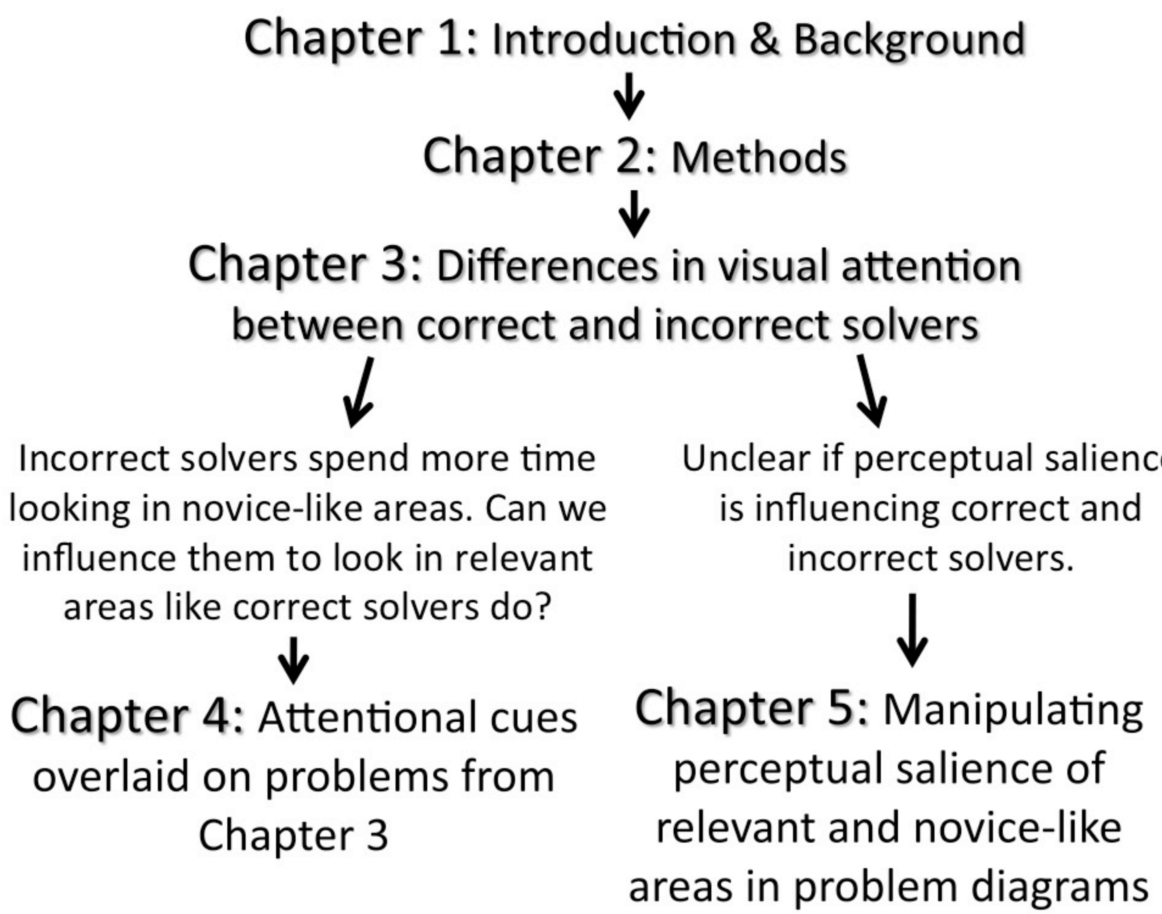
1. Does visual attention differ between those who correctly and incorrectly answer physics problems which contain relevant information in a diagram?
    - Are these differences in visual attention related to top-down cognitive processes or bottom-up perceptual processes?

2. Can short duration dynamic selection/integration visual cues influence students' reasoning and answers on physics questions with a diagram?
   - Does seeing these cues repeatedly on similar problems influence students' reasoning and answer choices on transfer problems?
   - Does seeing these cues influence visual attention while the cues are shown as well as on transfer problems?
3. Does perceptual salience of diagram elements influence students' answer choices and eye movements on physics problems which contain the relevant information in a diagram?
   - If perceptual salience does influence visual attention and answer choices, how should we account for this when creating instructional materials containing diagrams or animations?

Organization of Dissertation

This dissertation covers work from three different studies of visual attention and problem solving in physics. The first study is described in Chapter 3 titled 'Differences in Visual Attention Between Correct and Incorrect Problem Solvers.' This study was conducted in the Spring of 2010 to determine if the way students answer physics questions with a diagram is related to where they look in the diagram. We found differences in visual attention based on correctness. This finding motivated two additional studies which are described in Chapter 4 and Chapter 5. The work in Chapter 4 titled 'Can Short Duration Visual Cues Influence Students' Reasoning and Eye Movements in Physics Problems?' and completed in the Spring and Fall of 2011 is directly motivated by the findings described in Chapter 3, namely, those who answer incorrectly spend more time looking at distracting novice-like areas of a physics diagram. The work described in Chapter 4 attempts to use dynamic visual cues to draw students' attention away from these novice-like areas and to relevant areas of the problem diagrams and in turn help them reason about and answer the problems correctly. The work in Chapter 5 titled 'Do Perceptually Salient Elements in Physics Problems Influence Students' Eye Movements and Answers?" is motivated by questions left open at the conclusion of the study described in Chapter 3. In that study, we hoped to determine which processes were primarily influencing visual attention, top-down or bottom-up. Results suggested that bottom-up processes may play a role in attention allocation on these physics diagrams but several limitations prevented firm conclusions. The work described in Chapter 5 addresses these limitations and builds on the prior work with a more rigorous design to specifically determine how perceptual salience influences students' visual attention and answer choices. In summary, we suggest beginning the reading of this dissertation with Chapter 3 and then Chapters 4 and 5 in any order. A summary of the dissertation is shown in Figure 1.2.

Figure 1.2 Dissertation reading guide.

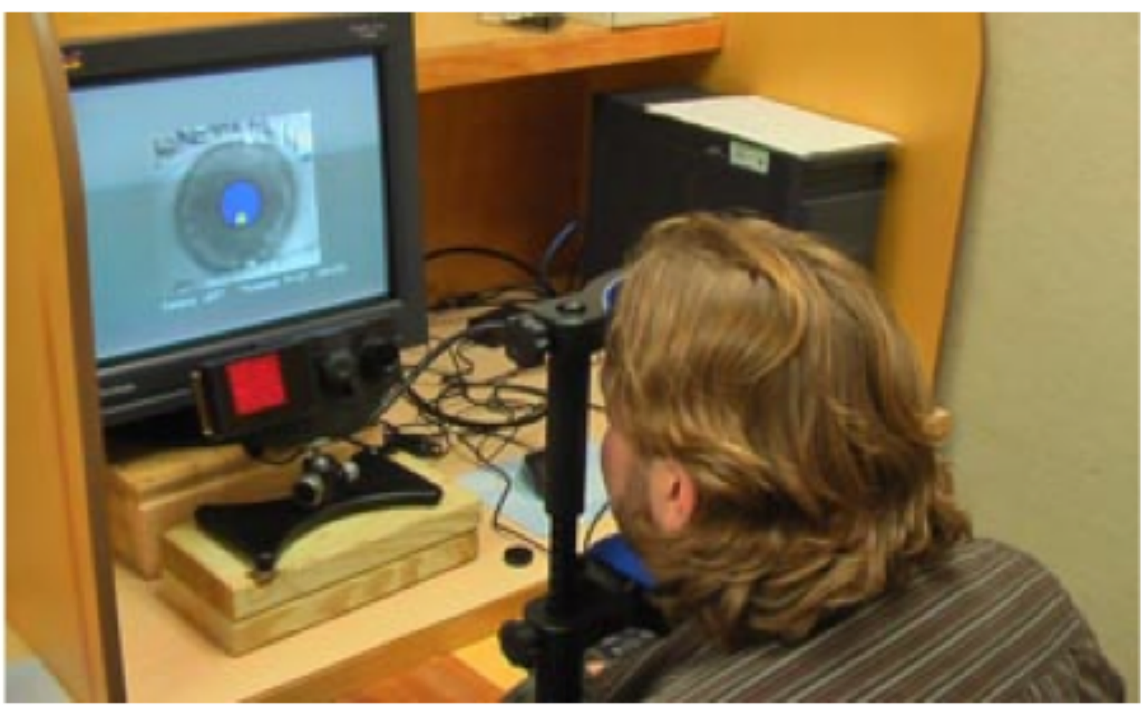


Chapter 2 - Eye Tracking Methods

Eye Tracking Technology

In all three studies eye movements were recorded with an EyeLink 1000 desktop mounted eye-tracking system (http://www.sr-research.com), which is accurate to less than 0.50° of visual angle. 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 participants' extraneous head movements. The eye tracker, chin rest and computer monitor are pictured in Figure 2.1. 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° x 25.5° of visual angle. An eye movement was classified as a saccade (i.e., in motion) if the eye's acceleration exceeded $8{,}500°/s^2$ and the velocity exceeded 30°/s. Otherwise, the eye was considered to be in a fixation (i.e., stationary at a specific spatial location). A nine-point calibration and validation procedure was used at the beginning of the experiment.

Figure 2.1 Participant viewing computer screen with head in chin rest and eye movements being recorded with Eye Link 1000 desktop eye tracker.



Area of Interest Analysis

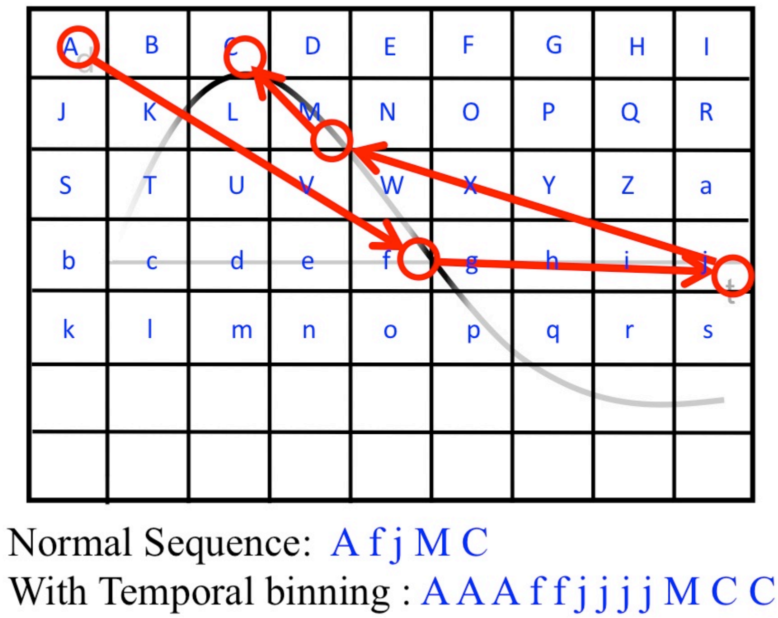
An "area of interest" (AOI) analysis was used in all three studies described in this dissertation. In this analysis of eye movements, areas of the physics diagrams were specified, for example, the area relevant to the correct answer or the most perceptually salient area. These areas were determined a priori based on the research questions guiding the study. Then, the amount of time (fixation time) each participant spent in each AOI was determined from the eye movement record. Finally, the time spent in each AOI was transformed into some other useful metric, such as percentage of total time viewing the diagram, and this new metric was compared between or within treatment groups, depending on the research design and questions.

Scan Path Analysis

A scan path is the series of fixations and saccades the eyes make over time. A scan path analysis is one where scan paths are compared pair wise to determine how similar they are. This method includes both temporal and spatial information and requires no decisions to be made about the data a priori, for example, one does not have to define AOIs based on an experimenter's definition or rating. Therefore, it is possible that differences exist in sets of eye movement data that are not detected by looking at fixation durations in AOIs.

In the studies described in Chapters 4 and 5, we used ScanMatch, (Cristino et al., 2010) which is an algorithm that compares two scan paths at a time and computes a number which represents their similarity in space and time. It is based on the Needleman-Wunsch algorithm used to compare DNA sequences. This algorithm overlays a labeled grid on to the image of interest and recodes the ordered locations and durations of fixations into a sequence of letters. Longer fixations result in repeated letters in the sequence (Figure 2.1). The letter sequences of two sets of eye movements are then compared to each other to calculate a similarity score. Letters nearer to each other in the grid receive a higher score than those farther apart. The similarity score is normalized so that a score near one represents two sequences of eye movements that are very similar spatially and temporally. The similarity scores are then compared according to the research questions being investigated.

Figure 2.2 Example of ScanMatch algorithm converting scan path into letter sequence used to calculate similarity score. Red circles represent fixations, red arrows represent saccades.



Chapter 3 - Differences in Visual Attention Between Correct and Incorrect Problem Solvers[1]

Introduction

Many physics problems contain diagrams and often these diagrams contain information that is both relevant to the solution of the problem and information that is irrelevant. Students commonly use this irrelevant information as they reason their way to an incorrect answer, when in fact they should simply ignore it. The use of irrelevant information in student answers has been observed in many studies, such as those by McDermott looking at common student difficulties in understanding motion (McDermott, 1984; McDermott et al., 1987).

Previous research, described in Chapter 1, has shown that there is competition for attention between bottom-up and top-down processes as people view visual stimuli. The key question addressed in the current study is how these processes interact when answering physics problems. We use eye movement data to infer the extent to which bottom-up and top-down processes influence people's attention as they answer introductory conceptual physics questions containing diagrams.

We hypothesize that those with adequate domain knowledge to correctly answer a problem will spend more time fixating on thematically relevant areas of a diagram that provide the solution to the problem than on irrelevant areas of the diagram. Conversely, we predict that those who answer incorrectly will spend more time fixating elsewhere in the diagram. More specifically, based on previous research in physics education concerning novice-like misconceptions, which consistently lead to incorrect answers, we hypothesize that those answering the problem incorrectly will spend more time fixating on areas of the diagram

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[1] The work in this chapter has been published previously as:

Madsen, A. M., Larson, A. M., Loschky, L. C., & Rebello, N. S. (2012). Differences in visual attention between those who correctly and incorrectly answer physics problems. *Physical Review Special Topics - Physics Education Research, 8* (1), 010122, doi:10.1103/PhysRevSTPER.8.010122. (included under the terms of the Creative Commons Attribution 3.0 License)

Madsen, A., Larson, A., Loschky, L., & Rebello, N. S. (2012). *Using ScanMatch scores to understand differences in eye movements between correct and incorrect solvers on physics problems.* Paper presented at the Symposium on Eye Tracking Research and Applications, Santa Barbara, CA, doi: 10.1145/2168556.2168591, copyright ACM 2012.

consistent with a novice-like conception. These participants will initially attend to perceptually salient areas of the diagram, but will quickly disengage their attention from these areas and instead attend to novice-like areas. Such effects would suggest a strong role for top-down factors in guiding attention while solving physics problems involving diagrams.

Alternatively, it has been shown that perceptual salience has a larger influence on novice learners' eye movements than those with more domain knowledge. Based on this finding, we could predict that the fixated locations of those who answer incorrectly are more likely to be influenced by perceptual salience than those who have adequate domain knowledge. Such effects would suggest a strong role for bottom-up factors in guiding attention during physics problem solving with diagrams. Thus, a key question is whether the attention of people who answer physics problems incorrectly is more influenced by the top-down factor of novice-like misconceptions or by the bottom-up factor of the perceptually salient areas of the diagram.

In this chapter, we address Research Question 1, which asks, "Does visual attention differ between those who correctly and incorrectly answer physics problems which contain relevant information in a diagram?" and goes on to ask, "Are these differences in visual attention related to top-down cognitive processes or bottom-up perceptual processes?" In order to answer these general questions in more detail, we examined the following further specified three-part research question:

How does the correctness or incorrectness of one's answer to a physics problem involving a diagram relate to the time spent *looking at* those areas of the diagram that are:

a) thematically relevant to the problem's solution? Or

b) consistent with novice-like misconceptions? Or

c) perceptually salient?

Study 1: Interviews to Determine Novice-Like Areas of Interest

Study 1: Methods

In order to define areas of a physics problem diagram that contain visual information related to a novice-like misconception, we conducted individual interviews with students enrolled in an introductory psychology course. We specifically looked at the interview segments where participants provided incorrect answers to the physics problems and observed the areas of the diagram that students identified and discussed while giving their verbal explanation. This information was used to define “novice-like” areas of interest (AOI) which a participant who answered incorrectly would use to come to their answer. These areas of interest will be used in the analysis for Study 2.

Participants

The participants were 13 students (eight females) enrolled in an introductory psychology course. All of the students had taken at least one physics course in high school, though some had taken an introductory physics course at the university level as well. They were given course credit for participation.

Materials

The materials consisted of 10 multiple-choice conceptual physics problems covering various topics in introductory physics including energy, kinematics, and graphing of motion (See Appendix A for a list of problems.). Each problem contained a diagram that had a thematically relevant visual component that students needed to attend to in order to correctly answer the question. For example, in Problem 4 (see Appendix A), to compare the speeds of ball A and ball B, one must attend to the distances between the balls at each time interval and ignore the point where the balls are aligned spatially. So, the distance between balls at two seconds and three seconds is the relevant area to attend to. These problems were chosen based on prior experience of the researchers which indicated that these problems could be answered using common naïve conceptions or improperly applied conceptual resources or ontological categories (depending on ones theoretical view) documented in physics education literature (McDermott, 1984; McDermott & Redish, 1999; McDermott et al., 1987).

Procedure

Each participant took part in an individual session which was between 20 and 40 minutes long. At the beginning of the session, participants were given a short explanation of the goal of the interview and the purpose of the research. Further, they were instructed to think aloud and explain their reasoning process as they answered each question. They were told they might be asked additional clarifying questions during their explanations. Participants were given one problem at a time, each printed on an 8 1/2 x 11 sheet of paper. They were allowed to write or draw on the problems as they deemed necessary. If a participant’s answer was not clear, the interviewer asked questions to clarify the meaning of the explanation. Participants' verbal explanations, gestures, and writing on the paper were recorded with a Flip video camera.

Study 1: Analysis

The purpose of these interviews was to determine which portion of each diagram was attended to by incorrect problem solvers. Therefore, only the interview segments where the participant gave a final incorrect answer were included in the analysis. A phenomenographical approach was used to code the interviews (Marton, 1986). Table 3.1 contains the answers and reasoning provided by participants who answered the problems incorrectly. Four of the 10 problems used in the interviews showed no consistent answering patterns among incorrect solvers after a first pass analysis. These problems are not included here, as there were no identifiable novice-like areas to be utilized in Study 2.

Study 1: Results and Conclusion

The six problems included in this analysis (see Appendix A) showed consistent incorrect reasoning patterns. These answer patterns align well with previous findings in the literature. Student difficulties with distance vs. time graphs were studied extensively by McDermott, Rosenquist and van Zee (1987) and Beichner (1994). McDermott, Rosenquist and van Zee interviewed students at all levels of introductory college physics as well as high school physics and physical science students. They found when students responded to a problem very similar to Problem 2 used in our study, they often selected the point where the graph crossed the x-axis because "the position was going from positive to negative," instead of correctly choosing the point on the graph where the slope was zero. In a similar study, Trowbridge and McDermott (1980) found that a common student misconception is the idea that when two objects have reached the same spatial position they have the same speed. In their study, Trowbridge and McDermott used a problem very similar to Problem 4 in our study, and found that a substantial number of students chose the instant when the balls passed each other as the time when they were moving at the same speed. In Problem 4 in our study, this instant of the balls passing is at one second, which is the most common incorrect answer we observed. Conflating position and speed is also observed in Problems 3 and 7 in our study. In Problem 7, we observed students incorrectly choosing the point where the graphs of two objects crossed as the point when the objects were moving at the same speed. This crossing point is the place where the objects have the same position, but not the same speed. In Problem 3, we observed students choosing the points where the graph crosses the x-axis as the place where the object's speed is zero. These crossing points are the places where the object has a zero position relative to the origin, but not a zero speed. So the incorrect answers we observed on Problems 3 and 7 align well with this documented student difficulty. Viennot (McDermott, 1984; Viennot, 1979) also investigated student difficulties with force and motion. She surveyed about 2,000 university and high school students in France, Belgium, and Britain and found that students often attempted to account for differences present in a diagram that may or may not be related to the problem solution. This is consistent with our findings in Problems 1 and 10. In Problem 1, tracks A and B are different, though one only needs to notice that the initial and final heights are the same, so the final speeds will be the same. Students who answered incorrectly in our study discussed the differences between the tracks to explain their answers. On Problem 10, one needs to notice that the heights of each slope are the same. Those who answered incorrectly in our study primarily reasoned using the fact that the slopes were changing.

In sum, there was strong agreement between our interview findings and documented student difficulties in the literature. This gave us confidence that the definitions of novice-like areas of interest, for each physics problem, do indeed represent the most common novice-like answers of the larger population of introductory physics students.

Table 3.1 Number of students providing each answer and reasoning on conceptual physics questions with a diagram.

Question # and Description	Answer	Reasoning	# of Responses
Q1. Roller Coaster	Final speed B > Final speed A	Compares drops and climbs on tracks A and B	2
		Height of initial drop on track A > height of initial drop on track B	2
	Final speed A > Final speed B	Compares drops and climbs on tracks A and B	5
Q2. Distance Time Graph 1	Point C	Distance changes from positive to negative	5
Q3. Distance Time Graph 2	Point A	Distance is zero	2
		Distance and time are zero	2
	Points A and C	Distance and time are zero	1
	Point C	Distance goes from negative to positive	1
Q4. Balls on Tracks	1 second	Balls at the same position at same time	5
	1.5 seconds	The balls are the same and have same acceleration	1
		Comparing distances between balls on track B.	1
Q7. Distance Time Graph 3	Points A and E	At point A objects have traveled zero distance at t=0 seconds, at point E objects are at same position at same time	2
	Point E	Objects traveled same distance in same time	3
		That is the point where the lines cross	2
Q10. Skier on Slope	B > C = A	Steepness of slope influences speed	1
	B > C > A		1
	A > B > C	Steepness of slopes influences speed, kinetic energy and potential energy	2
		Steepness of slope directly related to change in potential energy	1
	B > C > A	Relates slope, height and width of segment to change in potential energy	1

Study 2: Determining Differences in Visual Selective Attention Based on Correctness of Problem Solution

Study 2: Method

Participants

There were 24 participants in the study (three females, two were graduate students and one was a psychology student) with two different levels of experience in physics. Ten participants were first-year through fifth-year PhD students in physics who had either taught an introductory physics course or been a teaching assistant for an introductory physics lab. One participant was a postdoctoral candidate in physics who had received his PhD within the last two years and had teaching experience. Thirteen participants were enrolled in an introductory psychology course and had taken at least one physics course in high school, though some had also taken an introductory physics course at the university level. The PhD students and post-doc participated as volunteers and the psychology students received course credit for their participation. Because we were looking to compare those who answered the physics problems correctly to those who answered incorrectly, we selected participants with a broad range of experience. We expected that the PhD students would answer correctly, while the psychology students might answer incorrectly, though we knew that this might not always be the case since there is a wide distribution of expertise among introductory physics students and physics graduate students (Mason & Singh, 2011).

Materials

The materials consisted of the six multiple-choice introductory physics problems analyzed in Study 1 (see Appendix A).

Procedure

Each participant took part in an individual session lasting 20-40 minutes. At the beginning of the session, participants were given a short explanation of what to expect in the study. After calibrating the eye tracking system, if the validation's mean error was $\leq 0.50°$ of visual angle, the experiment began, otherwise the calibration and validation was repeated until successful. Next, the participant was instructed to silently answer 10 multiple-choice questions while their eye movements were recorded. Participants indicated their answer to each question using number keys on the keyboard. Between questions, a calibration drift correction procedure was done to ensure proper calibration throughout the experiment. This procedure required the participant to fixate on a small white dot in the middle of a gray screen and press a key. Pressing the key caused the screen to advance to the next problem when the participant's fixation was within a pre-defined area around the white dot. Finally, each participant was asked to provide a cued verbal retrospective report (Van Gog, Paas, Van Merriënboer, & Witte, 2005) for which they were shown a replay of their eye movements on each problem and asked to explain their thought processes (either after watching the replay of their eye movements or concurrently while watching them). This method has been found to produce more in-depth explanations than without viewing one's eye movements. If a participant's explanation was unclear, they were asked follow-up questions. Participants were given unlimited time to answer the questions and provide retrospective verbal reports. Verbal explanations and gestures were recorded with a Flip video camcorder.

Study 2: Analysis

To analyze participants' eye fixations, we defined areas of interest (AOIs). There were three different types of AOIs identified for each physics problem analyzed in Study 1. These types were thematically relevant AOIs, perceptually salient AOIs, and novice-like AOIs. The definition for the thematically relevant AOI came from three independent raters, one physics professor, and two PhD students in physics, who indicated, on each of the problems, the area which contained visual information necessary to answer the problem. The definition for the perceptually salient AOI in each problem was determined using an implementation of the Itti, Koch and Niebur saliency map algorithm in MATLAB (Harel, 2010). This MATLAB toolbox produced a heat map representation of relative saliency over the entire diagram for each problem (see Figure 3.1). The area on the diagram with the highest rating of saliency was used to define the perceptually salient AOI. If there were several portions of the diagram with the highest level of perceptual salience, according to the salience map, then all of these areas were used when defining the perceptually salient AOI.

The novice-like AOI was defined based on the interviews described above in Study 1. Figure 232 shows the thematically relevant, novice-like and perceptually salient areas of the problem whose heat map is shown in Figure 3.1.

Figure 3.1 Heat map of perceptual salience created using Itti, Koch and Niebur's salience algorithm. Red indicates area of highest perceptual salience.

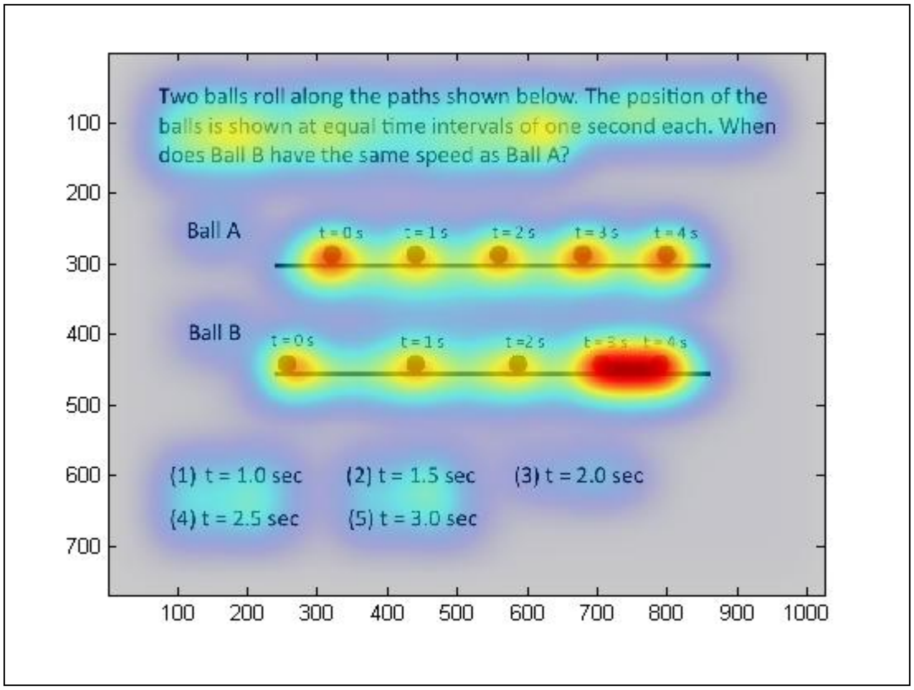
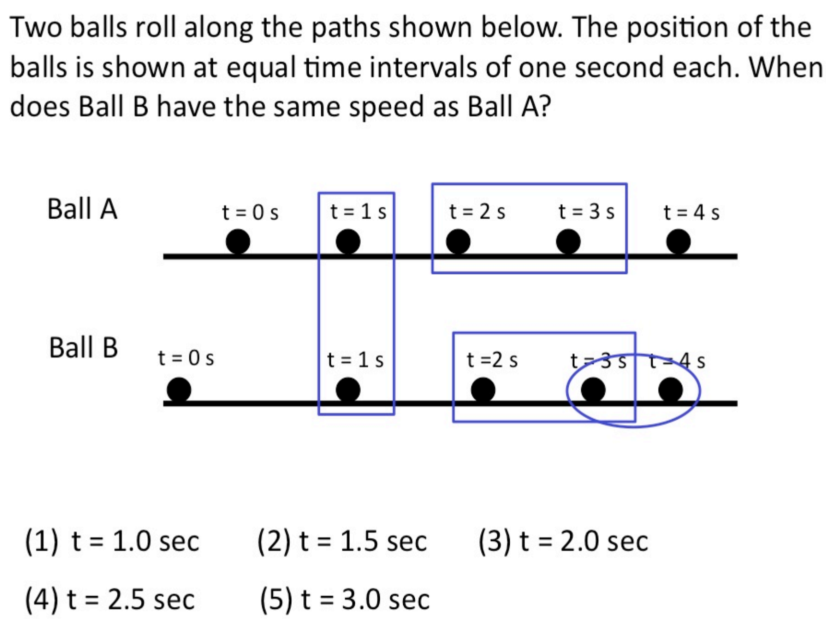


Figure 3.2 Thematically relevant AOI is the distance between balls at 2-3 seconds. Novice-like AOI is when the balls are at the same position, at 1 second. Perceptually salient AOI is oval around Ball B at 3 seconds and 4 seconds.



The areas of the diagram referred to by the majority of the interviewees from Study 1 who answered the problem incorrectly were defined as the novice-like AOI for each of the problems. These areas are listed in Table 3.2.

Table 3.2 Novice-like AOIs defined based on the most common incorrect student responses in Study 1.

Problem	Novice-like AOI
1	Roller coaster tracks
2	Point where graph crosses x-axis
3	Origin of graph
4	Point where balls A and B line up spatially
7	Point where graphs of two objects cross
10	Slopes A, B and C

These thematically relevant, perceptually salient and novice-like AOIs were applied to the problems analyzed in Study 1. Additionally, an AOI containing the entire diagram was applied to each of the problems. The total amount of time each participant spent fixating on each AOI was determined (total fixation time), as well as the total time spent looking at the entire diagram. To account for differences in total viewing time on each problem, the percentage of time spent in each respective AOI was determined by dividing the total viewing time, for each participant, in a specified AOI by the total time spent viewing the entire diagram (Cohen, Cohen, West, & Aiken, 2003). The percentage of time spent in each type of interest area was compared between students who answered the problem correctly and those who answered incorrectly for the entire problem set. There were a few instances where the eye movement data file was corrupted for a participant on a single problem. In this case, the participant's data was not included in the analysis.

We were also interested in determining if perceptual salience played a greater role in influencing eye movements in the first two seconds of viewing the problem diagram. To do this, we determined the first time the participant's eye left the problem statement to look elsewhere. Applying the same AOIs described previously, we selected two seconds of fixation data immediately following the transition from reading the problem statement to looking elsewhere in the problem. It should be noted that not all participants read the problem statement, viewed the diagram, and then the answer choices. Some participants looked from the problem statement to the diagram very briefly and then continued reading and some went from the problem statement to the answer choices. Thus, the first two seconds of fixation data represents many different patterns of viewing. We then converted the fixation time from the first two seconds to a percentage and compared the percentage of time spent in each type of interest area between students who answered the problems correctly versus those who answered incorrectly.

Study 2: Results and Discussion

Mixed factorial 2 x 6 ANOVAs with *proportion of time in each AOI type* as the dependent variable and *problem number* and *correctness of answer* as independent variables were conducted for all three AOI types. Results for the full trial period are reported in Table 3.3. Results for the first two seconds of viewing the diagram are reported in Table 3.5.

Full Trial Period

For the full trial period, we found a significant main effect for correctness of answer as well as for problem number for all three AOI types. We were looking for a main effect of correctness, as this would indicate there are differences in percentage of time spent in an AOI between those who answered correctly and those who answered incorrectly. The main effect of correctness addresses our research questions and will be further analyzed below. The main effect of problem number indicates there is at least one difference in proportion of time in each AOI type between different problems. We were not interested in how the proportion of time spent fixating varies between problems, as this is not relevant to our research questions, so the effect of problem number will not be further analyzed. We found a significant interaction between problem number and correctness of answer in the perceptually salient AOI. This means the relationship between correctness and time spent in the perceptually salient area is different across problems. This interaction is not relevant to our research question and will not be further investigated.

Table 3.3 Results of mixed factorial ANOVA for all three AOI types for full problem period.

	Thematically Relevant AOI		**Novice-like AOI**		**Perceptually Salient AOI**	
Effect	F	p	F	p	F	p
Problem #	F(5,128)=8.9	<.001	F(5,128)=14.1	<.001	F(5,128)=18.5	<.001
Correctness of Answer	F(1,128)=48.8	<.001	F(1,28)=34.0	<.001	F(1,128)=26.3	<.001
Problem #* Correctness of Answer	F(5,128)=0.88	0.500	F(5,128)=0.58	0.716	F(5,128)=4.6	.001

The main effect of correctness was further analyzed for each of the six different problems using a one-way ANOVA with *percentage of time* for all three AOI types as the dependent variable and *correctness of answer* as the independent variable. Results of one-way ANOVAs for each type of AOI for the full trial period are reported in Table 3.4. Mean percentage of fixation time, standard error for the correct and incorrect responders and the effect size using omega squared for each question are also shown in Table 3.4. An asterisk indicates a significant difference at the α=.05 level.

Table 3.4 Mean percentage time spent (± std err) and results of one-way ANOVA during entire problem period for thematically relevant, novice-like and perceptually salient AOIs for participants who answered the question correctly/incorrectly.

AOI Type	Problem	Answered Correctly	Answered Incorrectly	F	p	ω^2
Thematically Relevant	1	46.6 (± 5.5) (n=11)	33.2 (±5.7) (n=11)	F(1,20)=2.9	0.107	-
	2*	24.4 (± 2.9) (n=13)	11.6 (±3.3) (n=10)	F(1,21)=8.6	0.008	.06
	3*	28.5 (± 4.1) (n=18)	8.9 (±2.3) (n=6)	F(1,22)=7.1	0.014	.14
	4*	49.8 (± 3.9) (n=14)	25.5 (±4.1) (n=9)	F(1,21)= 17.5	<.001	.30
	7*	36.7 (±5.5) (n=15)	10.3 (± 2.1) (n=9)	F(1, 22) =13.1	0.002	.36
	10*	29.0 (± 5.0) (n=11)	15.1 (± 2.7) (n=13)	F(1,22)=6.6	0.018	.08
Novice-Like	1*	22.3 (± 4.5) (n=11)	43.5 (±7.3) (n=11)	F(1,20)=6.0	0.020	.21
	2*	12.7 (± 3.3) (n=13)	27.2 (±4.8) (n=10)	F(1,21)=6.6	0.018	.08
	3*	19.8 (± 3.7) (n=18)	39.4 (±5.4) (n=6)	F(1,22)=7.5	0.012	.14
	4	18.1 (± 2.5) (n=14)	26.8 (±3.9) (n=9)	F(1,21)=4.0	0.058	-
	7*	12.6 (±2.6) (n=15)	25.0 (± 6.0) (n=9)	F(1,22)=4.7	0.041	.05
	10*	41.2 (± 6.6) (n=11)	62.2 (± 5.1) (n=13)	F(1,22)=6.5	0.018	.23
Perceptually Salient	1	6.6 (± 1.9) (n=11)	13.0 (±2.5) (n=11)	F(1,20)=4.1	0.056	-
	2	19.3 (± 4.1) (n=13)	28.2 (±4.9) (n=10)	F(1,21)=1.9	0.179	-
	3*	9.5 (± 2.2) (n=18)	30.5 (±4.6) (n=6)	F(1,22) =20.1	0.001	.17
	4	11.9 (± 1.7) (n=14)	9.0 (±2.2) (n=9)	F(1,22)=1.1	0.316	-
	7*	19.1 (±3.0) (n=15)	39.5 (± 5.6) (n=9)	F(1,22) =12.3	0.002	.21
	10	4.2 (± 1.1) (n=11)	6.3 (± 1.6) (n=13)	F(1,22)=1.1	0.305	-

We found that on five out of six problems used in Study 2, those who answered the problem correctly spent a higher percentage of total viewing time fixating on thematically relevant areas in the problem diagram (Table 3.4). Those who answered correctly likely had the domain knowledge needed to solve each problem, and therefore spent more time viewing the relevant areas in each diagram. This result is consistent with previous findings where those with high levels of domain knowledge in a discipline, such as identifying fish locomotion (Jarodzka et al., 2010), art (Antes & Kristjanson, 1991), and chess (Charness et al., 2001), spend more time looking at areas of diagrams and pictures relevant to a task. Our finding is evidence for top-down processes playing a key role in guiding visual attention when solving physics problems correctly.

We also found that on five out of six problems, those who answered the problem incorrectly spent a higher percentage of total viewing time looking at areas of the diagram consistent with a novice-like response (Table 3.4). Furthermore, on the one problem that did not quite reach statistical significance (p = .058) the effect was in the same direction as the other five problems. These novice-like AOIs were determined through individual interviews described in Study 1, and were consistent with the physics education literature describing common student misconceptions. Importantly, the finding that incorrect solvers spent more time fixating on novice-like areas is evidence for their visual attention being guided by top-down processes. However, instead of attention being guided by scientifically correct domain knowledge, incorrect problem solvers' attention was guided by novice-like misconceptions. Thus, when solving physics problems, top-down processing plays a key role in guiding visual selective attention either to thematically relevant areas, or novice-like areas, depending upon the scientific correctness of a student's physics knowledge.

Concerning the effects of bottom-up processes in guiding attention during physics problem solving, we found that those who answered incorrectly spent significantly more time in perceptually salient areas during the full problem period on only two of the six problems, namely Problems 3 and 7. Nevertheless, for five of the six problems the effect was in the predicted direction, such that incorrect problem solvers spent a higher percentage of total time fixating on the perceptually salient AOIs than the correct problem solvers. However, four of those effects were not statistically significant. A likely explanation for this result is that in Problems 3 and 7, the perceptually salient AOI partially or completely overlapped with the novice-like AOI (Figures 3.3 and 3.4), which was not the case for the other four problems. We have already shown that those who answered the problem incorrectly spent significantly more time fixating on the novice-like AOIs on Problems 3 and 7 than those who answered the problem correctly. So the significant result for Problems 3 and 7 for the perceptually salient AOI is likely due to this AOI overlapping with the novice-like AOI. This result also seems to indicate that attending to the perceptually salient area is not necessarily a good predictor of correctness. These results appear to be consistent with a study of change blindness that found that problem solvers seldom notice changes in color, even though color is most perceptually salient (Feil & Mestre, 2010). Thus, when considering the full time period of problem solving, perceptual salience appears to have played a minimal role in guiding the attention of incorrect physics problem solvers. Nevertheless, previous vision research has suggested that the effects of bottom-up perceptual salience on eye movements are limited to the first two seconds of viewing a stimulus (Carmi & Itti, 2006). Thus, this seeming null result could be argued to have resulted from diluting the effect of saliency by including eye-movement data from the entire duration of the trial, rather than only the first two seconds. We therefore reanalyzed the data including only the first two seconds that participants spent viewing the diagram.

Figure 3.3 Itti, Niebur and Koch saliency map for Problem 3. The perceptually salient AOI overlapped the novice-like AOI, which was at the origin of the graph.

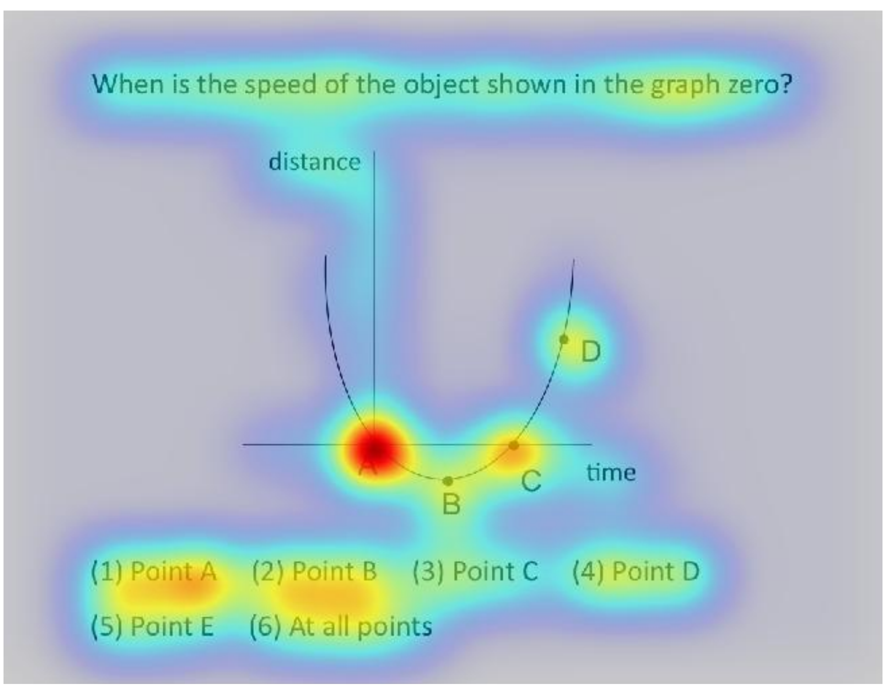
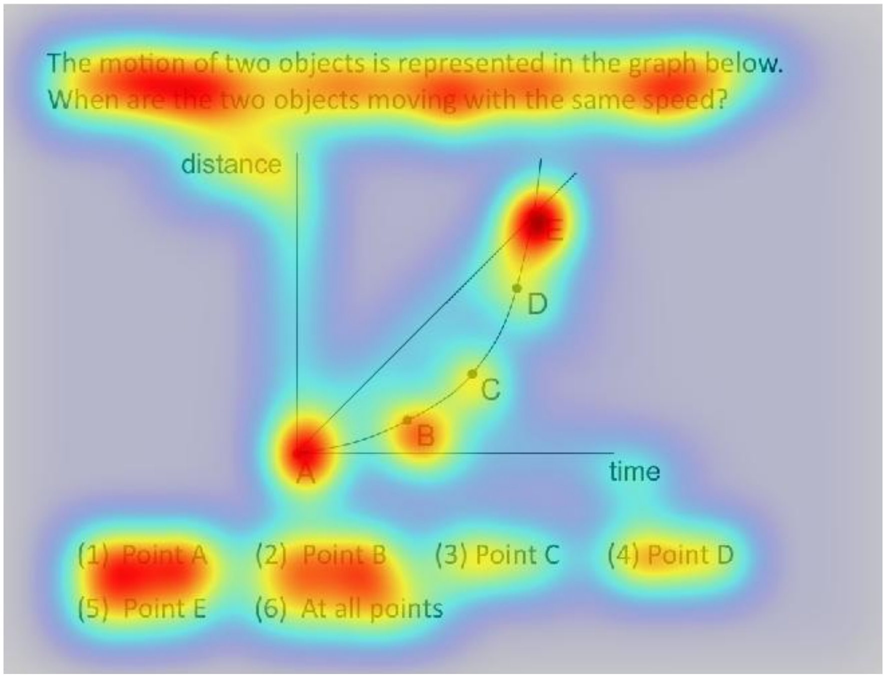


Figure 3.4 Itti, Niebur and Koch saliency map for Problem 7. The perceptually salient AOI partially overlapped with the novice-like AOI, which was at the point where the two lines cross.



First Two Seconds After Leaving Problem Statement

To reanalyze the data including only the first two seconds of viewing a diagram, we completed a mixed factorial 2 x 6 ANOVA with *proportion of time in each AOI type* as the dependent variable and *problem number* and *correctness of answer* as independent variables for all three AOI types for the first two seconds of viewing the diagram. These results are reported in Table 3.5. We were looking for a main effect of correctness, as this would indicate there are differences in percentage of time spent in an AOI between those who answered correctly and those who answered incorrectly. For the first two seconds after leaving the problem statement, we found no main effect for correctness of answer for any of the AOI types. So, there are no significant differences in proportion of time spent fixating in the AOI types between those who answered correctly and those who answered incorrectly for any of the problems and no further analysis was conducted.

We did find a main effect for problem number for the novice-like and perceptually salient AOIs. This means for each of these AOIs, there is at least one difference in proportion of time between the different problems when considering the data for all participants. We were not interested in how the proportion of time spent fixating varies between problems, as this is not relevant to our research questions. We also found a significant interaction between problem number and correctness of answer in the thematically relevant AOI. This means the relationship between correctness and time spent in the thematically relevant area is different across problems. This interaction also does not address our research questions, and is not analyzed further.

The mean percentage of fixation time spent looking in thematically relevant, novice-like and perceptually salient AOIs for participants who answered the question correctly and incorrectly for the first two seconds of viewing the diagram is displayed in Table 3.6. As mentioned above, there are no significant differences between the percentage of fixation time for correct and incorrect solvers shown in this table.

Table 3.5 Results of mixed factorial ANOVA for all three AOI types for the first two seconds of viewing..

	Thematically Relevant AOI		**Novice-like AOI**		**Perceptually Salient AOI**	
Effect	F	p	F	p	F	p
Problem #	F(5,128)=2.10	0.069	F(5,128)=6.72	<.001	F(5,128)=10.7	<.001
Correctness of Answer	F(1,128)=.495	0.483	F(1,28)=2.03	0.156	F(1,128=2.47	0.119
Problem # * Correctness of Answer	F(5,128)=2.30	0.048	F(5,128)=.036	0.999	F(5,128)=.671	0.646

Table 3.6 Mean percentage fixation time spent (± std err) during the first two seconds after leaving the problem statement for thematically relevant, novice-like and perceptually salient AOIs for participants who answered the question correctly/incorrectly

AOI Type	Problem	Answered Correctly	Answered Incorrectly
Thematically Relevant	1	13.5 (± 6.8) (n=11)	31.1 (±6.3) (n=11)
	2	10.9 (± 2.9) (n=13)	8.6 (±3.4) (n=10)
	3	9.7 (± 3.1) (n=18)	9.7 (±5.0) (n=6)
	4	26.5 (± 5.0) (n=14)	11.9 (±6.5) (n=9)
	7	17.6 (±6.5) (n=15)	17.6 (± 2.4) (n=9)
	10	13.0 (± 4.2) (n=11)	9.7 (± 4.1) (n=13)
Novice-Like	1	2.6 (± 1.4) (n=11)	9.4 (±2.7) (n=11)
	2	9.4 (± 4.3) (n=13)	13.0 (±6.2) (n=10)
	3	12.1 (± 3.2) (n=18)	15.2 (±9.0) (n=6)
	4	17.6 (± 4.2) (n=14)	22.3 (±6.1) (n=9)
	7	17.4 (± 4.7) (n=15)	20.8 (± 7.6) (n=9)
	10	30.7 (± 7.0) (n=11)	34.6 (± 5.2) (n=13)
Perceptually Salient	1	0.7 (± 0.7) (n=11)	2.5 (±1.8) (n=11)
	2	10.8 (± 3.2) (n=13)	21.8 (±8.1) (n=10)
	3	8.3 (± 2.7) (n=18)	9.0 (±4.1) (n=6)
	4	2.5 (± 2.5) (n=14)	2.3 (±2.3) (n=9)
	7	23.2 (±4.4) (n=15)	32.5 (± 8.0) (n=9)
	10	10.9 (± 4.9) (n=11)	11.6 (± 3.4) (n=13)

The reanalysis of the data for the first two seconds of viewing the diagram found no statistically significant differences between correct and incorrect solvers on any of the problems for the perceptually salient AOI. Indeed, there were no statistically significant differences between correct and incorrect solvers in time spent in the thematically relevant or novice-like AOIs. In sum, we found no support for the hypothesis that perceptual salience influences visual selective attention more for incorrect problem solvers during the first two seconds of diagram viewing. This result is consistent with previous studies (Einhauser et al., 2008; Hegarty et al., 2010) that have shown that top-down influences on visual attention tend to dominate bottom-up influences when a viewer is given a specific goal or task. Nevertheless, such null results for the effects of bottom-up saliency on visual attention are consistent with our own results, which considered both the full problem solving time period, and only the first two seconds, and found little if any effects.

However, before completely rejecting the hypothesis that bottom-up saliency affects attentional selection during physics problem solving, we must consider two observations that provide partial support for it. First, it may be that the early effect of perceptual salience on eye movements was present; however, the data lacked sufficient statistical power to detect it. Some support for this explanation is shown by comparing the mean difference for the correct versus incorrect problem solvers for the perceptually salient AOIs for the first two seconds of viewing the diagram (Table 3.6). Specifically, the percentage of time spent looking in the perceptually salient AOI is higher for incorrect solvers than correct problem solvers on five of the six problems, though not statistically significantly so. Thus, it is possible that a larger study with more observations might show this effect to be statistically significant. Secondly, the perceptual salience model proposed by Itti and Koch (2000) predicted that early in scene viewing eye movements are more influenced by bottom-up perceptual information than top-down knowledge. Therefore, the saliency model would predict that early in viewing a physics problem, correct and incorrect problem solvers would not have had sufficient amount time to apply their (correct or incorrect) top-down knowledge to guide their attention to thematically relevant or novice-like areas of the diagram. If so, during the first two seconds of viewing the diagram, there should be no difference between correct and incorrect problems solvers' percentage of total fixation time in either the thematically relevant or novice-like AOIs. These data support this hypothesis, which shows that there is no significant difference in viewing time for thematically relevant AOIs between correct and incorrect problem solvers. In sum, the data showed essentially no influence by top-down domain knowledge during the first two seconds of diagram viewing, though such effects were statistically significant later in time, when considering the full problem solving time period. Thus, based on the above two observations, we must withhold complete rejection of the hypothesis that bottom-up salience affects the visual selective attention of incorrect physics problem solvers. Even so, such an interpretation of the data should be made cautiously since it is based on null effects.

Study 3- Using ScanMatch Scores to Understand Differences in Eye Movements Between Correct and Incorrect Solvers on Physics Problems

In this study, we reanalyzed the data from Study 2 to further investigate the role of perceptual salience in guiding the attention of those who incorrectly answer conceptual physics questions containing a diagram. A scan path analysis was performed with the ScanMatch algorithm (Cristino, Mathôt, Theeuwes, & Gilchrist, 2010). This scan path analysis takes into account both spatial and temporal aspects of the eye movements and may be more sensitive to differences between correct and incorrect solvers.

We compare the average ScanMatch scores produced by comparing the correct solvers to one another (C-C comparison), the incorrect solvers to one another (I-I comparison), and the correct solvers to the incorrect solvers (C-I comparison). We hypothesize that if the incorrect solvers are being primarily led by the perceptual salience of the elements in the diagram, then it is likely that they will attend to the same elements in a similar order. For example, attention would be first guided to the most perceptually salient region, followed by the next most salient region, and so on (Itti & Koch, 2000). Thus, the I-I comparison would have higher ScanMatch scores than the C-C comparison, who might attend to perceptually salient areas early on in diagram viewing; however, the variable onset of top-down processes on eye movements would result in greater temporal and spatial variability of gaze towards thematically-relevant elements in the diagram, resulting in lower ScanMatch scores. The I-I and C-C groups would also have higher ScanMatch scores than the C-I group, since the correct solvers and incorrect solvers are known to spend different amounts of times looking at thematically-relevant and novice-like elements.

Conversely, if top-down processes are directing the attention of incorrect solvers, namely some form of naïve theory, the ScanMatch score of the I-I comparison should be similar to that of the C-C comparison. The domain knowledge possessed by those in both comparison groups, whether correct or incorrect knowledge, guides their attention to look at certain elements of the problem, but not in a particular order. Once again, the I-I comparison and the C-C comparison should have higher ScanMatch scores than the C-I comparison.

In summary:

Hypothesis 1: If perceptual salience is primarily influencing the attention of incorrect solvers, the I-I comparison will have higher ScanMatch scores than the C-C comparison.

Hypothesis 2: If top-down processes utilizing naïve theories are primarily influencing the attention of incorrect solvers, the I-I comparison and the C-C comparison will have similar ScanMatch scores, and these will both be higher than the C-I comparison

Study 3: Methods

Participants, materials, apparatus and procedure are identical to those described in Study 2 above.

Study 3: Analysis and Results

We used the ScanMatch toolbox for MatLab (Cristino et al., 2010) to compare the scan paths of our participants based on the correctness of their answers given for each problem. We calculated ScanMatch scores for three different comparisons of participants' scan paths. The correct-correct comparison (C-C) contained scores comparing each participant who answered a question correctly to one another. The incorrect-incorrect comparison (I-I) contained scores comparing each participant who answered a question incorrectly to one another. Finally, the correct-incorrect comparison (C-I) contained scores comparing those who answered correctly to those who answered incorrectly. We then completed a one-way ANOVA comparing the ScanMatch scores of the C-C comparison, I-I comparison, and C-I comparison for each problem. When we obtained a significant result, we used post-hoc contrasts to determine which comparisons contained a significant difference. We then referenced the mean score values for each comparison to determine the direction of this difference. When homogeneity of variance was violated, we used the Games-Howell test for the post-hoc contrasts, otherwise we used Tukey's HSD test for the contrasts. In Study 2, for which this analysis is a follow-up, the eye movements of only six of the 10 problems participants viewed were analyzed. This is because we found that four of the problems did not contain a consistent novice-like area of interest. On those four problems, participants who answered incorrectly reasoned from a wide variety of areas in the problem diagram. Without a precise definition for the novice-like area of interest, these problems could not be included in the original analysis. This scan path analysis is a follow-up on the previous analysis, so we analyze only those six problems included in the original study.

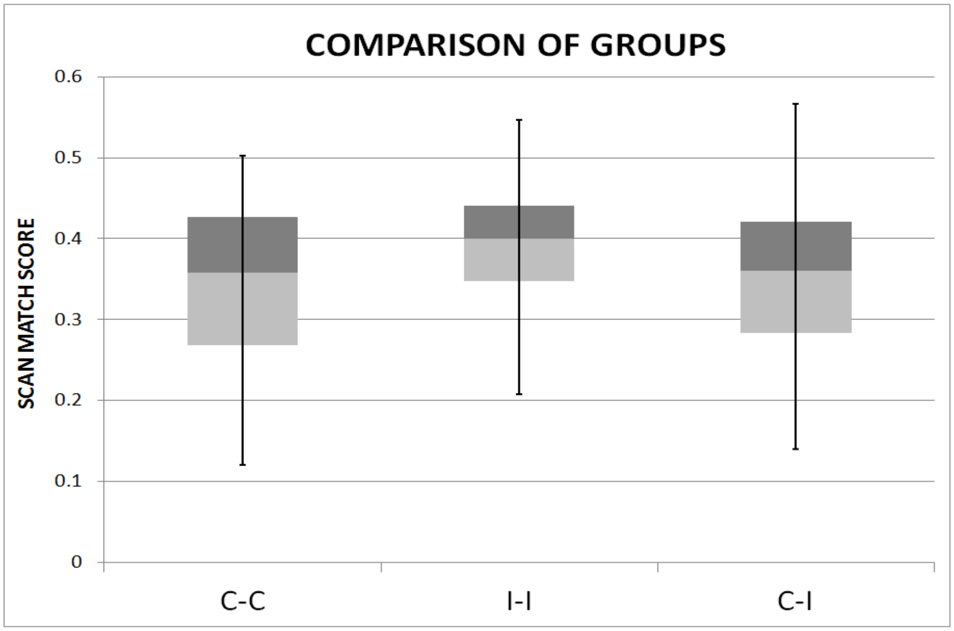
We found statistically significant main effects on three of the six problems tested (Table 3.7). On problem 1, the ANOVA showed a statistically significant main effect of comparison, $F(2,220) = 7.324$, $p = .001$. The contrasts revealed that the I-I comparison had significantly higher ScanMatch scores than the C-I comparison ($p < .001$). Problem 2 also showed significant main effect of comparison, $F(2,250) = 6.308$, $p = .002$. The contrasts showed that the I-I comparison ($p < .001$) had a higher ScanMatch score than the C-I comparison. Further, the I-I comparison had a significantly higher score than the C-C comparison ($p = .005$). A significant main effect was also found for problem 10, $F(2,273) = 3.583$, $p = .029$. On this problem, the I-I comparison had a significantly higher ScanMatch score than the C-I comparison ($p = .05$). There were no differences found between comparisons on problems 3, 4 and 7.

Table 3.7 Mean ScanMatch score for C-C, I-I, and C-I comparison for each problem used in the study.

Problem	Comparison	Mean	SD (±)	ω^2
1*	C-C (n=47)	.396	.068	
(n=11 correct	I-I (n=55)	.414	.056	.06
n=11 incorrect)	C-I (n=121)	.370	.080	
2*	C-C (n=90)	.330	.151	
(n=14 correct	I-I (n=36)	.413	.047	.19
n=10 incorrect)	C-I (n=127)	.371	.119	
3	C-C (n=137)	.351	.093	
(n=17 correct	I-I (n=21)	.400	.108	
n=7 incorrect)	C-I (n=119)	.364	.100	
4	C-C (n=90)	.379	.088	
(n=14 correct	I-I (n=35)	.398	.055	
n=9 incorrect)	C-I (n=126)	.362	.088	
7	C-C (n=105)	.312	.125	
(n=15 correct	I-I (n=36)	.311	.119	
n=9 incorrect)	C-I (n=135)	.298	.112	
10*	C-C (n=55)	.333	.086	
(n=11 correct	I-I (n=78)	.368	.091	.04
n=13 incorrect)	C-I (n=143)	.340	.078	

* indicated a significant difference at the α=.05 level

Figure 3.5 Box and whiskers plot showing the median, max, min and 1st and 3rd quartile of the ScanMatch scores for each group.



Study 3: Conclusions

We did not find significant differences in ScanMatch scores between those in the C-C comparisons and those in the I-I comparisons on five of the six problems analyzed in this study. This evidence is consistent with the hypothesis that the attention of incorrect solvers is primarily directed by top-down naïve theories and not the relative perceptual salience of the elements. This finding aligns well with our previous findings (Study 2) that showed no significant difference in the percentage of fixation time in the perceptually salient areas of the diagram during the full problem period, or the first two seconds of viewing the diagram, when the effects of perceptual salience should be most pronounced. It also aligns well with the findings showing significant differences in the percentage of time incorrect solvers spent in the novice-like areas of the diagram and the percentage of time correct solvers spent in the thematically-relevant areas of the diagram.

We found significant differences between the I-I and C-I comparisons on three of the six problems. These differences were expected as we have previously seen that correct solvers and incorrect solvers spend different amounts of time looking at thematically-relevant and novice-like elements in the problem, so their scan paths scores are likely to be different. It is curious that we did not find that the I-I comparison and the C-C comparison had higher ScanMatch scores than the C-I comparison on all of the problems. The problems used in the study included a text problem statement, diagram, and multiple-choice answers. The hypotheses set forward in this study assumed a similar reading pattern of the problem statement and answer choices for all participants. The hypotheses were formed assuming only differences in how the participants looked at the diagram. Differences in reading the problem statement and answer choices may have overwhelmed small differences in diagram viewing, resulting in no difference in the ScanMatch scores of the C-C and I-I comparisons compared to the C-I comparison.

Implications

These findings may have implications for educational interventions aimed at helping novices learn to answer such conceptual questions correctly. Researchers in physics education have devoted much attention to addressing these consistent wrong answer patterns by changing the way students think about how the world works. If it were true that this problem had an underlying perceptual component, these interventions would need to instead help students learn how to ignore salient elements and focus instead on thematically-relevant elements. The results of this study suggest that wrong answers have roots in the incorrect ways students think about how the world works, not how a problem diagram looks. So it seems that the educational interventions used to improve student understanding are on the right track.

Overall, these findings motivate the investigation of visual cues to redirect individuals' attention to relevant portions of the diagrams and potentially influence the way they reason about these questions. The problems used in Study 2 all contained AOIs consistent with novice-like misconceptions. Those who answered incorrectly spent more time looking at these novice-like AOIs. One way to help incorrect problem solvers pay attention to the relevant areas of a problem diagram is to overlay dynamic visual cues on it. Visual cues overlaid on physics problems such as those in the current study may help students to ignore the novice-like AOIs of diagrams, and instead pay attention to the thematically relevant AOIs in order to reason in a scientifically correct manner about the problem. The use of visual cues is explored in the work presented in Chapter 4.

Chapter 4 - Can Short Duration Visual Cues Influence Students' Reasoning and Eye Movements in Physics Problems?

Introduction

Based on successful use of visual cues in insight problem solving by Thomas and Lleras (2007) and others studies on visual cueing, we apply visual cueing to static physics problems in hopes that the cues will also serve as an implicit guide to improve problem solving performance.

Theoretical Background

There are two relevant theoretical frameworks which help us interpret the function and mechanism of visual cueing. The first, the Cognitive Theory of Multimedia Learning (Mayer, 2001), pertains to the use of multimodal information in learning. The second, Representational Change Theory (Ohlsson, 1992), is related to the cognitive mechanism involved in problems that require insight to solve. These have both been described in Chapter 1 of this dissertation. Below we discuss the connections between these frameworks and the current study. In our current study we utilize visual cues that serve to *select* relevant information and *integrate* related elements in a problem diagram. We did not study *organization* cues.

Connections between Theoretical Background and Current Study

We apply representational change theory to understand how visual cues can help learners solve physics problems. Ohlsson (1992) conceptualizes insight as "initial failure followed by eventual success." He explains that insight occurs when the problem solver is competent to solve the problem before him/her, reaches an impasse in the problem solving process, and then successfully breaks this impasse. Representational Change Theory is valid for problem solving processes in which this impasse-insight sequence occurs and we claim that this sequence is likely to occur in our study. First, the nature of our problems lent themselves to impasse and insight. We used introductory conceptual physics problems requiring students to activate specific conceptual resources (Hammer, 2000). Since these questions are not given in any particular context, such as the end of a chapter or during lecture, the students must first realize the appropriate concept. If they cannot realize an appropriate concept, they may reach an impasse, which could be resolved when they see the visual cues and focus on relevant information.

Further, since these questions are conceptual, once a student realizes the appropriate concept to use, there is not a long set of mental steps or calculations before getting to an answer. Instead, the student applies the appropriate conceptual resource and can quickly realize an answer. The problem diagrams also contain visual information consistent with an incorrect, "novice-like" answer. Students who answer these problems incorrectly attend to this novice-like visual information and activate conceptual resources which lead to the wrong answer (Madsen, Larson, Loschky, & Rebello, 2012). So the student needs to not only realize the appropriate concept, but also must suppress the use of these novice-like concepts which lead to incorrect answers. In our study, students first answer an initial problem and if incorrect, see a very similar problem. Students may also reach an impasse when they repeatedly see very similar problems overlaid with visual cues. During this process, the visual cues draw students' attention to areas they had previously ignored. The combination of answering a very similar problem several times while their attention is being redirected to an area they previously found irrelevant could cause them to second guess their previous answer. As they reconsider the diagram areas highlighted by visual cues, they may resolve their impasse with an insight, activate appropriate conceptual resources, and answer correctly.

In order to resolve an impasse, we hypothesize that visual cues can serve to help the student re-represent a problem in their mind. In line with Representational Change Theory, the purpose of visual cues is to help the student replace an existing unproductive representation with a productive one or add to their existing representation until it is adequate to solve the problem. This re-representation occurs through three possible mechanisms: elaboration, re-encoding or constraint removal. In our current study we explore visual cues that we believe help re-representation occur through elaboration and re-encoding, but not constraint removal.

Elaboration involves adding new information to the problem. This is useful for a learner who has gathered insufficient information to form productive mental representation of the problem, and has thus reached an impasse. Integration cues can help facilitate the addition of critical new information by helping the learner attend to information in a particular order and/or help the learner make comparisons between different elements of the diagram. A learner attending to the information provided by these cues is prompted to activate previously dormant information from the long-term memory and eventually encode a new representation for the problems.

Re-encoding, unlike elaboration, involves not just adding new information, but rather backtracking through previous layers of the problem solving process, eliminating unproductive layers in their mental representation of the problem and creating new productive layers of the mental representation. The re-encoding process is especially important for the problems used in our study, as the diagrams for these problems each contain an area(s) consistent with most common incorrect answer. This feature of the problems makes it likely that the students will activate unproductive naïve concepts when reasoning to an answer. In order to help them re-encode the problem representation in a scientifically accurate way selection cues could be used. Rather than provide new information that was not previously present in the diagram, these cues prompt the learner to suppress irrelevant information and enhance relevant information for solving the problem. The learner attends to the previously ignored relevant information, which in turn activates previously dormant prior knowledge from long-term memory and eventually encodes a new representation for the problems.

This study builds on previous research that investigated the visual attention of learners who correctly and incorrectly answer physics problems containing diagrams, which is described in Chapter 4. This study uses four of the six problems used in that work. We hypothesize that visual cues will be especially useful on these particular problems for two reasons. First, our previous study showed that participants who answer these problems incorrectly spend less time looking at relevant areas and more time looking at novice-like areas. Further, in a similar study of expert chess players solving problems with two possible solutions, it was found that when the players had found the first solution, they reported looking for a better one, though the eye movement record indicated they continued to look at features of the problem related to the solution they had already found (Bilalić, McLeod, & Gobet, 2008). Although they tried to seek out the better solution, their attention was fixated on their first idea. We know that participants who answer our study problems incorrectly spend more time looking in these novice-like areas. If they are similar to the chess players, they may try to consider other solutions, but will keep their attention fixated on areas consistent with their first idea. Selection cues can improve problem solving by helping solvers ignore the "novice-like" areas of the diagram, attend to the "expert-like" areas, and create a new mental representation of the problem. Using the new representation, the leaner can activate relevant concepts in long-term memory, thus extending the information available to the problem solver. When the relevant concept is available to the solver, she can apply the concept to answer the question correctly.

Second, the problems we used contained “expert-like” elements in the diagram that were spatially separate and needed to be compared. A learner at an impasse does not make the necessary connections between these elements that produce a productive mental representation of the problem. Integration cues can add information to the learner’s current mental representation by helping them make these necessary connections. To determine the most useful way to design the integration cues for these problems, we can use the eye movements of correct solvers from this study, look for patterns in the way correct solvers viewed the “expert-like” elements, and model our integration cues on these patterns.

In the current study, we use a subset of the physics problems used in Chapter 3 as well as recordings of the eye movements of those who responded correctly to design the visual cues. In this chapter, we aim to answer the following Research Question 2 which states, “Can short duration dynamic selection/integration visual cues influence students’ reasoning and answers on physics questions with a diagram?” We will also explore the following sub-questions:

- Does seeing these cues repeatedly on similar problems influence students’ reasoning and answer choices on transfer problems?
- Does seeing these cues influence visual attention while the cues are shown as well as on transfer problems?

Method

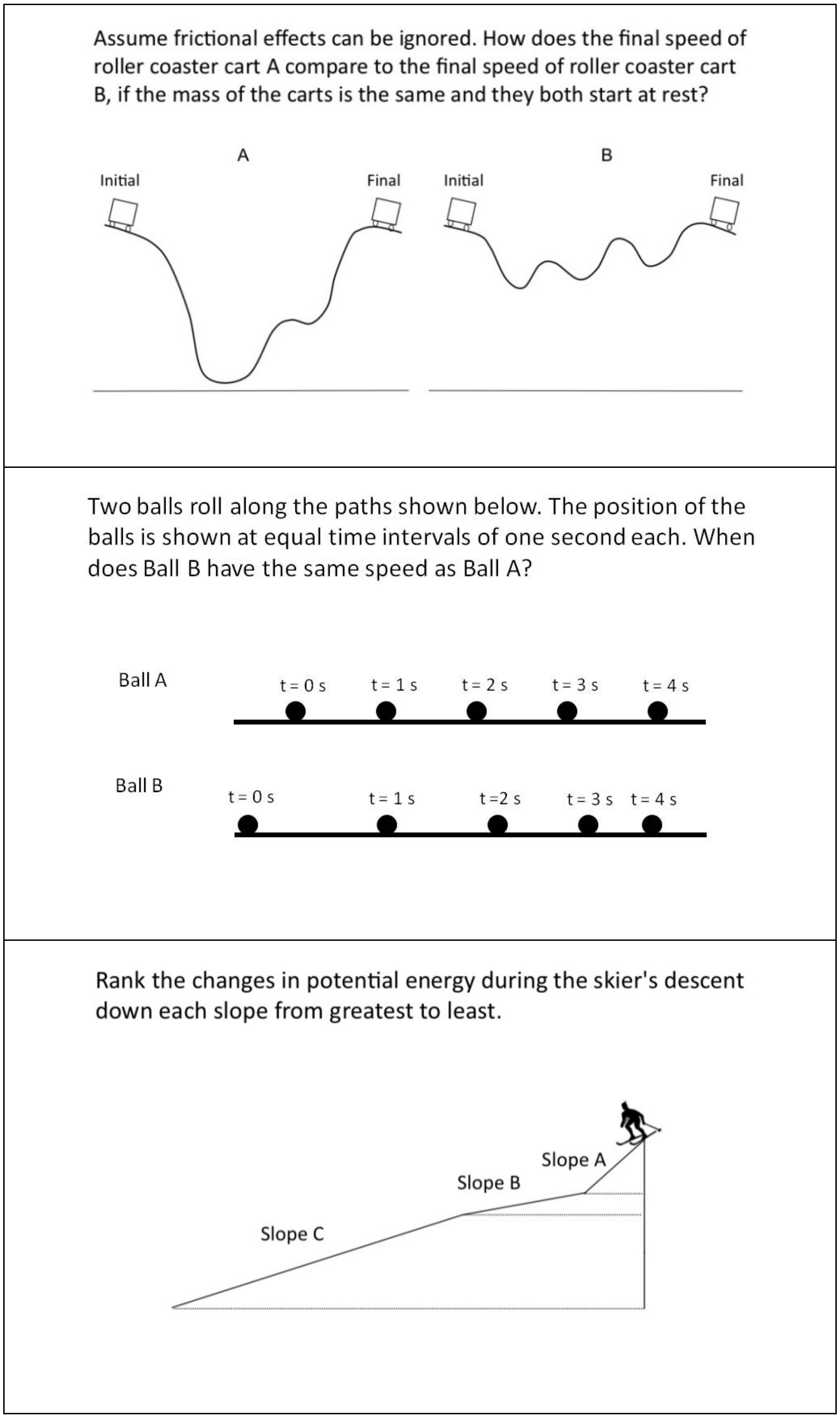
Participants

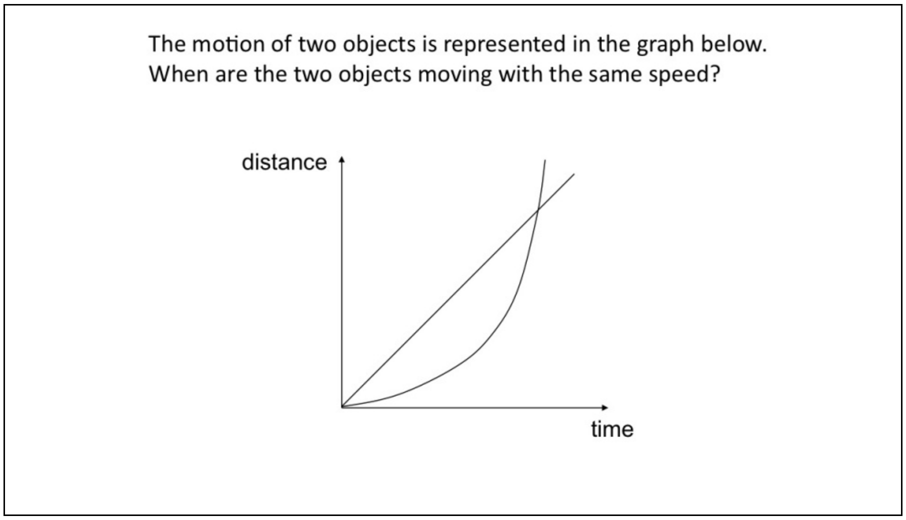
We conducted individual sessions with 63 individuals concurrently enrolled in either first or second semester introductory algebra-based physics course. Students were invited via an email sent to all students enrolled in the course and were paid $10 for participation. We collected data over two semesters, but ensured that students had covered relevant topics in their physics course before recruiting them to volunteer in our study. We invited students from the same courses to participate both semesters. We also ensured that each student only participated once.

Materials

The materials consisted of four sets of related conceptual introductory physics problems in which an accompanying diagram was necessary to answer the problem. These problems have been previously studied in the work presented in Chapter 3 and a complete description of the PER literature which describes them is available there. Three of the six problems discussed in Chapter 3 dealt with kinematics graphs. We choose to use one of these kinematic graph questions as well as the three other questions for a total of four problems in the current study. We refer to these problems as the Roller Coaster, Ball, Skier, and Graph problems (see Figure 4.1).

Figure 4.1 Four "initial" problems taken from Madsen et. al. 2012 and used in current study. Shown from top to bottom are the "Roller Coaster", "Ball", "Skier", and "Graph" problems.





For those in the “cued” condition, dynamic visual cues were overlaid on the problem diagram. The cues used in this study were a combination of *integration* and *selection* cues (de Koning et al., 2009). The visual cues were designed to mimic the eye movements of those who answered the same problems correctly in our previous study described in Chapter 3. 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 relevant area of interest. Similarities between participants were observed, and visual cues were modeled after these patterns.

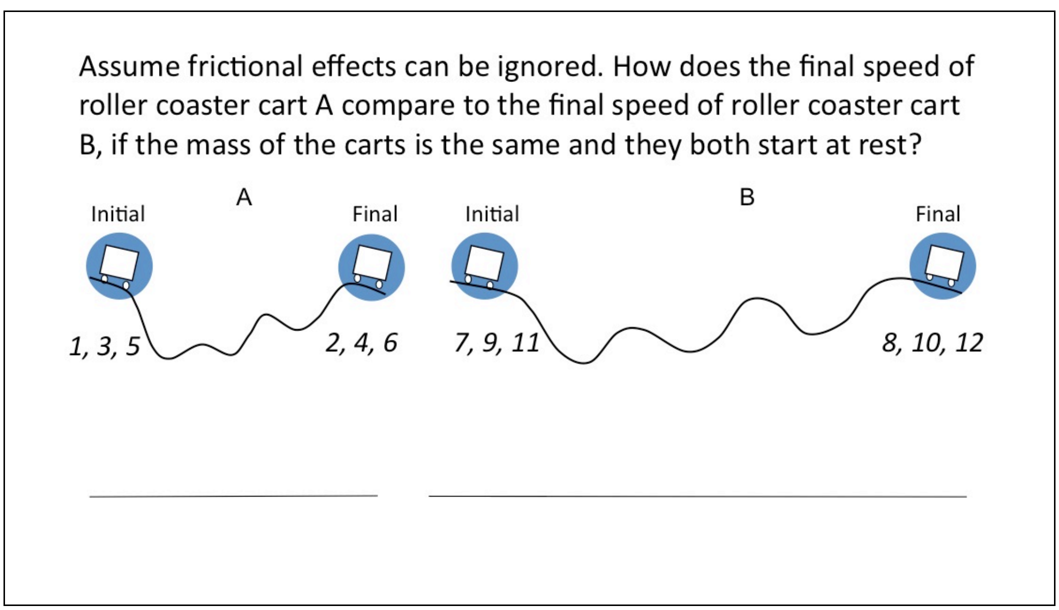
Cues on all four problem sets were intended to prompt selection and integration of expert-like elements in the problem diagrams. On the “roller coaster” problem, cues moved between the roller coaster carts to help students compare the heights of the roller coasters (Figure 4.2). The relationship between heights of the roller coasters is needed to determine the potential energy of each at the beginning and end of the path and then relate this to the amount of kinetic energy and finally the speed. Cues helped participants to *select* the roller coaster carts and not attend to the shape of the roller coaster tracks, which is the most commonly used feature when giving an incorrect answer. They also aimed to help participants *integrate* the roller coaster carts, which were spatially separated, so they could compare the heights of the initial and final carts.

On the “ball” problem, the cues aimed to help the students compare the distances between balls during the same time period (*integration)*, for example comparing the distance between the balls on track A and track B between one and two seconds. The balls on tracks A and B have the same speed when the balls have moved the same distance in the same one-second time interval. The cues were also intended to help the students *select* distances between successive balls and not compare the positions of the balls at the same time, as those who give an incorrect answer often do.

On the "skier" problem, the cues were designed to help the student compare the heights of each slope (*integration)*. The height of each slope is directly related to the change in potential energy. They were also designed to help the students to *select* the height and ignore the steepness of each slope, which is commonly used when giving a wrong answer.

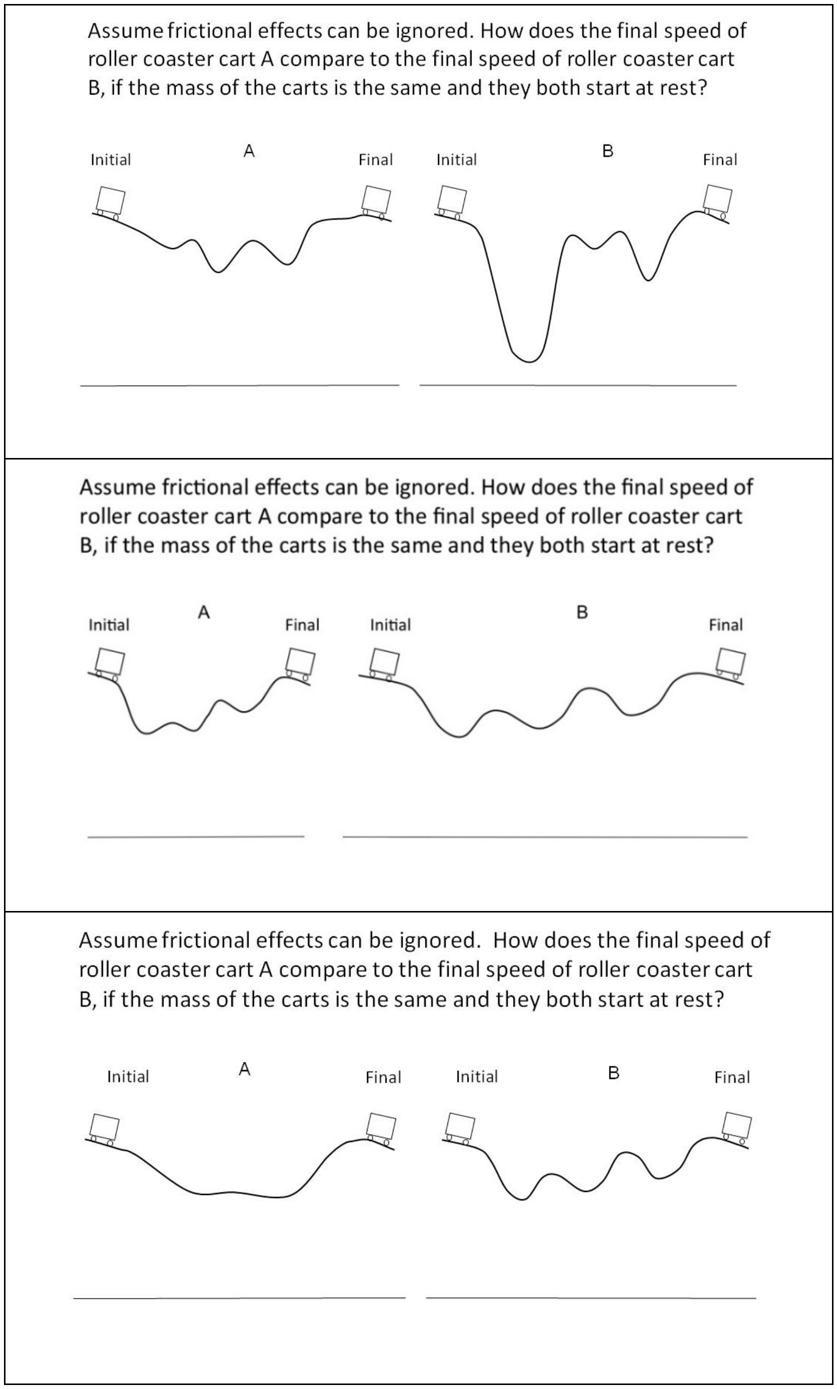
On the "graph" problem, the cues aimed to help the students judge the slope of the curved line at several points and compare this to the slope of the straight line (*integration)*. The speed of the two objects is the same when the slope of the two lines is the same. They were also intended to help the solvers attend to the slopes of the lines and not the points where the lines cross (*selection)*. At the crossing points, the two objects have the same position, but not the same speed, and students often confuse these two quantities.

Figure 4.2 Roller coaster "similar" problem used in study with visual cues overlaid. The blue dots are the visual cues and the numbers in italics show sequence of animated cues (the numbers were not seen by study participants).



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 which one had to use in order to answer the problem. The "similar" problems in each set had the same problem statement as the initial problem and the same surface features. The "novice-like" area of the diagram for each was manipulated in a way that would change the answer one would give if answering based on a novice-like conception. For example, in the similar problem set shown in Figure 4.3, the number and depth of bumps on the roller coaster track and horizontal distance between carts were varied. If a student uses the features of the track to determine the speed of the carts, their answer would be different for each of these problems. The transfer problem in each problem set tested the same concept as the initial and similar problems, though the surface features were different. For example, the roller coaster transfer problem shown in Figure 4.4 contains two tracks with different start and end heights. Now the student must reason about the potential and kinetic energy of tracks with the same difference in height.

Figure 4.3 Example of four "similar" problems used in the "roller coaster" problem set in the study.



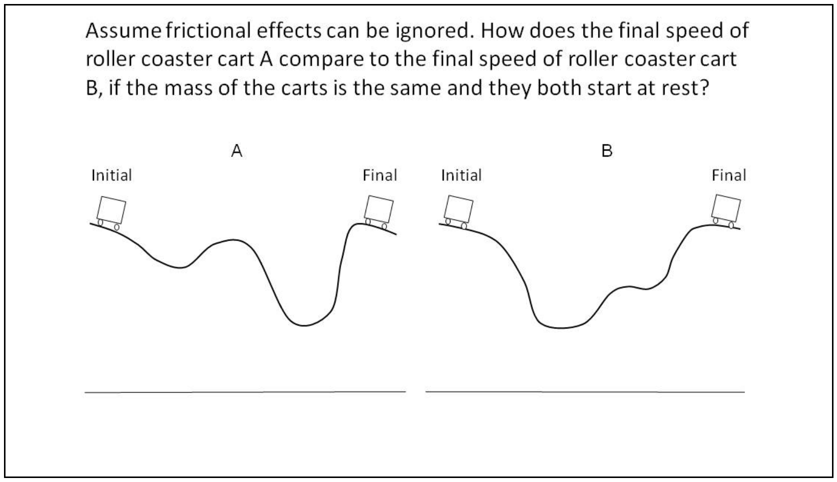
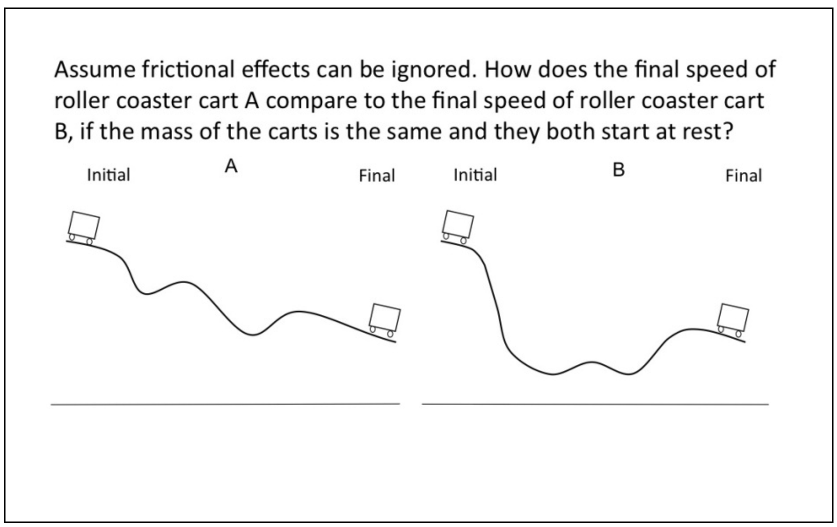


Figure 4.4 Example of a transfer problem used in the "roller coaster" problem set in the study.

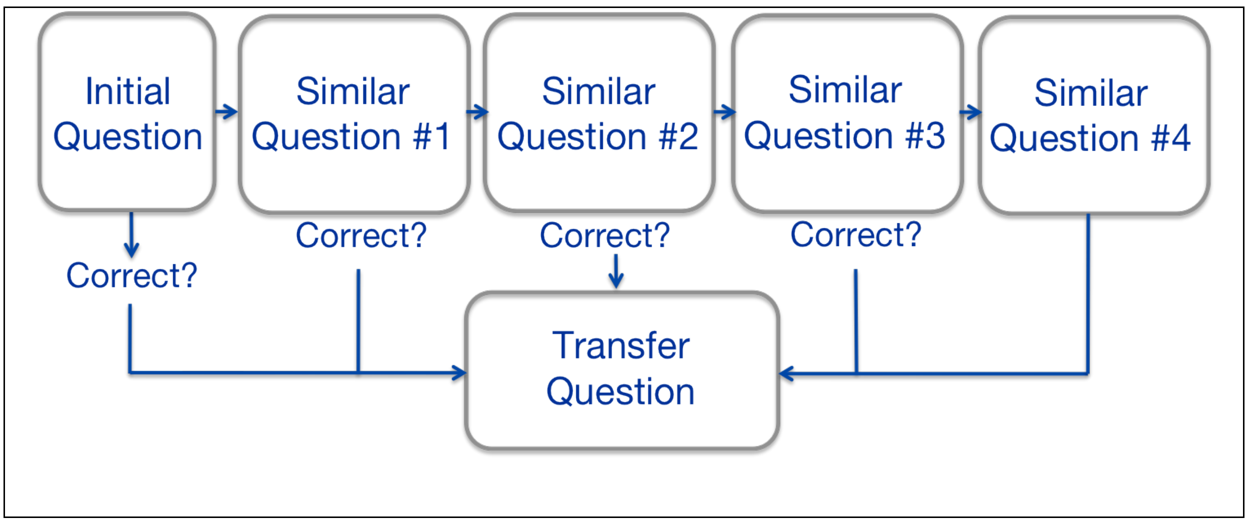


Study Design and Procedure

To ensure that the participants had sufficient prerequisite knowledge of the concepts tested in the study problems, each participant completed a pre-test, which consisted of four open-ended questions gauging their understanding of speed and potential energy. 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 cued condition were told that colored shapes may appear on some of the problems and when these appeared, they should follow them with their eyes. No further information about the purpose of the cues was given to participants.

Each participant was randomly assigned to the "cued" condition or the "non-cued" condition. Equal numbers of participants were assigned to each condition. The research design is shown in Figure 4.5. 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, 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. All participants viewed the four sets of problems in the same order.

Figure 4.5 Flow chart showing how the initial problem, similar problems, and transfer problems were administered to students in each of four problem sets.



Whenever a student was ready to provide an answer and explanation for 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 cued condition saw moving colored shapes overlaid on the similar problems. Moving colored shapes were used because color and motion have been found to be the most predictive of attentional selection because of their high perceptual salience (Carmi & Itti, 2006). The cues used for the roller coaster problem are shown in Figure 4.2 and those for the ball, skier, and graph problems are shown in Appendix B. Each colored shape appeared four seconds after the problem was presented to give the participant time to read the problem statement (although the problem statement for each similar problem was the same). The cues then appeared for 500 ms at 12 positions in the diagram for a total cueing time of six seconds. This six second time period was chosen as we modeled many aspects of our study after Thomas and Lleras' (2007) successful cueing work, in which visual cues were shown for four seconds. After the cues ended, participants could spend as much time as they wanted on the problem.

Participants' verbal explanations and gestures were recorded with a Flip video camcorder.

Analysis and Results

Participants were only included in our analysis if they correctly answered pre-test questions demonstrating knowledge of the concepts tested in the study problems. 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. There were cases where a participant did not demonstrate adequate understanding of one of the concepts tested, so their data for that concept were not included in this analysis. Further, we only included participants with usable eye movement data files. There were four participants whose eye tracking data files became corrupted and could not be used.

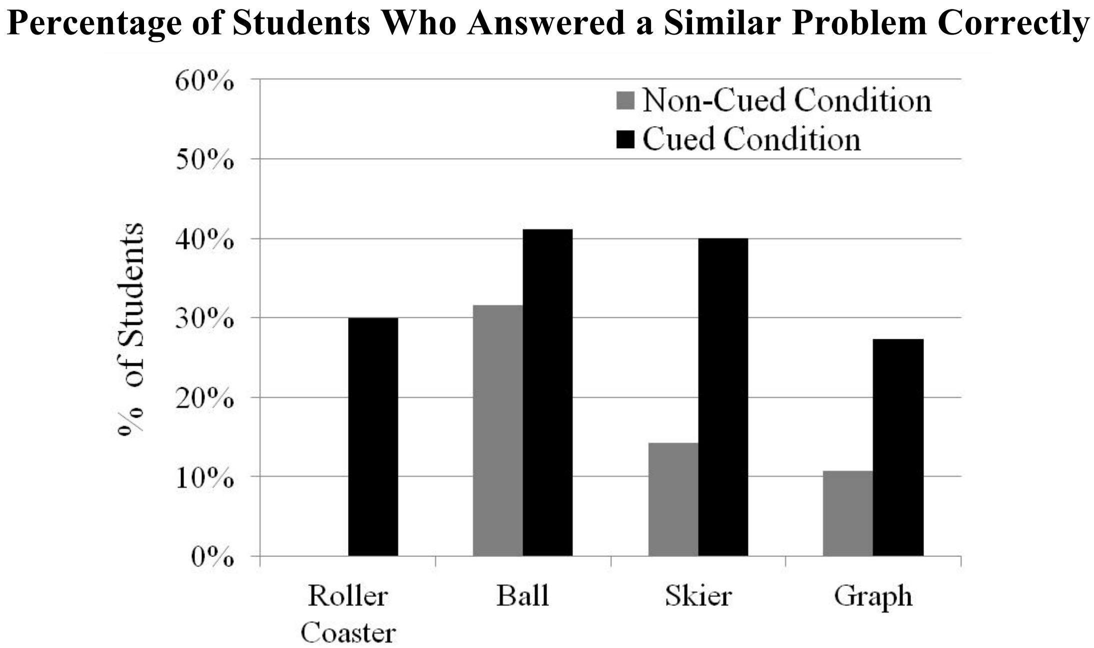
Improvements to Problem Solving Performance with Visual Cues

We first investigated the problem solving performance of participants by comparing how often those in the cued and non-cued condition who had answered the initial problem incorrectly answered one of the similar problems correctly. It is necessary to only look at the sub-group of students who answered the initial problem incorrectly, because those who gave the correct answer and reasoning would not benefit from the cues. We first compared the aggregate number of participants in the cued and non-cued conditions who gave an incorrect answer on the initial problem and then gave a correct answer and explanation on any of the four similar problems. Fisher's Exact Test (Fisher, 1922) was employed to test the significance of the difference between the cued and non-cued condition in the proportion of students who correctly answered a similar problem. Fisher's Exact Test is used with categorical data, which is encountered when participants are classified in two different ways, and small sample sizes. In our case, the two different ways of classification are as follows: 1) whether a participant belongs to the cued or non-cued condition or 2) whether a participant did or did not correctly answer a similar problem (after answering the initial problem incorrectly). Fisher's Exact Test examines whether students in one condition are more likely to change to answer a similar problem correctly than students in the other condition on the same problem set. We found a significant effect of cueing when looking at the data for all problems (p=.004), so we then repeated Fishers Exact Test for each of the four problem sets, to determine which problem sets contributed to the positive effect of the cues. Results of Fisher's Exact Test for each individual problem set as well as the phi coefficient representing the effect size are shown in Table 4.1. The total number of students included for each problem set is different and does not result in 63 total participants because we only included those who answered the initial problem incorrectly, who had satisfactorily answered the pre-test questions and who had usable eye-movement data files. Figure 4.6 displays the percentage of students in each group who change to a correct answer on a similar problem set.

Table 4.1 Summary of results of Fisher's Exact Test comparing those who did and did not answer on a similar problem correctly for the cued and non-cued conditions.

Problem Set	Condition	Answered Similar Problem Correctly	Did Not Answer Similar Problem Correctly	p	Effect Size (Φ coefficient)
Roller Coaster	Cued	6	14	.012*	.42
	Non-Cued	0	19		
Ball	Cued	7	10	.228	-
	Non-Cued	6	13		
Skier	Cued	4	6	.142	-
	Non-Cued	2	12		
Graph	Cued	6	16	.098	-
	Non-Cued	3	25		

Figure 4.6 Comparison of participants in cued and non-cued conditions who gave the correct answer and reasoning on a similar problem.



We found a statistically greater number of participants in the cued condition answered a roller coaster similar problem correctly (p= .012). This means that a mere six seconds of visual cueing for which the participants did not know the purpose resulted in significantly more students going from answering the roller coaster problem incorrectly to answering correctly and providing a scientifically correct explanation on a very similar problem. It is promising to find a difference using such a short intervention. We did not find significant differences on the ball, skier, or graph problems. Inferences on why this was the case will be reviewed in the Limitations and Future Work section.

Changes in Eye Movements on Similar Problems

We next investigated how the visual cues influenced participants' eye movements while viewing the similar problems. Prior to the experiment, participants in the cued group were told that they might see colored shapes appear on the screen and when they saw the shapes they should follow them with their eyes. Participants were not informed when they would see the shapes. Because of this, there were individual differences in how closely participants actually followed the moving colored shapes with their eyes. It may be that participants who did not follow the shapes closely did not benefit as much from the visual cue as those who watched each segment of the cue. To investigate this possibility, we employed a scan path analysis using the ScanMatch algorithm (Cristino et al., 2010). We isolated participants' eye movements while the cues were being shown for the first similar problem (since all cued participants saw this problem). We did this for participants in the cued condition and compared them to the scan path of the visual cues using the ScanMatch algorithm. We then compared the ScanMatch scores of those who had changed to a correct answer on a similar problem to those who had not. To do this, we employed the Kruskal–Wallis one-way analysis of variance in SPSS. This test is the non-parametric method to compare two or more independent groups and is the equivalent of the one-way ANOVA. This test was appropriate for our analysis since we had small group sizes which did not form a normal distribution. Average ScanMatch scores and standard error are reported in Table 4.2. We found a significant difference in ScanMatch scores between those who had answered a similar problem correctly and those who had not for the roller coaster problem only ($H(3) = 9.939$, $p = .019$). We did not find statistically significant differences on the ball, skier, or graph problems. This means that on the roller coaster problem, the participants who answered a similar problem correctly were following the visual cues more closely on similar problem 1. This suggests that on this problem there is a connection between how well one follows the visual cues with their eyes and if they change from an incorrect to correct answer and verbal explanation of their reasoning. We do not suggest a causal mechanism, but will explore this finding more in the conclusion.

Table 4.2 ScanMatch scores for cued participants who did and did not answer a similar problem correctly. * indicates a significant difference.

	ScanMatch Score (± Standard Error)		
Problem	Changed to Correct Answer on Similar Problem	Did Not Change to Correct Answer on Similar Problem	Effect Size η^2
Roller Coaster*	0.588 ± 0.031 (n=6)	0.379 ± 0.042 (n=14)	.47
Ball	0.552 ± 0.046 (n=7)	0.557 ± 0.044 (n=10)	-
Skier	0.700 ± 0.037 (n=4)	0.588 ± 0.058 (n=6)	-
Graph	0.652 ± 0.034 (n=6)	0.595 ± 0.028 (n=16)	-

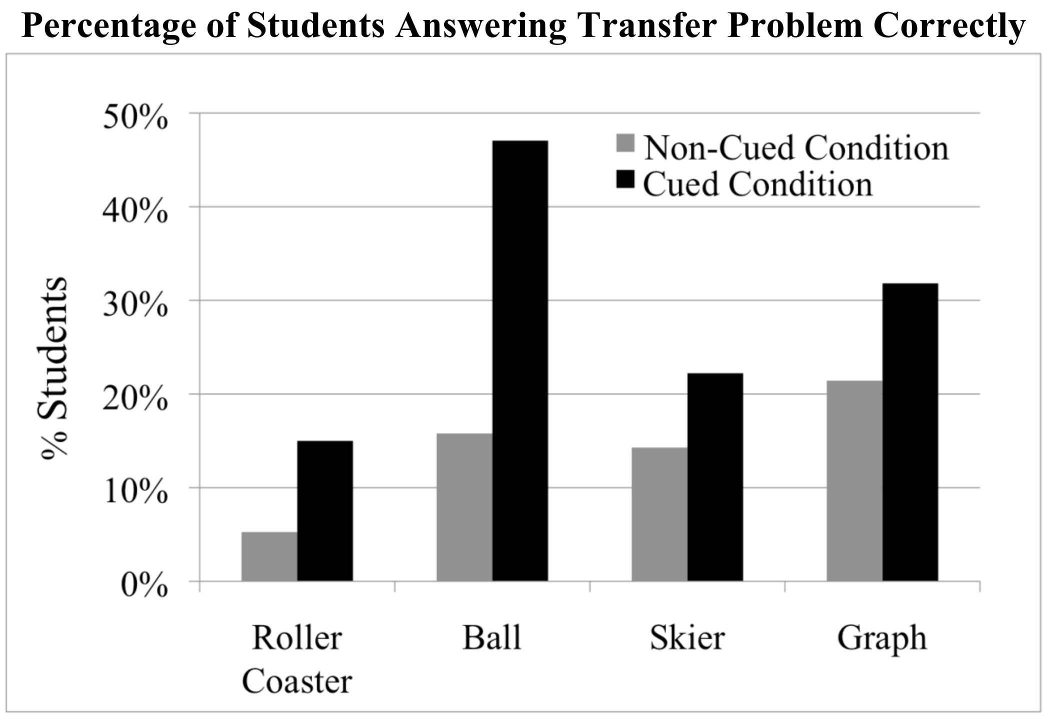
Problem Solving Performance on Transfer Problems

Showing that visual cues have the potential to help students give the correct answer and reason about a problem is an encouraging result, but we will only have evidence that some kind of learning has occurred if students can subsequently answer a related question with no cues. To investigate this possibility, we analyzed the correctness of those in the cued and non-cued conditions on the transfer problem for each problem set. We once again used Fisher's Exact Test to test for a difference in the number of students who had answered the transfer problem correctly in the cued and non-cued conditions for all problems. We found a significant effect of cueing ($p=.027$) so we repeated Fishers Exact Test for each individual problem set. Results are shown in Table 4.3. Figure 4.7 displays the percentage of students in the cued and non-cued conditions who answered each transfer problem correctly. We found that a statistically greater number of participants in the cued condition answered the "ball" transfer problem correctly and gave the correct reasoning ($p = .039$). We also note that the raw percentage correct on the transfer problem was higher for those in the cue condition than the non-cued condition for all four problem sets.

Table 4.3 Summary of results of Fisher's Exact Test comparing those who did and did not answer the transfer problem correctly for the cued and non-cued conditions. * indicates a statistically significant difference

Problem Set	Condition	# Participants Providing Correct Answer	# Participants Providing Incorrect	p	Effect Size (Φ coefficient)
Roller Coaster	Cued	3	17	.263	-
	Non-Cued	1	18		
Ball	Cued	8	9	*.039	.34
	Non-Cued	3	16		
Skier	Cued	2	7	.370	-
	Non-Cued	2	12		
Graph	Cued	7	15	.181	-
	Non-Cued	6	22		

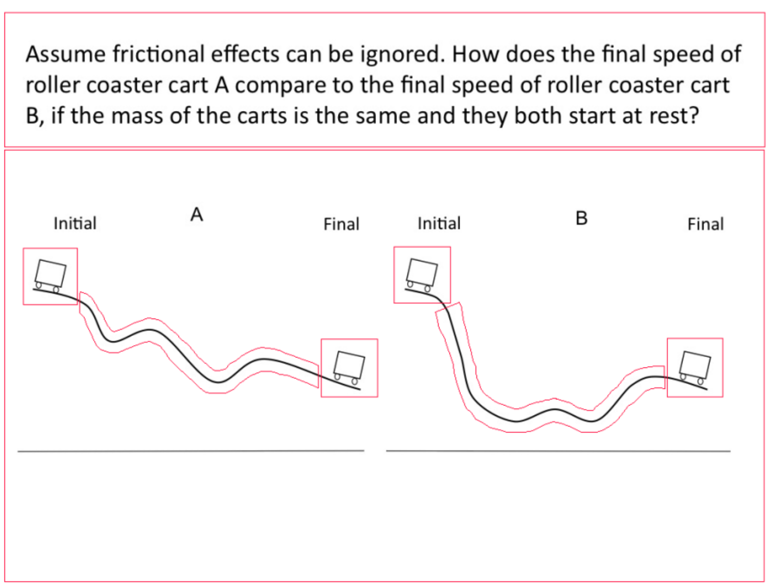
Figure 4.7 Comparison of participants in cued and non-cued conditions who gave the correct answer and reasoning on the transfer problem for each problem set in the study.



Changes in Eye Movements on Transfer Problems

The purpose of the visual cues was to redirect visual attention to relevant areas and help students integrate different important elements in a physics diagram. It may be that the brief visual cues did not help students answer the transfer problem correctly, although it may have influenced their visual attention. To test this idea, we completed an "areas of interest" (AOI) analysis on the eye movements on the transfer problem. To do this we defined two types of areas in each diagram, the "expert-like" and "novice-like" areas. The definitions for the "novice-like" areas of interest came from the individual think-aloud interviews and eye tracking analysis reported in our previous study described in Chapter 3. The "expert-like" areas were defined by expert raters and are also described in that chapter. For example, for the roller coaster problem, we defined the "expert-like" AOI around the roller coaster carts, as expert raters determined the relative heights of the carts are required to judge the final speeds of the carts on each track. We defined the "novice-like" AOI around the roller coaster tracks as we found through individual interviews and literature investigating a similar problem that those who answered incorrectly did so using features of the track. We mimic the AOI definitions used in this previous study in the current analysis for each problem set. The AOIs for the roller coaster problem are pictured in Figure 4.8. The eye tracker used in this study 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 or element in the diagram. After defining the “novice-like” and “expert-like” AOIs in the problem diagrams, we determined the amount of time each participant spent fixating in these areas and divided by the total time they spent fixating on the diagram to normalize for differences in viewing speeds. We then compared the percentage of time participants in the cued and non-cued condition spent in the “novice-like” and “expert-like” AOIs. If visual cues had positively influenced the eye movements of those in the cued condition, we would expect to see larger percentages of time in the “expert-like” AOIs than those in the non-cued condition. Further, we would expect to see smaller percentages of time in the “novice-like” areas than those in the non-cued condition. If cues had no influence on the eye movements of those in the cued condition, we would expect no differences in the percentage of time in either the “expert-like” or “novice-like” AOIs based on condition.

Figure 4.8 Expert-like and novice-like definitions of areas of interest (AOI) for the roller coaster transfer problem. The expert-like AOIs are around the roller coaster carts while the novice-like AOIs are around the tracks.



We compared the percentage of time spent in the novice-like and expert-like AOIs using a one-way ANOVA with *percentage of time in AOI* as the dependent variable and *cued or non-cued condition* as the independent variable for each transfer problem. We remind the reader that we only included the eye movements of those participants who had answered the initial problem incorrectly and had seen the similar problem(s). The results are displayed in Table 4.4 including the effect size using omega squared. For the roller coaster problem, we found that participants in the cued condition spent statistically higher percentage of fixation time in the expert-like AOI and smaller percentage in the novice-like AOI. We also found for the ball and skier problems, participants in the cued condition spent a smaller percentage of fixation time in the novice-like AOIs. This indicates that the cues helped participants in the cued condition allocate more visual attention to the expert-like area (on the roller coaster problem) which contain information needed to answer correctly, and allocate less visual attention to the novice-like areas (on the roller coaster, ball and skier problems) which contain visual information consistent with scientifically incorrect conceptions. So, seeing the visual cues influenced how participants viewed the transfer problems, but not how they answered them.

Table 4.4 Mean percentage fixation time spent (± std err) on the transfer problems for expert-like and novice-like AOIs for participants in the cued and non-cued conditions.

	Problem Set	**Cued**	**Non-Cued**	**ANOVA Results**	**p**	**ω^2**
Expert-like AOI	Roller* Coaster	18.5 ± 2.2 (n=21)	9.7± 1.7 (n=19)	F(1,38)=9.573	.004	.06
	Ball	28.4 ± 3.3 (n=17)	21.1 ± 3.9 (n=19)	F(1,34)=2.022	.164	-
	Skier	0.5 ± 0.3 (n=9)	1.0 ± 0.6 (n=14)	F(1,21)=.451	.509	-
	Graph	6.3 ± 1.0 (n=21)	6.7 ± 1.4 (n=28)	F(1,48)=.039	.844	-
Novice-like AOI	Roller* Coaster	18.0 ± 2.1 (n=21)	29.5 ± 3.1 (n=19)	F(1,38)=9.835	.003	.11
	Ball*	4.3 ± 1.4 (n=17)	10.9 ± 2.4 (n=19)	F(1,34)=5.372	.027	.021
	Skier*	18.2 ± 2.3 (n=9)	49.0 ± 3.5 (n=14)	F(1,21)=42.105	<.001	.50
	Graph	8.0 ± 1.2 (n=21)	11.6 ± 1.4 (n=28)	F(1,48)=3.427	.070	-

Conclusions

In this study we find some evidence that short duration, dynamic visual *integration* and *selection* cues improve students' problem solving performance on introductory conceptual physics problems as participants were able to correctly answer and reason about problems they were previously unable to. Of the four problem sets used, we found significantly more students changed to a correct answer after seeing the visual cues on the roller coaster problem. Through the lens of Representational Change Theory, this suggests that the cues may have helped the students' overcome an impasse and mentally re-represent the problem so that productive concepts or pieces of knowledge could be retrieved from long term memory and applied. We did not find this difference on the other three problem sets.

We also investigated how the dynamic visual cues influenced participants' eye movements while viewing the cues. We looked for a relationship between how well each participant followed the visual cues with their eyes, and whether they had changed from an incorrect answer on the initial problem to a correct answer and reasoning on a similar problem. To do this we calculated similarity scores between their eye movement scan path and the path of the visual cues using the ScanMatch algorithm and compared these similarity scores between those who had and had not correctly answered a similar problem. We found that for the roller coaster problem, those who successfully answered and reasoned about a similar problem had higher similarity scores (ScanMatch scores). This means that these participants were following the cue more closely with their eyes. This suggests a link between how well participants attended to the visual cues and how helpful the cue was at implicitly influencing their reasoning about the problem. We did not find the same difference on the other three problems. One would expect that if the cues were ineffective at helping students answer a similar problem correctly we would not find a relationship between the effectiveness of the cue and how well the students followed it with their eyes.

It is not enough that visual cues would help students answer a set of problems where the cues are visible. Visual cueing would be most educationally effective if after seeing visual cues repeated on several similar problems, students could then successfully answer and reason about related but different problems with no cues, which we have called a "transfer" problem in our study. We compared the correctness of answers and reasoning on the transfer problem associated with each of the four problem sets between those who had seen visual cues and those who had not. We found a significant difference in transfer problem correctness between conditions for the ball problem, with a greater number of participants in the cued condition answering this problem correctly. We also found the raw percentages of correct answers were greater for those in the cued condition on all four problem sets. Thus, we find some evidence that repeatedly showing novices visual cues on related problems may help them form a productive mental representation on similar future problems viewed without cues.

We also investigated how seeing the dynamic visual cues on similar problems may have influenced participants' visual attention on the transfer problems. We compared the percentage of fixation time spent in "novice-like" and "expert-like" areas of interest between those in the cued and non-cued conditions on the transfer problems associated with all four problem sets. We found that on the roller coaster problem, participants in the cued condition spent a significantly greater percentage of time looking in the "expert-like" AOI and a significantly smaller percentage of time in the "novice-like" AOI, than those is the non-cued condition. We also found for the ball and skier problems, those in the cued condition spent a significantly smaller percentage of fixation time looking in the "novice-like" AOI. This suggests that seeing the cues on this problem has an influence on participants' visual attention on subsequent un-cued problems and helps them to pay more attention to the expert-like elements (in one case) and less attention to the novice-like elements (in three of the four problem sets used). This is promising, as we know from previous work that those who answer a problem correctly spend more time looking at the "expert-like" areas of the problem and those who answer incorrectly spend more time looking at the "novice-like" areas. Helping participants look at helpful areas and ignore distracting areas when no visual cues are present could be a first step to helping them reason correctly about the problem.

This work adds to the building body of research in physics education on the importance of visual attention in physics problem solving (Feil & Mestre, 2010; Rosengrant, Thomson, et al., 2009; Smith et al., 2010; Tai et al., 2006). As educators and researchers, we often overlook the way our students view visual representations in physics. This study provides some evidence that the way a student looks at a visual representation can influence their reasoning, especially when the representation contains relevant and irrelevant elements. In light of this, we should help students become mindful of the way they allocate their visual attention in physics problem solving and assessment.

Chapter 5 - Do Perceptually Salient Elements In Physics Problems Influence Students' Eye Movements and Answers?

Introduction

We have previously investigated the influence of perceptual salience on visual attention while solving introductory physics problems with diagrams by recording eye movements in our study described in Chapter 3. In that study, several limitations prevented conclusions as to whether participants' eye movements were primarily influenced by bottom-up perceptual salience-driven processes or top-down novice-like knowledge-driven processes. The current study addresses these limitations.

In our current study we extend and build on our previous work to investigate the effects of perceptual salience on students' eye movements and answer patterns to introductory physics questions. We improve on our previous work described in Chapter 3 by manipulating the perceptual salience of "expert-like" and "novice-like" elements in problem diagrams. This allows us to ensure that the perceptually salient diagram elements and other elements of interest are spatially distinct. We have also expanded the number of problems used in the study. In this study we test the following possibilities.

From Heckler's (2011) work discussed in Chapter 1, it follows that initially, salient elements in the problem diagram capture learners' attention via automatic perceptual processes. If these salient areas are plausibly relevant to the problem solution, 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 the question incorrectly. Conversely, if the expert-like areas are most perceptually salient, participants will activate scientifically correct resources and will answer the question correctly. When the novice-like and expert-like areas are equally salient, participants will answer either correctly or incorrectly in equal proportions. In all of these cases, the underlying processes are automatic and salience driven. Consequently, students' answer patterns should be influenced by which area of the problem – novice-like or expert-like – is more salient.

Another possibility, based on the work of Hegarty et al. (2010) discussed in Chapter 1, is that there will be an interaction between the effect of the perceptual salience on visual attention and physics knowledge. As shown by Hegarty et al.'s study, learners with scientifically correct domain knowledge may exert stronger top-down influence on attention and be influenced less by perceptually salient diagram elements that learners who lack scientifically correct domain knowledge.

A third option, consistent with the findings in Chapter 3, is that the visual salience of the various regions will have little if any impact on viewers' attention or answers to physics problems. Instead, using top-down knowledge, learners will ignore visual salience and focus on the area of the figure consistent with their understanding of the relevant (or irrelevant) physics concepts.

The current study tests the aforementioned hypotheses. In sum, we address Research Question 3: "Does perceptual salience of diagram elements influence students' answer choices and eye movements on physics problems which contain the relevant information in a diagram?" If we find that perceptual salience does influence students' answers and attention, we will go on to investigate the related research question, "How should we account for this when creating instructional materials containing diagrams or animations?

Method

Participants

We conducted individual interview sessions with 60 students in second-semester algebra-based physics, "General Physics 2" (GP2), or in calculus-based physics, "Engineering Physics 2" (EP2). Students were invited to participate in the study via an email sent to all students enrolled in either course and were paid $20 for their participation.

Materials

The materials consisted of 15 introductory physics problems in which an accompanying diagram was necessary to answer the problem. Similar to the problems used in the studies described in chapters 3 and 4, the problems used in this study have features that students use to produce incorrect answers. We refer to these areas as "novice-like" areas of the diagram. The problem diagrams also contained areas that one needs to attend to in order to answer the question correctly. We refer to these areas as "expert-like" areas. The "expert-like" areas are identified in Table C.1 and C.2 (Appendix C) and the "novice-like" areas are identified in Table C.1 and C.2

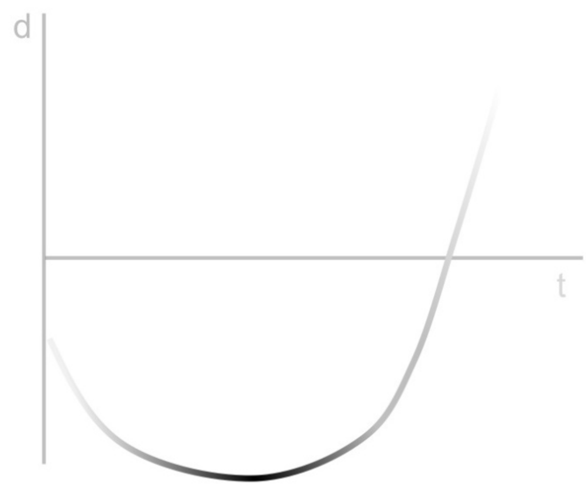
(Appendix C). Table 5.1 lists the previously studied questions from the PER literature, on which our study questions were based.

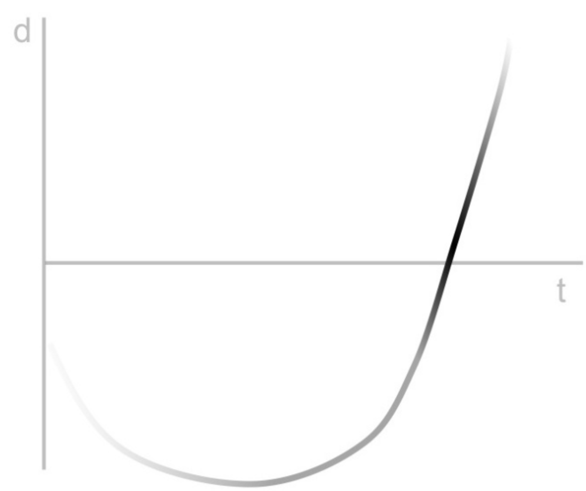
There are several ways that perceptual salience can be manipulated. In the current study we manipulate perceptual salience by manipulating luminance contrast because it is one of the simplest aspects of a diagram to change, while leaving other aspects of the figure, such as the thickness of lines, and size of shapes in the diagrams unchanged. Further, Harding and Bloj (2010) found that of contrast defined in terms of differences in luminance, color, spatial frequency, and orientation, only changes in the luminance contrast of elements in a natural scene had measurable effects on eye movements. Thus, we manipulated the perceptual salience of the novice-like and expert-like areas of the diagrams by altering their luminance contrast, that is their relative "darkness."

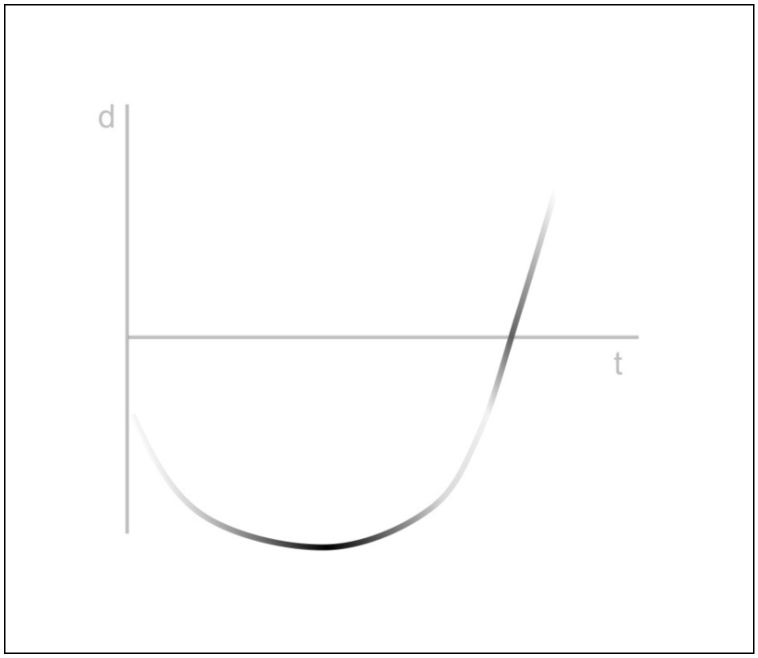
By changing the luminance contrast of diagram elements, we produced three versions of each problem: The perceptually salient area was either located at the novice-like area, the expert-like area, or both areas were approximately equally salient. For example in Figure 5.1, to answer correctly, one needs to find the point on the line where the slope is zero, which is where the speed of the object is zero (i.e., the expert-like area). The most common incorrect answer for this problem is the point where the line crosses the x-axis and the distance is zero (i.e., the novice-like area).

Figure 5.1 Three versions of a study problem. (Top diagram) Expert-like area most perceptually salient. (Middle diagram) Novice-like area most perceptually salient. (Bottom diagram) Expert and novice-like areas have equal levels of salience.

When is the speed of the object shown in the graph zero?







Heckler (2011) explains that the term "salience" is used in many contexts and may be defined operationally in a variety of ways, though it is important to use the term consistently. He offers an example of an informal definition of salience as "the quality of standing out or being more noticeable compared to other co-occurring dimensions" and an example of a more formal definition as "a quality of a cue or dimension that, separate from relative predictiveness, affects attention to and the learning of a cue relative to other present cues." He also provides an example of an operational definition of the salient dimension as "the one that attracts the most attention, as measured by eye tracking," though he does not specify a precise definition for salience used in his work. We operationally defined perceptual salience using Walther's (2006) model which is based on Itti and Koch's (2000) widely used and accepted model. Further, Walther's model is implemented in an easy to use and freely available Matlab toolbox called the Saliency Toolbox (Walther, 2006). The model employs an algorithm that determines a numerical value for relative perceptual salience. This was important for our study, because it provided a metric to determine the appropriateness of our manipulations of the diagram elements. The Saliency Toolbox determines the relative perceptual salience of different elements in the diagram based on contrasts in color, orientation, and luminance and outputs a numerical value representing the degree of perceptual salience of each element. In our study, the diagrams were black and white so the algorithm used contrasts in orientation and luminance to calculate salience. The algorithm then employs a “winner takes all” model and determines the order in which the diagram elements will be attended to. To ensure that the appropriate area(s) in each diagram were indeed the most perceptually salient, we manipulated the luminance contrast until the desired areas were predicted by the algorithm to be the first to be attended to.

When manipulating the problem diagrams, we took care to ensure that the peak salience values of elements in the desired areas (when there was more than one element) were very similar and much greater than the peak salience values of elements in the undesired areas. Thus, the percent difference in perceptual salience values between elements in the desired areas was less than 25%. Further, the percent difference in perceptual salience value between elements in the desired areas and those in the undesired areas was greater than 75%.

Table 5.1 Sources of questions used in study. Question description as used in original study and percentage of correct and incorrect student responses are listed for each question. Superscript numeral indicates source data was taken from in the case that there are several sources listed.

Question Description	Source	Related Problem in Current Study	% Correctness and Reasoning
When are the two objects moving with the same speed?	(Heckler, 2011)[1]; (Madsen et al., 2012)[2]; (Trowbridge & McDermott, 1980)	A	[1]60% (correct) when slopes are the same 40% (incorrect) when lines cross [2]73% (correct) when lines have the same slope 27% (incorrect) when lines cross.
When is the speed of the object shown in the graph zero?	(Madsen et al., 2012)	B	70% (correct) where slope is zero 30% (incorrect) point where line crosses x-axis
If 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?	(Madsen et al., 2012)[1]; (Trowbridge & McDermott, 1980)	C	[1]54% (correct) final speed is the same because of same heights 45 % (incorrect) final speed is different because of features of the track
Rank the changes in potential energy during the skiers descent down each slope from greatest to least.	(Madsen et al., 2012)	D	46% (correct) potential energy down each slope is the same 55% (incorrect) potential energy depends on the slope
Two frictionless slides are shaped differently but start at the same height, H, and end at the same level shown below. You and your friend, who has the same weight as you, slide down from the top on different slides starting from rest. Which of the following statements best describes who has a larger speed at the bottom?	(Singh & Rosengrant, 2003)	E	50% (correct) same speed at the bottom of the slide 50% (incorrect) different speeds depending on the shape of the slide.
At which point is the electric field greater, A or B?	(Heckler, 2011)	F	>40% (correct) capacitor with greater difference in voltage. 50% (incorrect) capacitor with greater central voltage

Which pendulum has a longer period?	(Heckler, 2011)	G	70% (correct) both pendulums have equal periods 30% (incorrect) longer pendulum
Two forces are applied in opposite directions at the ends of a rod. What is the net torque?	(Rimoldini & Singh, 2005)[1]; (Heckler, 2011)	H	[1](no exact values given) Many students considered torque and force as equivalent concepts.
How do the forces compare upon collision?	(Brown, 1989)	I	18% (correct) that forces are equal upon collision 82% (incorrect) that forces are different based on features of the objects colliding and relative speeds
At which point on the graph is the object turning around?	(Madsen et al., 2012)	J	58% (correct) point where slope changes from positive to negative 32% (incorrect) point where line crosses x-axis
Two balls roll along the path show. 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?	(Madsen et al., 2012)	K	65% (correct) when balls have traveled equal distance in one second 35% (incorrect) when balls are at the same position at the same time
At what time is the car moving faster?	(Heckler, 2011)	L	70% (correct) when the slope is greater 30% (incorrect) when the value of the point on the y-axis is greater
Which trajectory has a longer time of flight?	(Heckler, 2011)	M	25% (correct) taller trajectory, 75% (incorrect) wider trajectory
Two tanks are being filled by separate water hoses. Included is a graph representing the water in each tank as time goes on. Which tank is filling faster at a given time?	(Allain, 2001)	N	83% (correct) when the slope is greater 17% (incorrect) when the value of the point on the y-axis is greater
Which ball wins the race?	(Thaden-Koch, 2003); (Leonard & Gerace, 1996)	O	15% (correct) one ball wins due to initial slope 85% (incorrect) balls tie due to energy conservation and same initial and final positions

Design

We used an incomplete block design in which each participant viewed all 15 problems in a randomized order. They viewed 5 problems with the "expert-like" area most perceptually salient, 5 problems with the "novice-like" area most salient and 5 problems with the expert and novice-like areas of approximately equal salience. Assignment of saliency levels to problems was counter-balanced across subjects, and the experiment was designed so that 20 subjects viewed each manipulation of each problem, though an error occurred and two participants viewed the same set of problems in the same order. This resulted in a slight imbalance in our blocks.

Procedure

Each participant took part in an individual session, which lasted between 20 and 45 minutes. At the beginning of the session, participants were given a short explanation of the goal of the session and the purpose of the research. After calibrating the eye tracking system, if the validation's mean error was ≤ 0.50° of visual angle, the experiment began, otherwise the calibration and validation was repeated until successful. Next, the participant was instructed to silently answer 15 questions with diagrams while their eye movements were recorded. The problem statement and diagram appeared on different computer screens to prevent the perceptual salience of the text from interfering with the diagram. Participants were allowed to toggle between the text and diagram as often as needed using a game pad. They signaled that they were ready to answer using the game pad, and then indicated their answer on a paper copy of the diagram. Between questions, a calibration drift correction procedure was done to ensure proper calibration throughout the experiment. This procedure required the participant to fixate on a small white dot in the middle of a gray screen and press a key. Pressing the key caused the screen to advance to the next problem when the participant's fixation was within a pre-defined invisible square with an area of 1° squared around the white dot. Participants were given unlimited time to answer the questions.

Analysis and Results

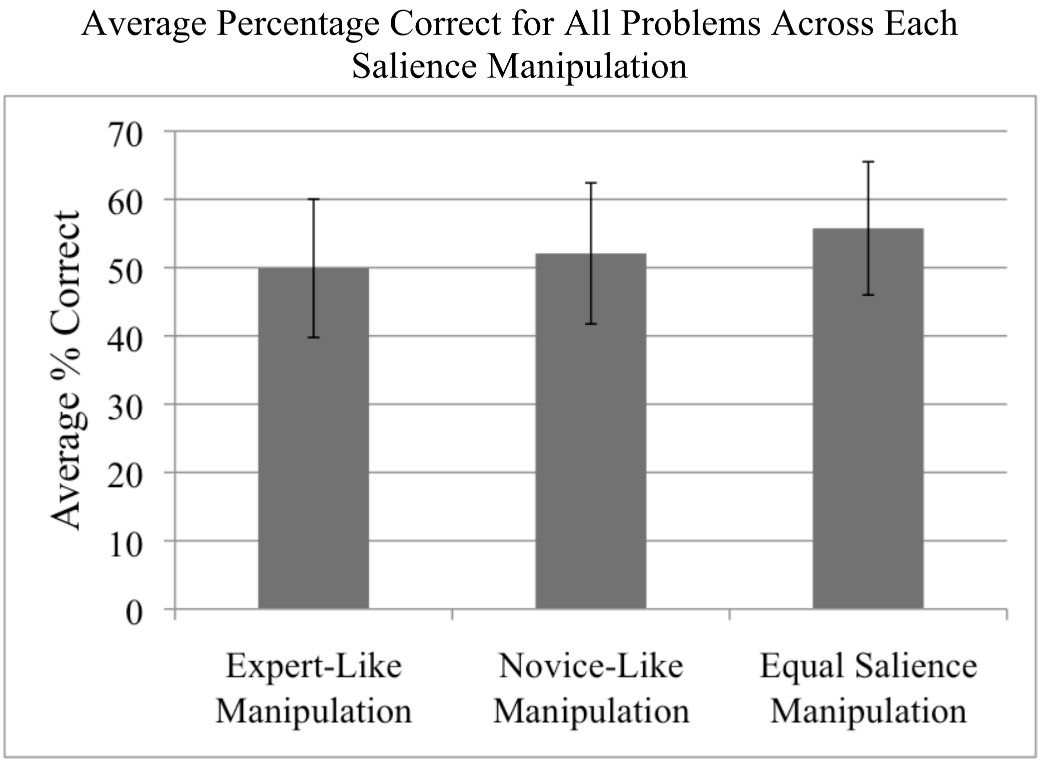
Correctness of Answers

We first determined how our salience manipulation influenced the correctness of participants' answers for each problem. To this end, we used a generalized linear mixed model with a binary distribution and implemented the model using the GLIMMIX procedure in SAS. We considered the salience manipulation and problem number as fixed factors and the subject as a random factor. The correctness of answer was the dependent variable. We found no main effect of the salience manipulation on correctness ($F(2,796) = 2.21$, $p = .11$) indicating that answer correctness was not influenced by which diagram element was made most salient. Specifically, as shown in Figure 5.2, there were no significant differences in learners' correctness when they viewed problem diagrams in which the salient area was in the expert area, the novice area¸ or the equally salient conditions. Table 5.2 shows the same data broken out by individual problems. Since participants viewed problems in a randomized order, problems in Table 5.2 are assigned a letter instead of a number for identification purposes. As suggested by Table 5.2, we found a significant main effect for problem ($F(14, 796) = 10.53$, $p < .001$) which means that correctness varied by problem. This is not surprising, as we would expect that the problems would likely vary somewhat in difficulty. Importantly, however, there was no significant interaction between problem and saliency manipulation.

Table 5.2 Average correctness of problems by salience manipulation given in percentage.

	Average Correctness (± Standard Error)		
Problem	Expert-Like Manipulation	Novice-Like Manipulation	Equal Salience Manipulation
A	45.0 ± 11.4	65.0 ± 10.9	40.0 ± 11.2
B	60.0 ± 11.2	50.0 ± 11.5	55.0 ± 11.4
C	35.0 ± 10.9	55.0 ± 11.4	50.0 ± 11.5
D	10.0 ± 6.9	19.0 ± 8.8	26.3 ± 10.4
E	55.0 ± 11.4	40.0 ± 11.2	55.0 ± 11.4
F	40.0 ± 11.2	55.0 ± 11.4	60.0 ± 11.2
G	80.0 ± 9.2	85.0 ± 8.2	95.0 ± 5.0
H	80.0 ± 9.2	75.0 ± 9.9	90.0 ± 6.9
I	14.3 ± 7.8	21.0 ± 9.6	10.0 ± 6.9
J	65.0 ± 10.9	40.0 ± 11.2	60.0 ± 11.2
K	25.0 ± 11.9	40.0 ± 11.2	50.0 ± 11.5
L	80.0 ± 9.2	80.0 ± 9.2	90.0 ± 6.9
M	35.0 ± 10.9	55.0 ± 11.4	65.0 ± 10.9
N	84.2 ± 8.6	76.2 ± 9.2	70.0 ± 10.8
O	40.0 ± 11.2	25.0 ± 9.9	20.0 ± 9.2

Figure 5.2 Problem accuracy as a function of salience manipulation. Error bars represent standard error.



Prior knowledge may affect the degree to which the salience manipulation influences the correctness of students' answers (Hegarty et al., 2010). For example, students with strong content knowledge may be less influenced by the salience manipulations. 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 two 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 either those who had previously taken GP1 ($F(2.28) = 2.11$, $p = .141$) or EP1 ($F(2.18) = .141$, $p = .87$). This indicates that, contrary to the finding presented in Hegarty et al.'s (2010) work, the salience manipulations did not influence problem correctness for either of these two subsets of students. Additionally we found no interaction between salience manipulation and previous semester mean test scores for either the GP1 group ($F(2,28) = 1.89$, $p = .17$) or EP1 group ($F(2,18) = 1.26$, $p= .31$). Again, contrary to the above-mentioned hypothesis, this means that the influence of the salience manipulation on how well students did on the physics problems did not differ as a function of their prior physics knowledge.

We found a main effect of previous semester test scores on correctness for the EP1 students ($F(1,9) = 5.36$, $p = .048$). This means that EP1 students who were in the top third of the average previous semester test score distribution answered the problems in our study more correctly than those in the bottom third of the previous semester's mean test score range. This finding suggests that our problems are indeed sensitive to learners' pre-existing differences in physics knowledge and application, and thus indicates that the problems have criterion validity as a measure of physics understanding.

Overall, we found that the salience manipulation did not influence the correctness of participants' answers when considering all participants. Additionally, we found the same null result for the subsets of participants previously enrolled in GP1 and EP1. We also found that for these subsets of students, the salience manipulation did not interact with students' pre-existing knowledge and application of physics concepts, as measured by their previous semester physics test scores. However, we did find that our physics problems were sensitive to differences in prior physics knowledge, and thus the lack of effect of saliency on correctness cannot be attributed to a lack of sensitivity of our dependent measure.

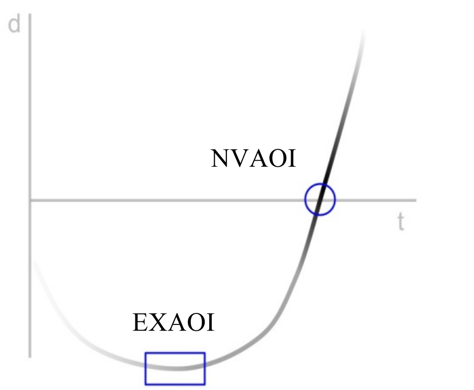
Dwell Time In Areas Of Interest for the First Two Seconds

We were also interested in determining how the salience manipulation influenced students' eye movements. To do this we conducted an area of interest analysis. 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 expert areas were determined by three independent raters, one physics professor, and two PhD students in physics who determined the area(s) in each problem which contained visual information necessary to answer the problem correctly (see Table 5.1). 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 (See Table 5.1). For example in Figure 5.3 (Top Left), to correctly answer the question, “When is the speed of the object shown in the graph zero?” one needs to find the area where the slope of the line is zero, which is where the speed of the object is zero (EXAOI). The most common incorrect answer for this problem is the point where the line crosses the x-axis and the distance is zero (NVAOI). To correctly answer the question, “Which pendulum takes longer to swing back and forth once?” (Figure 5.3, Top Right), one must compare the lengths of the pendulums shown (EXAOI). It has been shown that the most common wrong answer to this question involves comparing the masses on each pendulum (NVAOI). The eye tracker used in this study 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 in the diagram.

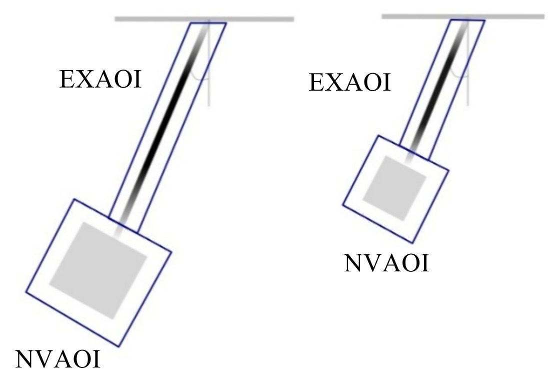
Since it has been shown that perceptual salience has its strongest effect during the first two seconds of viewing (Carmi & Itti, 2006). Thus, we determined the percentage of time in the first two seconds each participant fixated in each AOI for each salience manipulation. We wanted to compare eye movements across problems, so it was also necessary to take the physical 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 $pixels^2$). This produced a new dependent variable, percentage of total fixation time divided by the percentage of total area, which we will call PT/PA (also known as the domain relative ratio (Fletcher-Watson, Findlay, Leekam, & Benson, 2008)).

Figure 5.3 The expert (EX) and novice (NV) areas of interest (AOIs) overlaid on several problems used in study.

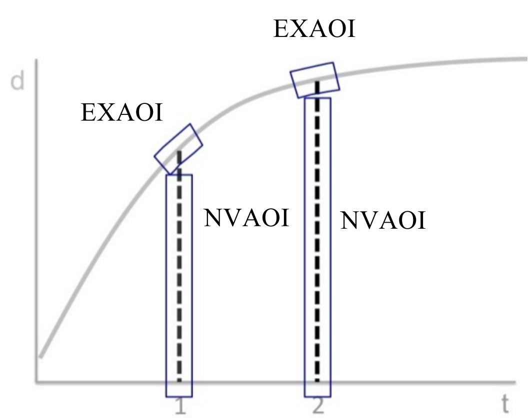
When is the speed of the object shown in the graph zero? (Problem B)



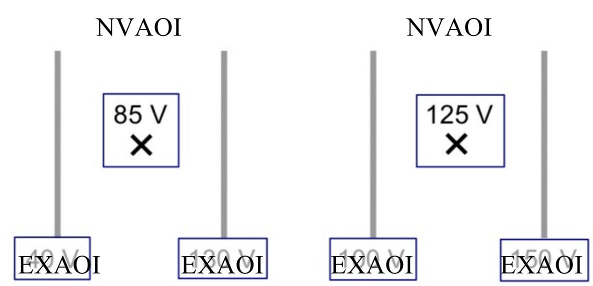
Which pendulum takes longer to swing back and forth once? (Problem G)



The motion of a car is represented in the graph. At which time is the car moving faster? (Problem L)



Between which pair of parallel plates is the electric field greater? (Problem F)



We used a generalized linear mixed model with a normal distribution and implemented the model using the GLIMMIX procedure in SAS. We considered the salience manipulation and problem number as fixed factors and the subject as a random factor. The PT/PA was the dependent variable. We found significant two way interactions interaction between AOI type and salience manipulation ($F(2,855) = 3.90$, $p = .021$) and AOI type and problem ($F(14,855) = 34.65$, $p < .001$). The interaction between AOI type and salience manipulation indicates that the PT/PA across all problems is different for some combinations of salience manipulation and AOI types.

To determine precisely where these differences lie, we completed simple effect pair wise comparisons using the Tukey-Kramer adjustment for each manipulation and AOI type and looked at the mean values of PT/PA to determine the direction of any differences found. Comparison of PT/PA across AOIs for a given salience manipulation is shown in Table 5.3. We notice that the raw values of PT/PA are greater for the NVAOI in all three salience manipulations. On the novice-like salience manipulation, participants had a significantly higher PT/PA in the NVAOI than in the EXAOI ($p = .011$). On the equal salience manipulation, we again found participants had a higher PT/PA in the NVAOI than in the EXAOI ($p < .001$). Overall this eye movement analysis indicates that participants spend significantly more PT/PA in the NVAOI on two of the three salience manipulations, though the raw PT/PA is greater in the NVAOI for all three salience manipulations. This indicates that participants look more at the novice-like area whether or not it is the most salient. This results points to top-down cognitive processes driving attention, as opposed to automatic bottom-up perceptual processes because participants visual attention was not influenced by the salience manipulations, as we predict would happen if automatic perceptual processes were dominant.

Table 5.3 PT/PA, standard error and significant results of pair-wise comparisons for significant interaction between area and manipulation for AOI analysis.

Significant Interaction	Manipulation Type	AOI Type	PT/PA	Std. Error	Significant Results of Pairwise Comparisons
Area*Man.	EX Man.	EXAOI	15.15	2.02	None
		NVAOI	20.59	2.02	
	NV Man.	EXAOI	17.44	2.02	NVAOI > EXAOI, p=.011
		NVAOI	26.30	2.02	
	EQ Man.	EXAOI	13.65	2.02	NVAOI > EXAOI, p<.001
		NVAOI	29.39	2.02	

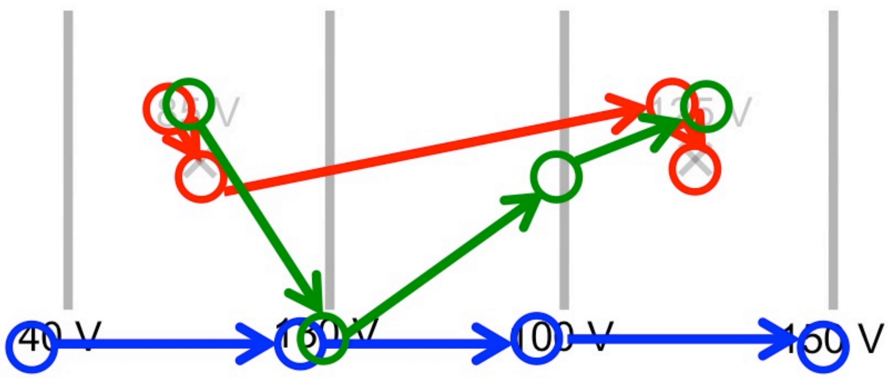
Scan Path Analysis

The area of interest analysis described above compared the percentage of time participants spent fixating in pre-defined areas. Using this method, we found that the raw PT/PA was higher in the NVAOI in all three salience manipulations and significantly higher in the novice and equal salience manipulations. This seems to indicate that the salience manipulation does not have a strong influence on how participants view the problem diagrams in the first two seconds. Another way to investigate the effect of perceptual salience on eye movements without pre-defining areas is to look at both the spatial and temporal aspects of eye movement scan paths using a scan path analysis. We compared how closely the participants' scan paths matched a predicted scan path produced by the Saliency Toolbox algorithm, which predicted where participants should look based on perceptual saliency of each image. Saliency Toolbox used contrasts in light intensity and orientation (e.g., of lines) to determine the order in which diagram elements would be fixated based on saliency. This algorithm assumes that when visual attention is primarily influenced by saliency, one's attention first selects the location with highest salience, this location is then fixated on, and after the information there has been sufficiently processed, one's attention moves to the next most salient spatial location. In this way, the algorithm produces an ordered list of x and y coordinates representing the saliency model's predicted scan path for the first two seconds of each problem and salience manipulation. We found the average fixation durations for participants on each problem and salience manipulation and used these as the fixation durations for the predicted scan paths (for each problem and salience manipulation). In this way, we ensured the temporal aspects of the predicted scan paths were as similar to the actual eye movement scan paths as possible, and any differences we found were likely to be a result of looking at different elements of the diagrams in a different order. Since the effects of salience are the strongest during the first two seconds of viewing, we compared the first two seconds of the participants' scan paths to a predicted scan path.

We used the ScanMatch algorithm to compare the Saliency Toolbox predicted scan path with the participants' scan paths for each problem in the salience manipulation the participants' saw (congruent comparison). We also computed an incongruent ScanMatch score by comparing participants' scan paths to the predicted scan paths of the salience manipulation they did not see. For example, if the participant viewed a problem with the expert-like area made most salient, we computed the ScanMatch score between their scan path and the predicted scan paths for the expert like manipulation (congruent comparison) as well as a score between their scan path and the novice-like salience manipulation, even though they did not view this manipulation (incongruent comparison) (Figure 5.4). We then compared the congruent and incongruent comparisons for each problem and manipulation (Table 5.4). A high ScanMatch score indicates that participants' eye movements were very similar to the saliency model's predicted scan path.

If perceptual salience of the problem diagrams influenced participants' eye movements, the ScanMatch scores for the congruent comparisons should be much higher than for the incongruent comparisons.

Figure 5.4 Example of scan-paths for expert-like salience manipulation (congruent for this image) in blue, novice-like salience manipulation (incongruent for this image) in red and a given participant's scan path in green.



Red = Most Salient Scan Path for Novice-like Salience Manipulation (Incongruent)

Blue = Most Salient Scan Path for Expert-like Salience Manipulation (Congruent)

Green = Participants' Scan Path

We completed a mixed factorial 2 (salience manipulation) x 2 (comparison type) x 14 (problem number) ANOVA with *ScanMatch score* as the dependent variable. Problem A was not included in this analysis because of a compatibility issue between the eye movement coordinates produced by Saliency Toolbox, the actual eye movements and the ScanMatch algorithm on this problem only. Critically, if we find an effect of comparison type, this would indicate that the ScanMatch score of the congruent and incongruent comparisons are different. We found a significant three-way interaction between comparison type, salience manipulation and problem number ($F(13, 1044) = 16.6$, $p < .001$). This means that the effect of comparison type on ScanMatch score varies by problem and salience manipulation. We then completed one-way ANOVAs for each problem and manipulation to determine where significant differences existed in the data. ScanMatch scores for expert-like and novice-like salience manipulations including congruent and incongruent comparisons are shown in Table 5.4. Results of the one-way ANOVAs and effect sizes are shown in Table 5.5.

Table 5.4 Scan Match scores for congruent and incongruent comparisons for each problem and salience manipulation. * indicates a significant difference between congruent and incongruent comparisons favoring the congruent condition; † indicates a significant difference favoring the incongruent condition.

ScanMatch Score ± Standard Error				
Problem	Expert-Like Manipulation		Novice-Like Manipulation	
	Congruent Comparison	Incongruent Comparison	Congruent Comparison	Incongruent Comparison
B	0.336 ± .014	0.330 ± .014	0.336 ± .014	0.350 ± .014
C	0.151 ± .014	0.153 ± .014	0.150 ± .014	0.149 ± .014
D	0.178 ± .016	0.148 ± .014	0.175 ± .014	0.184 ± .014
E	* 0.334 ± .014	0.246 ± .014	† 0.308 ± .014	0.382 ± .014
F	† 0.252 ± .014	0.294 ± .014	* 0.248 ± .014	0.180 ± .014
G	0.292 ± .014	0.287 ± .014	0.284 ± .014	0.292 ± .014
H	0.228 ± .014	0.223 ± .014	0.217 ± .014	0.229 ± .014
I	* 0.299 ± .014	0.245 ± .014	† 0.246 ± .014	0.273 ± .014
J	0.287 ± .014	0.280 ± .014	0.265 ± .014	0.254 ± .014
K	† 0.217 ± .014	0.285 ± .014	* 0.312 ± .014	0.216 ± .014
L	0.302 ± .014	0.312 ± .014	0.269 ± .014	0.283 ± .014
M	* 0.313 ± .015	0.219 ± .015	† 0.220 ± .014	0.323 ± .014
N	† 0.148 ± .014	0.294 ± .014	* 0.305 ± .014	0.172 ± .017
O	0.257 ± .014	.209 ± .014	0.223 ± .015	0.261 ± .015

Table 5.5 Results of One-Way ANOVA Simple Effect Contrasts For ScanMatch Scores for congruent and incongruent comparisons of scan paths and effect size given with omega squared. " –" indicates no significant difference.

Problem	Expert-Like Manipulation		Novice-Like Manipulation	
	ANOVA Results	Effect Size (ω^2)	ANOVA Results	Effect Size (ω^2)
B	-	-	-	
C	-	-	-	
D	-	-	-	
E	Congruent > Incongruent F(1,39)=14.9, p<.001	.02	Incongruent > Congruent F(1,39)=5.05, p=.03	.03
F	Incongruent > Congruent F(1,39)=5.30, p=.027	-.003	Congruent > Incongruent F(1,39)=15.8, p<.001	.03
G	-	-	-	
H	-	-	-	
I	Congruent > Incongruent F(1,39)=14.6, p<.001	.01	Incongruent > Congruent F(1,39)=4.56, p=.034	<.001
J	-	-	-	
K	Incongruent > Congruent F(1,39)=13.7, p=.001	.03	Congruent > Incongruent F(1,39)=39.2, p<.001	.08
L	-	-	-	
M	Congruent > Incongruent F(1,37)=13.4, p=.001	.06	Incongruent > Congruent F(1,37)=35.4, p<.001	.09
N	Incongruent > Congruent F(1,37)=35.4, p<.001	.19	Congruent > Incongruent F(1,33)=30.6, p<.001	.13
O	-	-	-	

We found significant difference for congruent and incongruent comparisons for six of 14 problems tested. We did not find that the congruent comparison ScanMatch scores were consistently higher than the incongruent ScanMatch scores, which would have been evidence for perceptual salience guiding eye movements. Instead we found that the eye movements were more similar to one predicted scan-path, regardless of salience manipulation viewed. For example, in problem I, the congruent comparison is greater than the incongruent comparison for the expert-like salience manipulation, meaning the scan paths of participants were more similar to the predicted scan path for the expert-like salience manipulation (when they saw the expert-like salience manipulation). Further, for the novice-like salience manipulation, the incongruent comparison was greater than the congruent comparison. This means that the scan paths of participants were more similar to the predicted scan path of the expert-like salience manipulation, even though they viewed the novice-salience manipulation.

We see the same pattern of scan paths being more similar to either the expert-like or novice-like predicted scan path, regardless of what salience manipulation the participants actually saw for all six of the 14 significant results described in Table 5.5. This means that the salience manipulation does not seem to have an influence on the scan paths of participants. This suggests that top-down cognitive processes instead of bottom-up processes are primarily influencing the participants' eye movements.

Scan Path Analysis of Correct and Incorrect Responders

In the previous analyses, we have investigated how salience manipulation influenced correctness of answers and eye movements separately and found no evidence to support the conjecture that salient and plausibly relevant diagram elements initially attract attention, participants do not consider other diagram elements and subsequently participants answer the questions based on the salient elements. One final way to test this conjecture is to look at correctness of answers and eye movements together in the same analysis. If eye movements are initially attracted to perceptually salient elements (as defined by the Saliency Toolbox algorithm), a participant should have a high ScanMatch score. If participants viewing a problem diagram with the novice-like areas most salient, attended to the novice-like areas and thought about concepts related to these areas, it would follow that they would answer incorrectly (and have a high scan match score on the novice-like salience manipulation). On the other hand, if they were viewing a problem diagram with the expert like area most salient, they would attend to helpful information, think about productive concepts and answer correctly (and have a high ScanMatch score on the expert-like salience manipulation).

To this end, we look at how the *congruent* ScanMatch score predicted the correctness of a participant's answer. We only included data for the expert-like and novice-like salience manipulations, as the equal salience manipulation would not lead to a correct or incorrect answer as both the novice-like and expert-like areas are salient. We used a generalized linear mixed model with a binary distribution and implemented the model using the GLIMMIX procedure in SAS. We considered the ScanMatch score and problem as fixed factors and the subject as a random factor. The correctness of answer was the dependent variable. We treated the data for the expert-like and novice-like salience manipulations separately. In our first implementation of the model, we tested for a significant interaction between the ScanMatch score and the problem. We found no significant interaction for either the expert-like or novice-like salience manipulations. We then used the same generalized linear mixed model with a binary distribution, implemented using the GLIMMIX procedure in SAS, to test for a significant effect of problem or ScanMatch score (but this time we did not include the interaction between these factors). For both the expert-like and novice-like salience manipulations we found no significant effect of ScanMatch score ($F(1,200) = < .001$, $p = .99$ and $F(1,206) = .18$, $p = .67$ respectively). This tells us that the degree to which one closely follows the predicted scan path during the first two seconds of viewing the diagram does not predict correctness of answer. This is consistent with our previous findings that correctness of answer is not related to salience manipulation, and neither are eye movements. We found a significant effect of "problem" for both the expert-like and novice-like salience manipulations ($F(14,200) = 4.13$, $p < .001$ and $F(14,206) = 3.03$, $p < .001$, respectively). This means that ScanMatch scores varied by problem, which we expect but is not relevant to our research questions.

What Factors Influence Correctness of Answers and Eye Movements?

We have just reported on an extensive analysis investigating how manipulation of the perceptual salience of expert-like and novice-like elements in a problem diagram might influence the correctness of participant's answers and their eye movements. We repeatedly find no evidence to support Heckler's conjecture about the role of perceptual salience in physics problem solving. We then ask ourselves, what factors influence participants to look at certain diagram elements and answer questions in the way they do? If it is not the bottom up information in features of the diagram that guide attention and then, in line with our third hypothesis discussed in the introduction, visual attention and answers must be governed by top-down process. In our previous study we found that participants' who answered a physics problem correctly spent more time looking at thematically-relevant areas which contained information leading to the correct answers. We also found that those who answered incorrectly spent more time looking in areas consistent with a novice-like conceptions. This is evidence that it is the participants' knowledge, correct or incorrect, which guides their attention and determines their answer. If we found the same pattern in the problems involved in the current study, we would have more evidence to support the claim that top-down cognitive processes guide problem solving on these problems.

We completed the same analysis as reported in Madsen et. al (2012). We determined the percentage of time participants spent in the expert-like and novice-like AOIs for the full problem period for each problem and salience manipulation. This differs from the AOI analysis discussed above which computed the percentage of time divided by the percentage of area (PT/PA) for the first two seconds of viewing. In the current analysis, we used the percentage of time (as opposed to the PT/PA) because we are comparing time spent fixating on EXAOIs between correct and incorrect responders (the same comparison will be made for NVAOIs), so we do not need to compare across areas of different size., therefore normalization by area is not necessary. We look at the full problem period, as this is where we found effects of correctness in the previous work. We conducted a 2 x 15 mixed factorial ANOVA with *percentage of time in each AOI type* as the dependent variable and *problem number* and *correctness of answer* as independent variables were conducted for the EXAOI and NVAOI. We found a significant interaction between problem and correctness for both the expert-like and novice-like AOIs ($F(14, 870) = 2.983$, $p < .001$ and $F(14,870) = 3.770$, $p < .001$, respectively). This means that the effect of correctness on percentage of time in each AOI type varies by problem. To determine which problems contain significant differences in proportion of time spent in each AOI type, we conducted one-way ANOVAs with *percentage of time* for EXAOI and NVAOIs as the dependent variable and *correctness of answer* as the independent variable. Results of one-way ANOVAs for each type of AOI for the full trial period as well as mean percentage of fixation time and standard error for the correct and incorrect responders for each question are also shown in Table 5.6. An asterisk indicates a significant difference at the $\alpha=.05$ level. Six problems in our current study (problems A-D, J, and K) were also used in the Madsen et. al (2012) study, though in the previous study they were multiple choice questions whereas in the current there were no answer choices given. The significance of the differences between correct and incorrect solvers on these previously used problems is also reported in Table 5.6.

For the EXAOI, the raw percentage of fixation time is greater for those who answer correctly for 12 out of 15 problems, and significantly greater for six of the 15 problems. For the NVAOI, for 11 of 15 problems, the raw percentage of fixation time is greater for those who answer incorrectly, significantly greater for 4 of 15 problems and nearly significantly greater ($p = .067$) for 1 of 15 problems. We notice that some of the problems have a high percentage of correct or incorrect responses. Because these problems were either too easy or too hard for these students, they do not discriminate well between students who answered correctly or incorrectly. If we look only at those problems with average correctness between 30% and 70%, then there are five problems out of eight in which those who answered correctly spent a significantly higher percentage of time in the EXAOI and the raw percentage of time is greater on seven of these eight problems. There are five problems out of eight in which those who answered incorrectly spent a significantly or nearly significantly higher percentage of time in the NVAOI and the raw percentage of time is greater on seven of these eight problems. It should also be noted that for the six problems which were used in the previous Madsen et. al study, we found the same significant differences on five of five problems for the EXAOI and one additional significant difference on the remaining problem not found in the previous study. For the NVAOI, we found the same significant (or nearly) differences for four of the six problems. Thus, there is strong agreement between our previous and current results. This is important because the AOIs for problems used in both studies had been carefully determined based on interviews with students where we noted where students pointed to and what they talked about to come to incorrect answers. So it is on this subset of problems that we expect the best chance to find differences between correct and incorrect solvers, which we did.

These significant differences and trends in percentage of fixation time in the EXAOI and NVAOI between those who answer the problem correctly and incorrectly in are evidence for top-down cognitive processes primarily influencing visual attention in physics problems. The participants in our study viewed the problem diagrams with the important elements made more perceptually salient and despite these salience manipulations, there is still a difference in the percentage of time spent in the EXAOI and NVAOI based on correctness of answer. So we find evidence to suggest it is the way the participants utilize the domain knowledge they possess to reason and answer these physics problems that influences where they look as opposed to the salient features in the problem diagram itself.

Table 5.6 Mean percentage time spent ± std err and results of one-way ANOVA and effect size given with omega squared during entire problem period for expert and novice-like AOIs for participants who answered the question correctly/incorrectly.* indicates significant difference, p <.05 and † indicates a nearly significant difference. Significance of comparisons for the subset of problems used in Chapter 3 and the current study are also reported.

AOI Type	Prob.	Answered Correctly	Answered Incorrectly	F	p	ω^2	% correct	Previous Result from Chapter 3
Expert-like	A*	10.2 ± 1.7 (n=30)	1.8 ± 0.5 (n=30)	F(1,58)=21.51	<.001	.09	50.0	significant
	B*	7.3 ± 1.4 (n=33)	1.5 ± 0.7 (n=27)	F(1,58=12.89	0.001	.04	55.0	significant
	C*	28.4 ± 2.8 (n=29)	21.4 ±1.8 (n=31)	F(1,58)=4.56	0.039	.06	48.3	not significant
	D*	14.8 ± 3.5 (n=11)	7.0 ± 0.8 (n=49)	F(1,58)=9.24	.004	.04	18.3	significant
	E	25.1 ± 2.6 (n=32)	24.8 ± 2.6 (n=28)	F(1,58)=.005	0.944		53.3	
	F	28.8 ± 2.9 (n=31)	26.0 ± 2.3 (n=29)	F(1,58)=.514	0.476		51.7	
	G	30.4 ± 2.8 (n=52)	23.4 ± 5.8 (n=8)	F(1,58)=.887	.350		86.7	
	H	30.1 ± 2.4 (n=49)	36.5 ± 5.1 (n=11)	F(1,58)=1.28	.263		81.7	
	I	9.3 ± 1.4 (n=9)	10.1 ± 1.5 (n=51)	F(1,58)=.055	.100		15.0	
	J*	5.0 ± 1.1 (n=33)	1.4 ± 0.7 (n=27)	F(1,58)=6.95	.011	.004	55.0	significant
	K*	44.9 ± 2.8 (n=23)	25.5 ± 1.8 (n=37)	F(1,58)=37.67	<.001	.52	38.3	significant
	L	17.1 ± 2.4 (n=50)	10.5 ± 4.2 (n=10)	F(1,58)=1.37	.247		83.3	
	M	4.3 ± 0.8 (n=31)	5.2 ± 1.0 (n=29)	F(1,58)=.625	.432		51.7	
	N	15.1 ± 1.8 (n=46)	14.9 ± 2.4 (n=14)	F(1,58)=.003	.953		76.7	
	O	25.3 ± 3.3 (n=17)	27.2 ± 2.2 (n=43)	F(1,58)=.228	.635		28.3	
Novice-Like	A*	6.9 ± 1.5 (n=30)	26.7 ± 3.6 (n=30)	F(1,58)=12.63	0.001	.88	50.0	significant
	B*	4.3 ± 0.9 (n=33)	11.2 ± 2.1 (n=27)	F(1,58)=10.32	0.002	.38	55.0	significant
	C	13.9 ± 1.6 (n=29)	16.8 ±1.9 (n=31)	F(1,58)=1.34	.253		48.3	significant

D	27.1 ± 3.5 (n=11)	32.4 ±2.5 (n=49)	F(1,58)=.896	0.348		18.3	significant
E	31.2 ± 2.3 (n=32)	32.6 ± 2.8 (n=28)	F(1,58)=.143	0.707		53.3	
F*	39.5 ± 2.4 (n=31)	49.4 ± 1.8 (n=29)	F(1,58)=10.50	0.002	.13	51.7	
G	16.7 ± 1.9 (n=52)	23.4 ± 5.0 (n=8)	F(1,58)=1.66	.203		86.7	
H	26.6 ± 2.7 (n=49)	23.8 ± 4.6 (n=11)	F(1,58)=.220	.641		81.7	
I	53.7 ± 6.8 (n=9)	65.5 ± 2.7 (n=51)	F(1,58)=2.80	.816		15.0	
J†	9.0 ± 1.7 (n=33)	14.7 ± 2.6 (n=27)	F(1,58)=3.63	.062		55.0	nearly significant
K*	18.5 ± 1.2 (n=23)	32.4 ± 2.0 (n=37)	F(1,58)=27.32	<.001	.26	38.3	significant
L	13.1 ± 1.5 (n=50)	9.8 ± 1.6 (n=10)	F(1,58)=.941	.336		83.3	
M	23.5 ± 2.2 (n=31)	19.6 ± 2.3 (n=29)	F(1,58)=1.47	.231		51.7	
N	21.9 ± 1.8 (n=46)	15.7 ± 2.8 (n=14)	F(1,58)=3.01	.088		76.7	
O	11.0 ± 2.6 (n=17)	12.5 ± 1.6 (n=43)	F(1,58)=.221	.640		28.3	

Conclusions

It is important to understand whether and how perceptual salience of elements in physics problem diagrams influences students' answers and eye movements. We found that manipulation of perceptual salience via luminance contrast of expert and novice elements in a physics problem diagram did not influence the correctness of students' answers. Additionally, based on Hegarty et. al's (2010) work, we might expect that the effect of perceptual salience on attention and answer choices would decrease with increasing domain knowledge. When we factored in previous semester physics test grades, we still found no effect of this type of salience manipulation on correctness of answer.

We also did not find an effect of our salience manipulation on the percentage of fixation time divided by percentage of area (PT/PA) for either the expert or novice AOIs. This indicates that attention was not drawn to perceptually salient portions (according to the Saliency Toolbox) of the diagram in the first two seconds of viewing, when the effects of perceptual salience on visual attention should be most pronounced. We did however find that participants spent significantly more time fixating in the NVAOI for the "novice-like" and "equal" salience manipulations, and the raw percentage of time spent fixating in the NVAOI was also greater for the “expert-like” salience manipulations. This indicates that participants attended to the novice-like area more than the expert-like area in these physics problems, regardless of relative perceptual salience. This is evidence that what participants’ were thinking about, not the relative perceptual salience of the diagram features, primarily influenced their visual attention.

To further investigate how perceptual salience influenced participants eye movements, we used a scan path analysis which takes into account both spatial and temporal aspects of the eye movements. We calculated similarity scores (ScanMatch scores) between participants’ scan paths and predicted scan paths for both the expert-like and novice-like salience manipulations. We found that participants’ scan paths were more similar to either the predicted scan path produced from the expert-like salience manipulation or the novice-like salience manipulation. This means that despite of the salience manipulation, participants’ scan-paths were more similar to the one predicted scan path. This indicates that the salience manipulation of the problem diagrams was not influencing participants’ eye movements.

We also looked at how closely participants attended to the perceptually salient diagram elements may have predicted the correctness of their answer. It may be that a high similarity score between participants’ eye movements and the predicted scan path for the expert salience manipulation would result in a high probability of answering correctly, because, in line with Heckler’s conjecture, participants’ attention was initially caught by salient and plausible elements which were then used to reason to an answer. If instead participants viewed the novice-like salience manipulation, they would have a high similarity score between their eye movements and the predicted scan path for this manipulation and have a high probability of answering incorrectly. We did not find this to be the case. The ScanMatch score for the congruent comparisons did not predict correctness for either the novice-like or expert salience manipulations. This evidence is contrary to Heckler’s conjecture.

Since we did not find evidence of perceptual salience influencing eye movements and answer choices, we sought to determine if top-down factors may have influenced visual attention on these study problems. If the way the participants utilize the domain knowledge they possess to reason and answer these physics problems influences where they look in the problem diagram, we expect a difference in the percentage of time spent looking in the expert-like and novice-like AOIs depending on correctness of answer. This is because participants who answered the problem correctly likely have applied their domain knowledge in a scientifically correct way while those who answered the problem incorrectly did not. It was the way these participants reasoned to their answer (whether correct or not) that influenced their eye movements. We compared the percentage of time spent looking in the novice and expert-like areas of interest for both the novice-like and expert-like salience manipulations between those who answered correctly and incorrectly for the full problem period. Despite the fact that the perceptual salience of important diagram elements was manipulated, we found that on problems with a fairly even distribution of correct and incorrect answers, regardless of the salience manipulation, participants who answered the problem correctly spent a significantly higher percentage of time in the EXAOI on five out of eight problems and those who answered incorrectly spent a significantly or nearly significantly greater percentage of time in the NVAOI on five of eight problems.

Overall we find no evidence to support Heckler's conjecture that when initially viewing a physics problem, salient elements in the problem diagram capture the learner's attention via automatic bottom-up perceptual processes. If these salient areas are relevant to the problem solution and plausible, students activate certain reasoning resources based on these elements and answer accordingly. We have no evidence that our perceptually salient elements (due to manipulations of luminance contrast) captured visual attention or influenced students' answer choices. On the contrary, we did find evidence that it is what the participants are thinking about that influenced where they looked and it follows that these cognitive processes also influenced their answers.

Chapter 6 - Conclusions

Overview of Work

The purpose of this work was to investigate and influence visual attention in physics problem solving. We looked at how top-down and bottom-up perceptual processes influenced visual attention in physics problems with a diagram that contained relevant and novice-like elements. We also investigated the possibility of using dynamic visual cues to influence problem solvers visual attention, reasoning and answer choices on these physics problems. We used an eye tracker to record eye movements of participants and used these as a primary data source.

Research Questions Answered

Research Question 1

In our first study we investigated differences in visual attention between those who correctly and incorrectly answer physics problems with relevant information in a diagram. In addition, we looked for evidence of top-down cognitive and bottom-up perceptual processes influencing visual attention for correct and incorrect solvers. We had two hypotheses about how visual attention would differ between these groups. First, we hypothesized that those with adequate domain knowledge to correctly answer a problem would spend more time fixating on thematically relevant areas of a diagram that provide the solution to the problem. Conversely, those who answer the problem incorrectly would spend more time fixating elsewhere in the diagram. More specifically, we hypothesized that those answering the problem incorrectly would spend more time fixating on areas of the diagram consistent with a novice-like misconception. These participants would initially attend to perceptually salient areas of the diagram, but would quickly disengage their attention from these areas and instead attend to novice-like areas. Such effects would suggest a strong role for top-down factors in guiding attention while solving physics problems involving diagrams. Alternatively, our second hypothesis was that those who answer incorrectly are more likely to be influenced by perceptually salient diagram elements than those who have adequate domain knowledge, as it has been shown that perceptual salience has a larger influence on novice learners' eye movements. Such effects would suggest a strong role for bottom-up factors in guiding attention during physics problem solving with diagrams. We found that those who answered the problems correctly spent more time fixating on thematically relevant areas on five of six problems analyzed and those who answered incorrectly spent more time fixating on novice-like areas on five of six problems analyzed for the full problem period. We found differences in time spent fixating on the perceptually salient areas on two of the six problems analyzed for the full problem period, though in these problems the perceptually salient area either partially or completely overlapped with the novice-like area. These findings align more closely with our first hypothesis, suggesting that top-down cognitive processes are dominant in physics problem solving and incorrect solvers are guided by incorrect knowledge, not perceptual salience. We expected to find the strongest effect of bottom-up perceptual processes in the first two seconds of viewing, so we compared the time spent in the thematically relevant, novice-like and perceptually salient areas in this time period. We found no differences based on correctness. We did notice that the raw percentage of time spent looking in the perceptually salient AOI is higher for incorrect solvers than correct problem solvers on five of the six problems, though not statistically significantly so. Thus, it is possible that a larger study with more observations might show this effect to be statistically significant. To further investigate the effect of perceptual salience on attention both spatially and temporally, we conducted a scan path analysis comparing how similar correct solvers scan paths were to one another (C-C), how similar incorrect solvers scan paths were to one another (I-I) and how similar correct solvers scan paths were to incorrect solvers scan paths (C-I). Higher similarity scores on I-I comparisons than the C-C comparisons would suggest dominance of bottom-up processes, as those being led by perceptual salience are predicted to look at the same diagram elements in the same order. We did not find significant differences in ScanMatch scores between those in the C-C comparisons and those in the I-I comparisons on five of the six problems analyzed in this study. This evidence is consistent with the hypothesis that the attention of incorrect solvers is primarily directed by top-down naïve theories, inappropriately used conceptual resources or categorization into incorrect ontological categories and not the relative perceptual salience of the elements. This finding aligns well with our previous findings that showed no significant difference in the percentage of fixation time in the perceptually salient areas of the diagram during the full problem period, or the first two seconds of viewing the diagram, when the effects of perceptual salience should be most pronounced. It also aligns well with the findings showing significant differences in the percentage of time incorrect solvers spent in the novice-like areas of the diagram and the percentage of time correct solvers spent in the thematically-relevant areas of the diagram. So overall, we find support for the hypothesis that top-down cognitive processes primarily drive visual attention and correct and incorrect solvers on physics problems.

Research Question 2

In our second study we wanted to know if short duration dynamic selection/integration visual cues influenced students' reasoning and the way they answer physics questions with a diagram. We find some evidence these cues improve students' problem solving performance on conceptual physics problems, as participants were able to correctly answer and reason about problems they were previously unable to. Of the four problem sets used, we found that significantly more students changed to a correct answer after seeing the visual cues on the roller coaster problem. We did not find this difference on the other three problem sets.

We also investigated how the dynamic visual cues influenced participants' eye movements while viewing the cues. We looked for relationships between how well each participant followed the visual cues with their eyes and whether they changed from an incorrect answer on the initial problem to a correct answer and reasoning on a similar problem. We found that for the roller coaster problem, those who successfully answered and reasoned about a similar problem had higher similarity scores. This suggests a link between how well participants attended to the visual cues and how helpful the cue was at implicitly influencing their reasoning about the problem. We did not find the same difference on the other three problems. One would expect that if the cues were ineffective at helping students answer a similar problem correctly we would not find a relationship between the effectiveness of the cue and how well the students followed it with their eyes.

We wanted to know if after seeing visual cues repeated on several similar problems, students could then successfully answer and reason about related but different problems with no cues. We compared the correctness of answers and reasoning on the transfer problem associated with each of the four problem sets between those who had seen visual cues and those who had not. We found a greater number of participants in the cued condition answering the ball problem correctly. We also found the raw percentages of correct answers were greater for those in the cued condition on all four problem sets. Thus, we find some evidence that repeatedly showing novices visual cues on related problems may help them form a productive mental representation on similar future problems viewed without cues.

We also investigated how seeing the dynamic visual cues on similar problems may have influenced participants' visual attention on the transfer problems. We compared the percentage of fixation time spent in "novice-like" and "expert-like" areas of interest between those in the cued and non-cued conditions on the transfer problems. We found that on the roller coaster problem, participants in the cued condition spent a significantly greater percentage of time looking in the "expert-like" AOI and a significantly smaller percentage of time in the "novice-like" AOI. We also found for the ball and skier problems, those in the cued condition spent a significantly smaller percentage of fixation time looking in the "novice-like" AOI. This suggests that seeing the cues on this problem has an influence on participants' visual attention on subsequent un-cued problems and helps them to pay more attention to the expert-like elements (in one case) and less attention to the novice-like elements (in three of the four problem sets used). This is promising, as we know from previous work that those who answer a problem correctly spend more time looking at the "expert-like" areas of the problem and those who answer incorrectly spend more time looking at the "novice-like" areas. Helping participants to look at helpful areas and ignore distracting areas when no visual cues are present is likely a first step to helping them reason correctly about the problem.

Research Question 3

In our third study, we looked at how perceptual salience of diagram elements influenced students' answer choices and eye movements on physics problems with the relevant information in a diagram. Overall we find no evidence to support Heckler's (2011) conjecture that when initially viewing a physics problem, salient elements in the problem diagram capture the learner's attention via automatic bottom-up perceptual processes. If these salient areas are relevant to the problem solution and plausible, students activate certain reasoning resources based on these elements and answer accordingly. We found no evidence that our perceptually salient elements (due to changes in luminance contrast) captured visual attention or influenced students' answer choices. On the contrary, we found evidence that it is what the participants are thinking about that influenced where they looked and it follows that these cognitive processes also influenced their answers.

Specifically, we found that manipulation of perceptual salience via luminance contrast of expert and novice elements in a physics problem diagram did not influence the correctness of students' answers and we factored in previous semester physics test grades, we still found no effect of this type of salience manipulation on correctness of answer. We also did not find an effect of our salience manipulation on the percentage of fixation time divided by percentage of area (PT/PA) for either the expert or novice AOIs. This indicates that attention was not drawn to perceptually salient portions (according to the Saliency Toolbox) of the diagram in the first two seconds of viewing. We did however find that participants spent significantly more time fixating in the NVAOI for the "novice-like" and "equal" salience manipulations, and the raw percentage of time spent fixating in the NVAOI was also greater for the "expert-like" salience manipulations. This indicates that participants attended to the novice-like area more than the expert-like area in these physics problems, regardless of relative perceptual salience. We calculated similarity scores (ScanMatch scores) between participants' scan paths and model scan paths for both the expert-like and novice-like salience manipulations. We found that participants' scan paths were more similar to either the model scan path produced from the expert-like salience manipulation or the novice-like salience manipulation. This means that despite of the salience manipulation, participants' scan-paths were more similar to the one model scan path. This indicates that the salience manipulation of the problem diagrams was not influencing eye movements. We looked at how closely participants attended to the perceptually salient diagram elements may have predicted the correctness of their answer. The similarity (ScanMatch) score for the congruent comparisons did not predict correctness for either the novice-like or expert salience manipulations.

Since we did not find evidence of perceptual salience influencing eye movements and answer choices, we sought to determine if top-down factors may have influenced visual attention on these study problems. We compared the percentage of time spent looking in the novice and expert-like areas of interest for both the novice-like and expert-like salience manipulations between those who answered correctly and incorrectly for the full problem period. Despite the fact that the perceptual salience of important diagram elements was varied, we found that on problems with a fairly even distribution of correct and incorrect answers, those who answered correctly spent a significantly higher percentage of time in the EXAOI on five out of eight problems and those who answered incorrectly spent a significantly or nearly significantly greater percentage of time in the NVAOI on five of eight problems.

Limitations and Future Work

In this section we will synthesize some of the limitations and related changes that should be made in future work. We will also suggest additional broader directions the work could take.

With regard to differences in visual attention based on correctness of answer, we found differences in the time spent in the areas of interest for the problems studied in Chapters 3 and 5, though these problems only represented a limited number of introductory physics problems, primarily dealing with kinematics graphs and conservation of energy. To increase the generalizability of our conclusions, these studies should be repeated with more problems from other areas of introductory physics to determine if these differences in visual attention occur in many contexts or are specific to those contexts studied. It would also be important to include students having a wider range of prior knowledge of physics. We looked at visual attention of introductory physics students, primarily from algebra based courses and a handful of graduate students. Intermediate and advanced undergraduate students as well as physics professors could be included in future studies to observe a possible continuum on how visual attention changes with experience and level of domain knowledge. Additionally, the studies could be improved by using a larger number of participants, which would increase the statistical power and enable us to more thoroughly test the perceptual saliency hypothesis. Further, there were several problems described in Chapter 5 where the pattern of differences between correct and incorrect solvers was not observed. Since the areas of interest for these problems were not defined using data from student interviews, it may that conducting interviews and then redefining areas of interest would produce the pattern of differences, or that differences based on correctness only exist on certain problems. This should be investigated in future work.

In the studies in Chapter 3 and 5, the conclusions we have drawn about the influence of perceptual salience on visual attention must remain tentative as in each study we only used one computational model of visual salience, the Saliency Toolbox which implemented Itti's algorithm (1998). It would be important in future studies to utilize and compare other definitions for perceptual salience to determine if perceptual salience as predicted by a different algorithm influences eye movements and answer choices. Further, in the study described in Chapter 5, we only manipulated the luminance contrast of the images, but we found that this manipulation did not influence bottom-up attention. High perceptual salience can also be achieved through relatively greater contrast in terms of color, intensity, motion etc. compared to the other elements, though these were not investigated in this study. In the future, it would be informative to vary other dimensions of perceptual salience as well as combinations of these and look for influences on eye movements and answer choices. Perhaps manipulations of other dimensions of salience would capture attention on these problems more effectively. Further, the diagrams used in both studies were simple black and white line drawings. We might observe a stronger effect of bottom-up processes if we had used more complicated diagrams, for example, color photos of real world scenarios. In future work, diagram types in addition to simple black and white figures should be investigated. Finally, if future work showed that the problem solving process had an underlying perceptual component, we would need to explore interventions that would need to help student's change how they look at a problem by ignoring salient elements and focusing instead on thematically-relevant elements.

The work described in Chapter 5 could also be improved. In our study design, we chose to collect written responses from participants for each problem, but did not collect explanations of reasoning for these answer choices. While this minimized interaction among the interviewer and participant and accompanying verbal or non-verbal cues that may have influenced participants' answers and reasoning, we do not know why the participants gave the answers they did. Thus, there is a chance that we have included false positives in our data. This be addressed in future work, for example, by collecting verbal explanations from participants using careful interviewing techniques or having participants write out an explanation along with their answer.

The studies reported in Chapter 3 and 5 suggest that top-down cognitive processes dominate in physics problem solving. We found differences in the way participants' viewed different areas of the diagram based on the correctness of their answer. This finding is evidence for the domain knowledge students' possess and use strongly influencing eye movements, though we cannot rule out the influence of the problem solving task itself on visual attention. Previous research has found that participants look at perceptually salient areas when free viewing a scene, but when a search task is introduced, the influence of perceptually salience on eye movements is no longer seen (Underwood et al., 2006). So we might find no influence of perceptual salience in our study because physics problem solving in inherently a directed task or because participants use their prior knowledge to direct their attention or a combination of both. We do not have evidence to disentangle these possible effects so we can make no conclusions regarding the precise mechanism of top-down influence on attention.

With regard to the visual cueing work described in Chapter 4, we find some evidence that visual cues overlaid on static problems can help a student answer similar problems correctly, a transfer problem correctly, and can even influence visual attention on the transfer problem so that participants spend more time looking at relevant areas and ignoring irrelevant areas. But, we find this to be true only for some of the problem sets used in this study. We then ask ourselves, why we did not see the same positive results on the other problem sets? Our answers to this question motivate our future work.

First we speculate on why the cues on the roller coaster problem were effective at helping students answer the similar problems correctly, but not the cues on the ball, skier, or graph problems. Upon examining the cues, we notice that the roller coaster cues were especially simple. The simple back and forth motion highlighting the roller coaster carts were repeated several times. On the other hand, the visual cues used in the ball, skier, and graph problems moved in a more complex pattern. For example, in the ball problem, the cue moved between balls in track A at a given time period, then moved between balls on track B at the same time period, and were then repeated with a different set of balls. This pattern was only shown once for six seconds and it is likely that the pattern was simply too complicated to draw significant meaning from it in such a short time. Simpler cues should be used in future work and the time the cue is shown should be varied. Also, the cue onset occurred four seconds after a similar problem was shown. It may be that students needed more time to familiarize themselves with the problem before they could concentrate on and draw meaning from the cues. Thus, the cue onset time should also be varied in future work. We designed the cues to mimic the patterns that correct solvers used when viewing the problem diagrams. When helping someone who does not know how to solve a problem, showing them what an "expert" does may not be helpful, as an expert's problem solving process is likely streamlined and condensed. There are also many types of visual cues that could be applied to a given problem, and we only tried one type, namely flashing colored shapes that helped the participants *select* and *integrate* important diagram elements. In future versions of this study, we plan to use very simple cues that are easily encoded and understood by students. To ensure that the cues are "student friendly" we plan to first test various versions of visual cues on a given problem with a large number of introductory physics students in individual interviews. During these interviews, we will observe the problem solving process of an introductory student (as opposed to an "expert") and will offer different types of cues starting with the most implicit moving to the most explicit. For example, on the roller coaster problem, we could start by highlighting the carts and dimming the tracks, then we could try highlighting the carts in a temporal order (as we did in this study). Were this unhelpful, we could add even more information to the problem by overlaying lines under each cart representing the vertical height of each cart. Trying many variations of cues on a large number of students will allow us to gather much information about how the students' perceive the visual cues. We can then tweak the cues accordingly and try them with a new set of students. In this process we can note the individual qualities of the students to extract patterns as to whom the cues help and specifically how they are helpful. Additionally, there may be an interaction between the individual attributes of a student and the types of cues that are effective on certain problems. With this information, we hope to establish a broad framework for effective visual cues that takes into account features of the student, the cues and the type of problem. This framework would be developed iteratively testing the framework with new sets of problems and students and once again use eye tracking to measure how these cues influence visual attention.

Additionally, there may only be 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 to be 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.

In this study, we did not tell students what the cues were for, similar to Thomas and Lleras' (2007) work. We hoped that the cues would implicitly influence students to re-represent a problem and overcome an impasse. While we did find evidence that the cues were helpful on the roller coaster problem, they were not helpful on the other three problem tests. We informally asked a subset of participants what they thought of the visual cues and found that students' ideas about the cues showed a lot of variation. It may be that students' impressions of the cues influenced how useful the cues were at helping the students. In the future, we plan to tell students that the cues are helpful and we predict that students will benefit more from the cues when they know their purpose.

Further, in this study we found a difference in the similarity scores (ScanMatch) between those who did answer a similar problem correctly and those who didn't. This means that that there was a difference in how well the participants followed the cues with their eyes and this difference was related to their success on the similar problems. We predict that participants will follow the cues more closely and purposefully if they know they are helpful (as opposed to just being random flashing shapes), and they will get more from the cues since they are actually looking at them and will in turn answer more similar problems correctly.

We also found differences between the cue and no cue groups on only one of the four transfer problems tested. It may be that the three 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 future studies, we will first test our transfer problems with students in individual or group interviews to gain insight into how the students view the transfer problems and the connections they see between the similar and transfer problems.

In conclusion, there is much work to be done to understand the factors that lead to helpful cues. This study offers hope that cueing can potentially serve as effective conceptual scaffolding for novice physics students, but much work is necessary to perfect this method.

Anticipated Broader Impacts

The work on visual cueing described above offers hope that cueing can serve as effective conceptual scaffolding for physics students, but much work is necessary to understand and perfect this method. Once guidelines for successful cues on physics problems have been determined, there is tremendous opportunity to use cues in physics learning. For example, online homework environments are commonly used at both the secondary and university level. When students are working individually on homework problems with an associated diagram, visual cues could be overlaid and act as implicit hints to guide problem solving. Visual cues could be provided on a set of similar problems, much like in our study, and this would hopefully lead to students performing better on un-cued related problems. Further, eye-tracking technology is rapidly advancing and eye trackers using the camera on a computer, tablet or smart phone are now available (Bulling & Gellersen, 2010; Chynał & Sobecki, 2010; Holland & Komogortsev, 2012). As this technology becomes more popular and accessible, gaze contingent cueing schemes can be used. This means that depending on where a participant looks, customized visual cues would appear as hints. For example, if a student spends a certain amount of time fixating in a novice-like area in a diagram, a cue would appear that redirects their attention to a relevant area. If another student is looking at one piece of a relevant area, a visual cue can appear that models a productive way to integrate the information in several relevant areas.

References

Allain, R. J. (2001). *Investigating the Relationship Between Student Difficulties with the Concept of Electric Potential and the Concept of Rate of Change.* (Ph.D.), North Carolina State University, Raleigh, NC.

Antes, J. R., & Kristjanson, A. F. (1991). Discriminating artists from nonartists by their eye-fixation patterns. *Perceptual and Motor Skills, 73*(3), 893.

Beichner, R. J. (1994). Testing student interpretation of kinematics graphs. *American Journal of Physics, 62*(8), 750.

Bilalić, M., McLeod, P., & Gobet, F. (2008). Why good thoughts block better ones: The mechanism of the pernicious Einstellung (set) effect. *Cognition, 108*(3), 652-661. doi: 10.1016/j.cognition.2008.05.005

Boehnke, S. E., & Munoz, D. P. (2008). On the importance of the transient visual response in the superior colliculus. *Current Opinion In Neurobiology, 18*(6), 544-551. doi: 10.1016/j.conb.2008.11.004

Boucheix, J. M., & Guignard, H. (2005). What animated illustrations conditions can improve technical document comprehension in young students? Format, signaling and control of the presentation. *European Journal of Psychology of Education, 20*(4), 369-388.

Boucheix, J. M., & Lowe, R. K. (2010). An eye tracking comparison of external pointing cues and internal continuous cues in learning with complex animations. *Learning and instruction, 20*(2), 123-135.

Brown, D. E. (1989). Students' concept of force: the importance of understanding Newton's third law. *Physics education, 24*(6), 353.

Bulling, A., & Gellersen, H. (2010). Toward mobile eye-based human-computer interaction. *Pervasive Computing, IEEE 9*(4), 8-12.

Carmi, R., & Itti, L. (2006). Visual causes versus correlates of attentional selection in dynamic scenes. *Vision Research, 46*(26), 4333.

Charness, N., Reingold, E., Pomplun, M., & Stampe, D. (2001). The perceptual aspect of skilled performance in chess: Evidence from eye movements. *Memory & cognition, 29*(8), 1146-1152.

Chi, M. T. H. (1992). Conceptual change within and across ontological categories: Examples from learning and discovery in science *Cognitive Models of Science: Minnesota Studies in the Philosophy of Science* (pp. 129-186). Minneapolis, MN: University of Minnesota Press.

Chynał, P., & Sobecki, J. (2010). Comparison and analysis of the eye pointing methods and applications. *Computational Collective Intelligence. Technologies and Applications* 30-38.

Cohen, J., Cohen, P., West, S. G., & Aiken, L. S. (2003). *Applied Multiple Regression - Correlation Analysis for the Behavioral Sciences*. Mahwah: Lawrence Erlbaum Associates.

Corbetta, M., Akbudak, E., Conturo, T. E., Snyder, A. Z., Ollinger, J. M., Drury, H. A., . . . Shulman, G. L. (1998). A common network of functional areas for attention and eye movements. *Neuron, 21*(4), 761-773.

Craig, S. D., Gholson, B., & Driscoll, D. M. (2002). Animated pedagogical agents in multimedia educational environments: Effects of agent properties, picture features and redundancy. *Journal of Educational Psychology, 94*(2).

Cristino, F., Mathôt, S., Theeuwes, J., & Gilchrist, I. D. (2010). ScanMatch: A novel method for comparing fixation sequences. *Behavior research methods, 42*(3), 692.

De Graef, P., De Troy, A., & d'Ydewalle, G. (1992). Local and global contextual constraints on the identification of objects in scenes. *Canadian Journal of Psychology/Revue canadienne de psychologie 46*(3).

de Koning, B. B., Tabbers, H. K., Rikers, R. M., & Paas, F. (2010). Attention guidance in learning from a complex animation: Seeing is understanding? *Learning and Instruction 20*(2), 111-122.

de Koning, B. B., Tabbers, H. K., Rikers, R. M. J. P., & Paas, F. (2007). Attention cueing as a means to enhance learning from an animation. *Applied Cognitive Psychology, 21*(6), 731.

de Koning, B. B., Tabbers, H. K., Rikers, R. M. J. P., & Paas, F. (2009). Towards a Framework for Attention Cueing in Instructional Animations: Guidelines for Research and Design. *Educational Psychology Review, 21*(2), 113-140.

Desimone, R., & Duncan, J. (1995). Neural Mechanisms of Selective Visual Attention. *Annual Review of Neuroscience, 18*(1), 193.

Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research, 36*(12), 1827-1837.

Docktor, J. L., & Mestre, J. P. (2011). A Synthesis of Discipline-Based Education Research in Physics. *White paper commissioned by the National Research Council*, 147.

Docktor, J. L., Mestre, J. P., Gire, E., & Rebello, N. S. (2012). *Eye Patterns While Interpreting Kinematics Graphs*. Poster presented at the American Association of Physics Teachers Annual Conference, Philidelphia, PA.

Duchowski, A. (2007). *Eye tracking methodology: Theory and practice* (Vol. 373). Secaucus, NJ: Springer-Verlag New York, Inc.

Duncker, K. (1945). On problem-solving. *Psychological Monographs, 58*(5), i-113.

Einhauser, W., Rutishauser, U., & Koch, C. (2008). Task-demands can immediately reverse the effects of sensory-driven saliency in complex visual stimuli. *Journal of Vision, 8*(2). doi: 10.1167/8.2.2

Etkina, E., Mestre, J., & O'Donnell, A. (2005). The impact of the cognitive revolution on science learning and teaching. In J. M. Royer (Ed.), *The Cognitive Revolution in Educational Psychology* (pp. 119-164). Greenwich, CT: Information Age Publishing.

Feil, A., & Mestre, J. P. (2010). Change Blindness as a Means of Studying Expertise in Physics. *Journal of the Learning Sciences, 19*(4), 480-505. doi: 10.1080/10508406.2010.505139

Fischer, S., Lowe, R. K., & Schwan, S. (2008). Effects of presentation speed of a dynamic visualization on the understanding of a mechanical system. *Applied Cognitive Psychology, 22*(8), 1126-1141.

Fisher, R. A. (1922). On the interpretation of $\chi 2$ from contingency tables, and the calculation of P. *Journal of the Royal Statistical Society*, 87-94.

Fletcher-Watson, S., Findlay, J. M., Leekam, S. R., & Benson, V. (2008). Rapid detection of person information in a naturalistic scene. *Perception, 37*(4), 571-583.

Foulsham, T., & Underwood, G. (2007). How does the purpose of inspection influence the potency of visual salience in scene perception? *Perception, 36*(8), 1123-1138.

Gire, E., Docktor, J., Rebello, N. S., & Mestre, J. P. (2012, July 28-August 12). *Exploring Representational Fluency with Eye Tracking.* Talk presented at the American Association of Physics Teachers Summer Meeting, Philidelphia, PA.

Grant, E. R., & Spivey, M. (2003). Eye movements and problem solving: Guiding attention guides thoughts. *Psychological Science, 14*(5), 462.

Halloun, I. A., & Hestenes, D. (1985). The initial knowledge state of college physics students. *American journal of Physics, 53*(11), 1043-1055.

Hammer, D. (2000). Student resources for learning introductory physics. *American Journal of Physics, 68*(S1), S52.

Harding, G., & Bloj, M. (2010). Real and predicted influence of image manipulations on eye movements during scene recognition. *Journal of Vision, 10*(2), 17.

Harel, J. (2010). A Saliency Implementation in MATLAB.

Heckler, A. F. (2011). The Ubiquitous Patterns of Incorrect Answers to Science Questions: The Role of Automatic, Bottom-Up Processes. In J. P. Mestre & B. H. Ross (Eds.), *Psychology of Learning and Motivation: Cognition In Education*. Oxford, UK: Academic Press.

Hegarty, M., Canham, M. S., & Fabrikant, S. I. (2010). Thinking About the Weather: How Display Salience and Knowledge Affect Performance in a Graphic Inference Task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*(1), 37-53.

Hegarty, M., & Just, M. A. (1993). Constructing mental models of machines from text and diagrams. *Journal of memory and language, 32*(6), 717-742.

Henderson, J. M., Brockmole, J. R., Castelhano, M. S., & Mack, M. L. (2007). Visual saliency does not account for eye movements during visual search in real-world scenes. In R. V. Gompel, M. Fischer, W. Murray & R. W. Hill (Eds.), *Eye movements: A window on mind and brain* (pp. 537-562). Amsterdam: Elsevier.

Henderson, J. M., Weeks, P. A., & Hollingworth, A. (1999). The effects of semantic consistency on eye movements during complex scene viewing. *Journal of Experimental Psychology: Human Perception & Performance, 25*(1), 210-228.

Hoffman, J. E., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception & Psychophysics, 57*(6), 787-795.

Holland, C., & Komogortsev, O. (2012). *Eye tracking on unmodified common tablets: challenges and solutions.* Paper presented at the *Symposium on Eye Tracking Research and Applications*, Santa Barbara, CA.

Huk, T., & Steinke, M. (2007). Learning cell biology with close-up views or connecting lines: Evidence for the structure mapping effect. *Computers in Human Behavior, 23*(3), 1089-1104.

Hunt, A. R., & Kingstone, A. (2003). Covert and overt voluntary attention: linked or independent? *Cognitive Brain Research 18*(1), 102-105.

Ibrahim, B., & Rebello, N. S. (2012). Representational task formats and problem solving strategies in kinematics and work. *Physical Review Special Topics-Physics Education Research 8*(010126.).

Irwin, D. E. (1992). Memory for position and identity across eye movements. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18*(2).

Irwin, D. E. (2004). Fixation Location and Fixation Duration as Indices of Cognitive Processing. In J. Henderson & F. Ferreria (Eds.), *The interface of language, vision, and action: Eye movements and the visual world*. New York, NY: Psychology Press.

Irwin, D. E., & Andrews, R. V. (1996). Integration and accumulation of information across saccadic eye movements. In T. Inui, J. L. McClelland & e. al. (Eds.), *Information* *integration in perception and communication. Attention and performance* (Vol. 16, pp. 125-155). Cambridge, MA, USA: Mit Press.

Irwin, D. E., & Gordon, R. D. (1998). Eye Movements, Attention and Trans-saccadic Memory. *Visual Cognition, 5*(1-2), 127-155. doi: 10.1080/713756783

Itti, L., & Koch, C. (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision Research, 40*(10-12), 1489-1506.

Itti, L., Koch, C., & Niebur, E. (1998). A model of saliency-based visual attention for rapid scene analysis. *Pattern Analysis and Machine Intelligence, IEEE Transactions, 20*(11), 1254-1259.

Jamet, E., Gavota, M., & Quaireau, C. (2008). Attention guiding in multimedia learning. *Learning and Instruction 18*(2), 135-145.

Jarodzka, H., Scheiter, K., Gerjets, P., & van Gog, T. (2010). In the eyes of the beholder: How Experts and Novices Interpret Dynamic Stimuli. *Learning and Instruction, 20*(2), 146-154.

Jeung, H. J., Chandler, P., & Sweller, J. (1997). The role of visual indicators in dual sensory mode instruction. *Educational Psychology, 17*(3), 329-345.

Johnson, B., & Christensen, L. (2008). *Educational research: Quantitative, qualitative, and mixed approaches* (Third ed.). Thousand Oaks, CA: Sage Publications.

Johnson-Laird, P. N. (1983). *Mental models: Towards a cognitive science of language, inference, and consciousness* (Vol. 6): Harvard University Press.

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review, 87*(4), 329-353.

Kalyuga, S., Chandler, P., & Sweller, J. (1999). Managing split-attention and redundancy in multimedia instruction. *Applied Cognitive Psychology 13*(4), 351-371.

Kohl, P. B., & Finkelstein, N. D. (2005). Student representational competence and self-assessment when solving physics problems. *Physical Review Special Topics- Physics Education Research, 1*(010104).

Kowler, E., Anderson, E., Dosher, B., & Blaser, E. (1995). The role of attention in the programming of saccades. *Vision Research, 35*(13), 1897-1916.

Kriz, S., & Hegarty, M. (2007). Top-down and bottom-up influences on learning from animations. *International Journal of Human-Computer Studies, 65*(11), 911-930.

Kustov, A. A., & Robinson, D. L. (1996). Shared neural control of attentional shifts and eye movements. *Nature, 384*(6604), 74-77.

Large, A., Beheshti, J., Breuleux, A., & Renaud, A. (1998). Effect of animation in enhancing descriptive and procedural texts in a multimedia learning environment. *Journal of the American Society for Information Science, 47*(6), 437-448.

Leonard, W. J., & Gerace, W. J. (1996). The Power of Simple Reasoning. *The Physics teacher, 34*(5), 280.

Loftus, G. R., & Mackworth, N. H. (1978). Cognitive determinants of fixation location during picture viewing. *Journal of Experimental Psychology: Human Perception and Performance, 4*(4).

Loman, N. L., & Mayer, R. E. (1983). Signaling techniques that increase the understandability of expository prose. *Journal of Educational Psychology, 75*(3).

Lorch, R. F., & Lorch, E. P. (1996). .Effects of organizational signals on free recall of expository text. *Journal of Educational Psychology; Journal of Educational Psychology, 88*(1), 38.

Lowe, R. (1999). Extracting information from an animation during complex visual learning. *European Journal of Psychology of Education, 14*(2), 225-244.
Lowe, R. K. (1989). Search strategies and inference in the exploration of scientific diagrams. *Educational Psychology, 9*, 27–44.
Madsen, A. M., Larson, A. M., Loschky, L. C., & Rebello, N. S. (2012). Differences in visual attention between those who correctly and incorrectly answer physics problems. *Physical Review Special Topics - Physics Education Research, 8*(1), 010122.
Madsen, A. M., Larson, A. M., Loschky, L. C., & Rebello, N. S. (2012). *Using ScanMatch scores to understand differences in eye movements between correct and incorrect solvers on physics problems.* Paper presented at the Symposium on Eye Tracking Research and Applications, Santa Barbara, CA.
Marton, F. (1986). Phenomenography— A Research Approach to Investigating Different Understandings of Reality. *Journal of Thought, 21*(Journal Article), 24.
Mason, A., & Singh, C. (2011). Assessing expertise in introductory physics using categorization task. *Physical Review Special Topics: Physics Education Research, 7*(2).
Mautone, P. D., & Mayer, R. E. (2001). Signaling as a cognitive guide in multimedia learning. *Journal of Educational Psychology, 93*(2), 377.
Mautone, P. D., & Mayer, R. E. (2007). Cognitive aids for guiding graph comprehension. *Journal of Educational Psychology 99*(3).
Mayer, R. E. (2001). Introduction to Multimedia Learning. In R. E. Mayer (Ed.), *The Cambridge Handbook of Multimedia Learning*. Cambridge ; New York: Cambridge University Press.
McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception and Psychophysics, 17*(6), 578.
McDermott, L. C. (1984). Reserach on Conceptual Understanding in Mechanics. *Physics Today, 37*(7), 24.
McDermott, L. C., & Redish, E. F. (1999). Resource Letter: PER-1: Physics Education Research. *American Journal of Physics, 67*(9), 755.
McDermott, L. C., Rosenquist, M. L., & van Zee, E. H. (1987). Student difficulties in connecting graphs and physics: Examples from kinematics. *American Journal of Physics, 55*(6), 503.
Meltzer, D. E. (2005). Relation between students' problem-solving performance and representational format. *American Journal of Physics, 73*.
Meyer, B. J. (1975). *The organization of prose and its effects on memory*. New York: North-Holland Publishing Company.
Nobre, A. C., Gitelman, D. R., Dias, E. C., & Mesulam, M. M. (2000). Covert visual spatial orienting and saccades: Overlapping neural systems. *Neuroimage, 11*(3), 210-216.
Ohlsson, S. (1992). Information-processing explanations of insight and related phenomena. In M. T. Keane & K. J. Gilhooley (Eds.), *Advances in the psychology of thinking* (Vol. 1, pp. 1-44). London: Harvester-Wheatsheaf.
Oostendorp, H. V., & Beijersbergen, M. J. (2007). *Animated diagrams: their effect on understanding, confidence and mental effort*. Paper presented at the Bi-Annual Meeting of the European Association on Research on Learning and Instruction, Budapest, Hungary.
Ozcelik, E., Arslan-Asi, I., & Cagiltay, K. (2010). Why does signaling enhance multimedia learning? Evidence from eye movements. *Computers in Human Behavior, 26*(1), 110.
Parkhurst, D. J., Law, K., & Niebur, E. (2002). Modeling the role of salience in the allocation of overt visual attention. *Vision Research, 42*(1), 107-123.

Parkhurst, D. J., & Neibur, E. (2003). Scene content selected by active vision. *Spatial vision, 16*(2), 125-154.

Pringle, H. L., Irwin, D. E., Kramer, A. F., & Atchley, P. (2001). The role of attentional breadth in perceptual change detection. *Psychonomic bulletin & review, 8*(1), 89.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological bulletin, 124*(3), 372.

Redish, E. F. (1994). Implications of cognitive studies for teaching physics. *American Journal of Physics., 62*(9), 796-803.

Rickards, J. P., Fajen, B. R., Sullivan, J. F., & Gillespie, G. (1997). Signaling, notetaking, and field independence–dependence in text comprehension and recall. *Journal of Educational Psychology 89*(3).

Rimoldini, L. G., & Singh, C. (2005). Student understanding of rotational and rolling motion concepts. *Physical Review Special Topics - Physics Education Research, 1*(1), 010102.

Rosengrant, D., Hearrington, D., Alvarado, K., & Keeble, D. (2011). *Following student gaze patterns in physical science lectures.* Paper presented at the 2011 Physics Education Research Conference, Omaha, NE.

Rosengrant, D., Heuvelen, A. V., & Etkina, E. (2009). Do students use and understand free-body diagrams? *Physical Review Special Topics-Physics Education Research 5*(010108).

Rosengrant, D., Thomson, C., & Mzoughi, T. (2009). Comparing Experts and Novices in Solving Electrical Circuit Problems with the Help of Eye-Tracking. *AIP Conference Proceedings, 1179*(1), 249-252.

Scheiter, K., & Eitel, A. (2010). The Effects of Signals on Learning from Text and Diagrams: How Looking at Diagrams Earlier and More Frequently Improves Understanding. In A. K. Goel, M. Jamnik & N. H. Narayanan (Eds.), *Diagrammatic Representation and Inference* (Vol. 6170, pp. 264-270): Springer Berlin Heidelberg.

Scialfa, C. T., Thomas, D. M., & Joffe, K. M. (1994). Age differences in the useful field of view: An eye movement analysis. *Optometry and Vision Science, 71*(12), 736-742.

Seufert, T., & Brünken, R. (2006). Cognitive load and the format of instructional aids for coherence formation. *Applied Cognitive Psychology 20*(3), 321-331.

Sheinberg, D. L., & Zelinsky, G. J. (1993). A cortico-collicular model of saccadic target selection. In G. d'Ydewalle & J. V. Rensbergen (Eds.), *Perception and cognition: Advances in eye movement research* (Vol. 4, pp. 333-348). Amsterdam, Netherlands: North-Holland/Elsevier Science Publishers.

Simons, D. J., & Chabris, C. F. (1999). Gorillas in our midst: Sustained inattentional blindness for dynamic events. *Perception, 28*(9), 1059.

Singh, C., & Rosengrant, D. (2003). Multiple-choice test of energy and momentum concepts. *American journal of physics, 71*(6), 607.

Smith, A. D., Mestre, J. P., & Ross, B. H. (2010). Eye-gaze patterns as students study worked-out examples in mechanics. *Physical Review Special Topics: Physics Education Research, 6*(2), 020118.

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science, 12*(Journal Article), 257-285.

Tabbers, H. K., Martens, R. L., & Merriënboer, J. J. (2004). Multimedia instructions and cognitive load theory: Effects of modality and cueing. *British Journal of Educational Psychology, 74*(1), 71-81.

Tai, R. H., Loehr, J. F., & Brigham, F. J. (2006). An exploration of the use of eye−gaze tracking to study problem−solving on standardized science assessments. *International Journal of Research Methods in Education, 29*(2), 185.

Thaden-Koch, T. C. (2003). *A Coordination Class Analysis of College Students' Judgements About Animated Motion.* (Doctor of Philosophy), University of Nebraska at Lincoln, Lincoln, NE.

Thomas, L. E., & Lleras, A. (2007). Moving eyes and moving thought: On the spatial compatibility between eye movements and cognition. *Psychonomic Bulletin Review, 14*(4), 663.

Thomas, L. E., & Lleras, A. (2009). Swinging into thought: Directed movement guides insight in problem solving. *Psychonomic Bulletin Review, 16*(4), 719.

Treisman, A. M., & Gelade, G. (1980). A Feature-Integration Theory of Attention. *Cognitive Psychology, 12*(1), 97-136. doi: 10.1016/0010-0285(80)90005-5

Trowbridge, D., & McDermott, L. (1980). Investigation of student understanding of the concept of velocity in one dimension. *American Journal of Physics, 48*(12), 1020.

Tuckman, B. W. (1994). *Conducting Educational Research* (Fifth ed.). Orlando: Harcourt Brace College Publishers.

Tversky, B., Heiser, J., Mackenzie, R., Lozano, S., & Morrison, J. (2008). Enriching Animations. In R. Lowe & W. Schnotz (Eds.), *Learning with Animation: Research Implications for Design* (pp. 304-356.). New York: Cambridge University Press.

Underwood, G., Foulsham, T., van Loon, E., Humphreys, L., & Bloyce, J. (2006). Eye movements during scene inspection: A test of the saliency map hypothesis *European Journal of Cognitive Psychology, 18*, 22.

Underwood, G., Jebbett, L., & Roberts, K. (2004). Inspecting pictures for information to verify a sentence: Eye movements in general encoding and in focused search. *Quarterly Journal of Experimental Psychology Section A, 57*(1), 165-182.

Underwood, G., Templeman, E., Lamming, L., & Foulsham, T. (2008). Is attention necessary for object identification? Evidence from eye movements during the inspection of real-world scenes. *Consciousness And Cognition, 17*(1), 159-170. doi: 10.1016/j.concog.2006.11.008

Van der Stigchel, S., Meeter, M., & Theeuwes, J. (2006). Eye movement trajectories and what they tell us. *Neuroscience & Biobehavioral Reviews, 30*(5), 666-679. doi: 10.1016/j.neubiorev.2005.12.001

Van Gog, T., Jarodzka, H., Scheiter, K., Gerjets, P., & Paas, F. (2009). Attention guidance during example study via the model's eye movements. *Computers in Human Behavior 25*(3), 785-791.

Van Gog, T., Paas, F., Van Merriënboer, J. J. G., & Witte, P. (2005). Uncovering the Problem-Solving Process: Cued Retrospective Reporting Versus Concurrent and Retrospective Reporting. *Journal of Experimental Psychology: Applied, 11*(4), 237.

Van Someren, M. W., Barnard, Yvonne F., & Sandberg, J. A. (1994). *The think aloud method: A practical guide to modelling cognitive processes*. London: Academic Press.

Velichkovsky, B. M. (1995). Communicating attention: Gaze position transfer in cooperative problem solving. *Pragmatics & Cognition, 3*(2), 199-223.

Viennot, L. (1979). Spontaneous Reasoning In Elementary Dynamics. *European Journal of Science Education, 1*(2), 205-221.

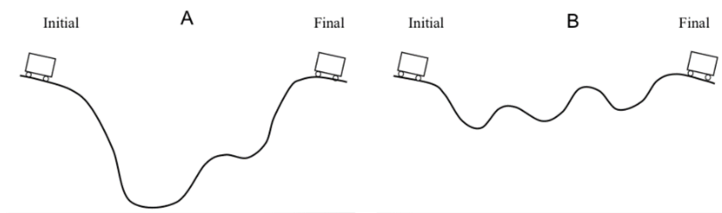
Walther, D. (2006). Modeling attention to salient proto-objects. *Neural networks, 19*(9), 1395.

Appendix A - Study Problems From Chapter 3

Figure A.1 Problems used in studies 1-3 from Chapter 3.

Problem 1 used in studies 1-3.

If 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?



(1) The cart A is moving faster at the final position

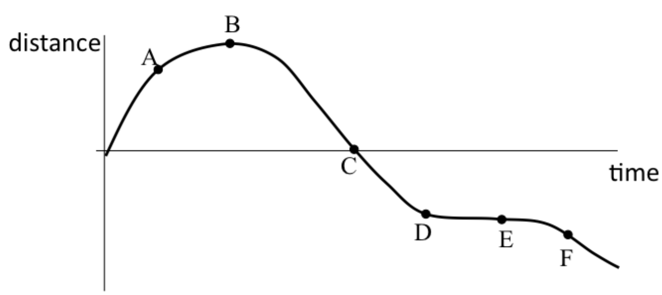
(2) The cart B is moving faster at the final position

(3) Carts A and B have the same speed at the final position

(4) There is not enough information to decide

Problem 2 used in studies 1-3.

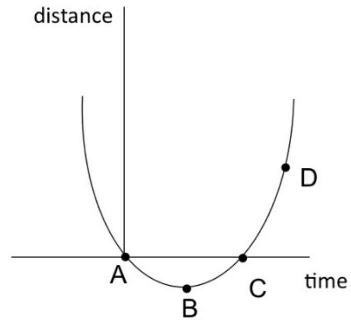
At which point on the graph is the object turning around (moving away then coming back)?



(1) A (2) B (3) C (4) D (5) E (6) F

Problem 3 used in studies 1-3.

When is the speed of the object shown in the graph zero?

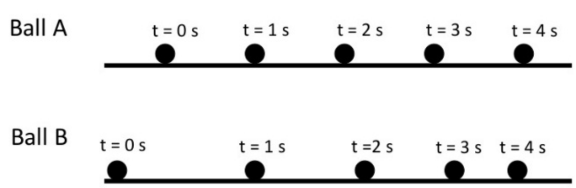


(1) Point A (2) Point B (3) Point C (4) Point D

(5) Point E (6) At all points

Problem 4 used in studies 1-3.

Two balls roll along the paths shown below. 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?

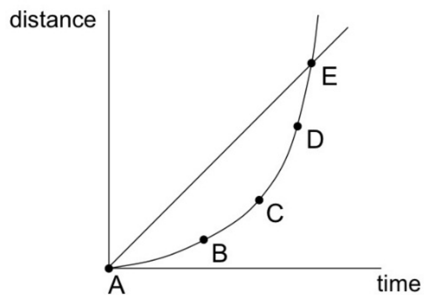


(1) t = 1.0 sec (2) t = 1.5 sec (3) t = 2.0 sec

(4) t = 2.5 sec (5) t = 3.0 sec

Problem 7 used in studies 1-3.

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

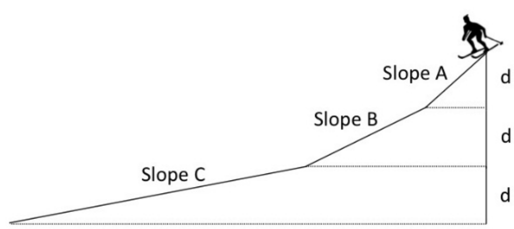


(1) Point A (2) Point B (3) Point C (4) Point D

(5) Point E (6) At all points

Problem 10 used in studies 1-3.

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



(1) $\Delta PE_A > \Delta PE_B > \Delta PE_C$

(2) $\Delta PE_C > \Delta PE_B > \Delta PE_A$

(3) $\Delta PE_A = \Delta PE_B = \Delta PE_C$

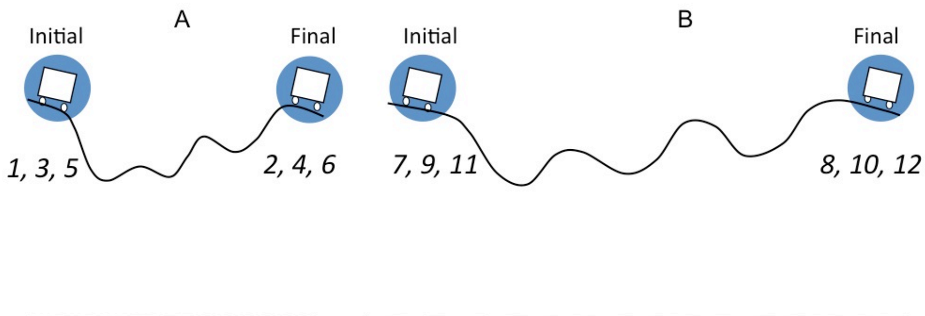
(4) $\Delta PE_A = \Delta PE_B > \Delta PE_C$

(5) $\Delta PE_B > \Delta PE_C = \Delta PE_A$

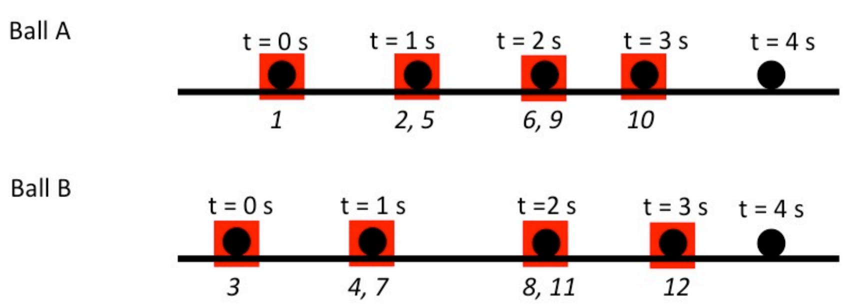
Appendix B - Cue Patterns from Chapter 4

Figure B.1 Problems used in study with visual cues overlaid. The colored shapes in each problem are the visual cues and the numbers in italics show sequence of animated cues (the numbers were not seen by study participants). From top to bottom: roller coaster problem, ball problem, skier problem, graph problem.

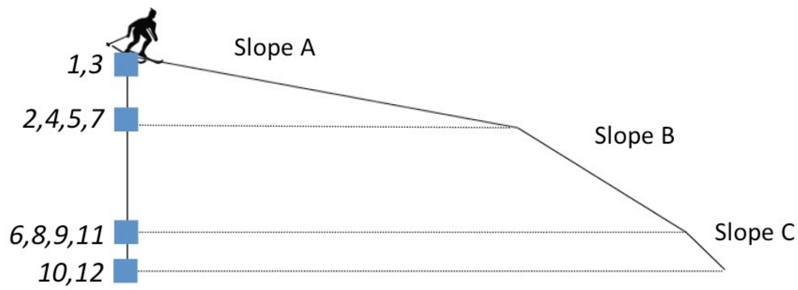
Assume frictional effects can be ignored. How does the final speed of roller coaster cart A compare to the final speed of roller coaster cart B, if the mass of the carts is the same and they both start at rest?



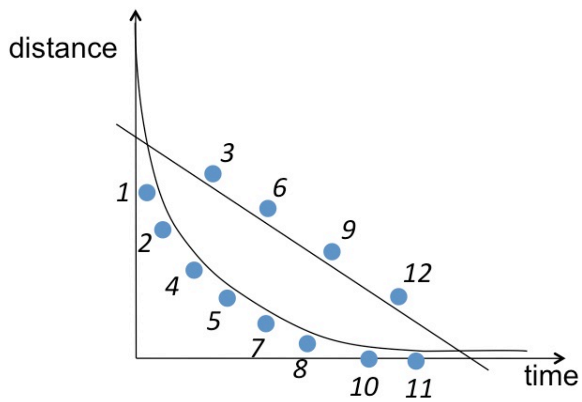
Two balls roll along the paths shown below. The position of the balls is shown at equal time intervals of one second each. When does Ball B have the same speed as Ball A?



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

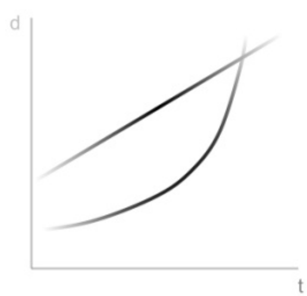
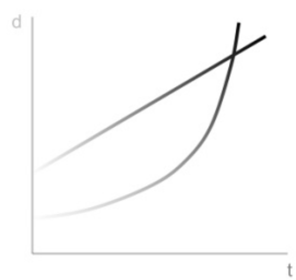
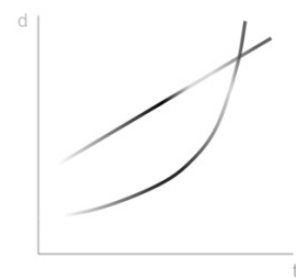
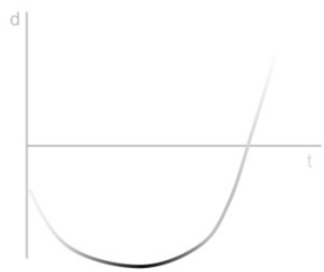
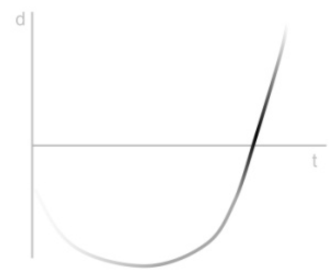
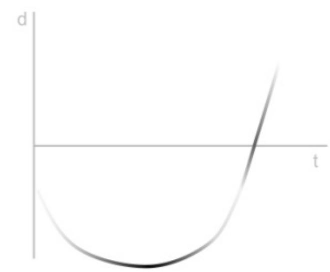


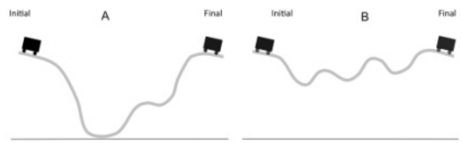
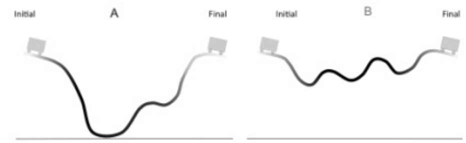
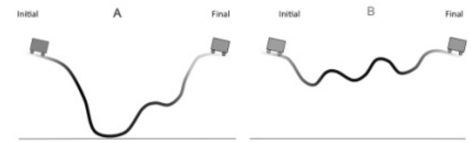
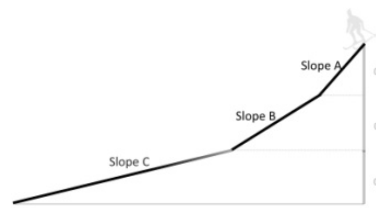
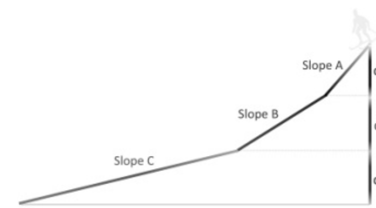
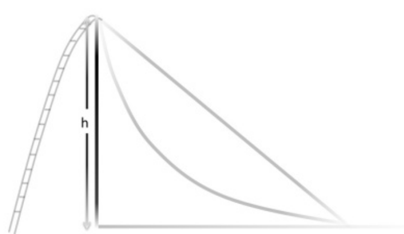
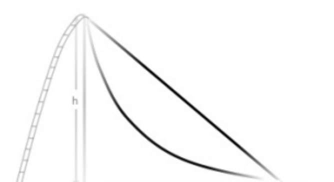
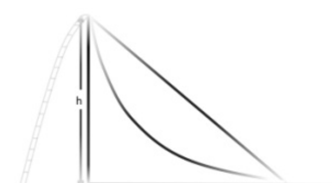
The motion of two objects is represented in the graph below. When are the two objects moving with the same speed?

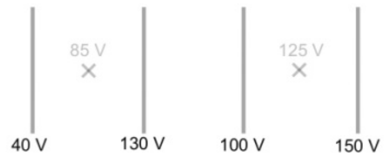
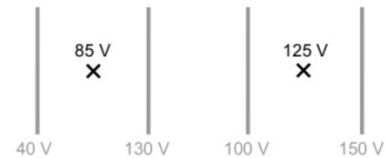
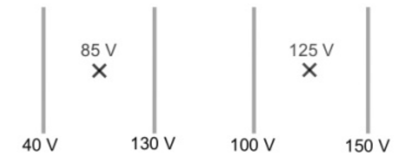
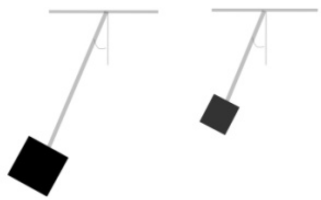
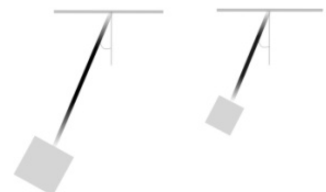
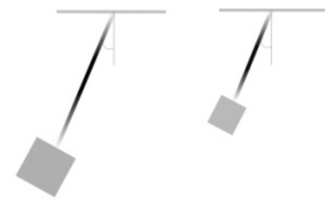


Appendix C - Additional Material from Chapter 5

Table C.1 All problems used in study described in Chapter 5 shown with "expert-like" and "novice-like" areas most perceptually salient as well as both areas having equal levels of perceptual salience.

Problem Designation	Expert-Like Salience Manipulation	Novice-like Salience Manipulation	Equal Salience Manipulation
A			
B			

C	Initial A Final Initial B Final	Initial A Final Initial B Final	Initial A Final Initial B Final
D	Slope A Slope B Slope C d d d	Slope A Slope B Slope C d d d	Slope A Slope B Slope C d d d
E	h	h	h

F	85 V 125 V 40 V 130 V 100 V 150 V	85 V 125 V 40 V 130 V 100 V 150 V	85 V 125 V 40 V 130 V 100 V 150 V
G			
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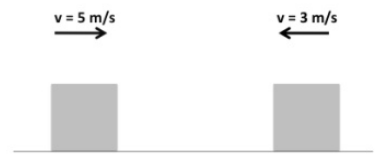
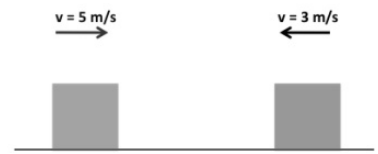
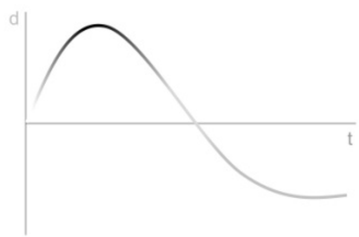
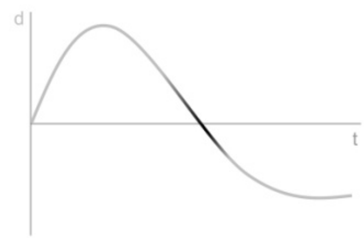
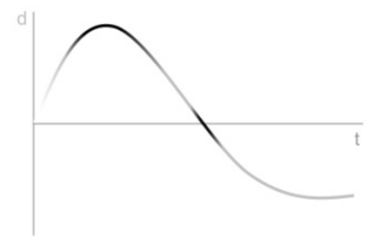
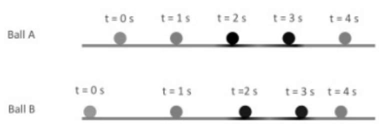
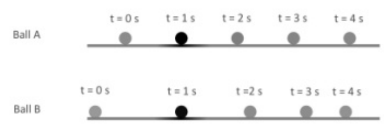
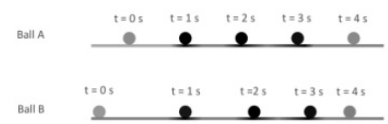
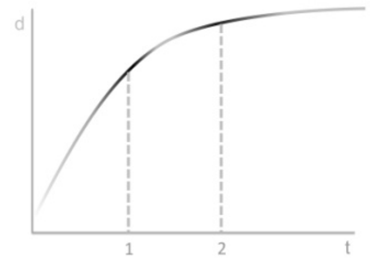
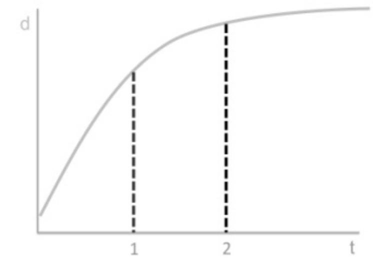
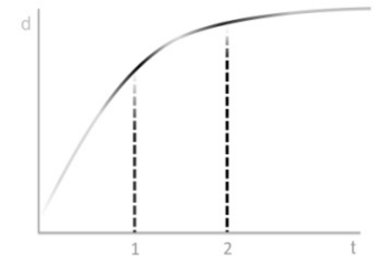
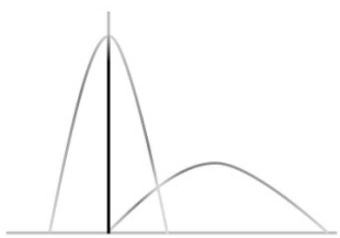
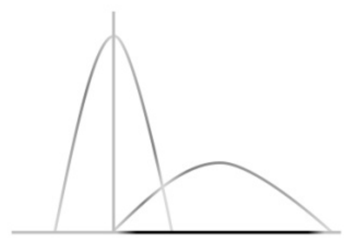
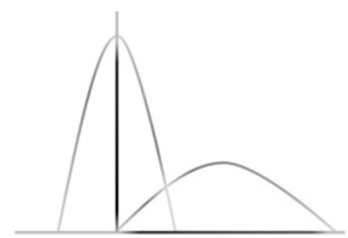
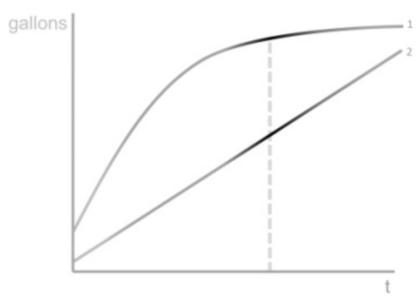
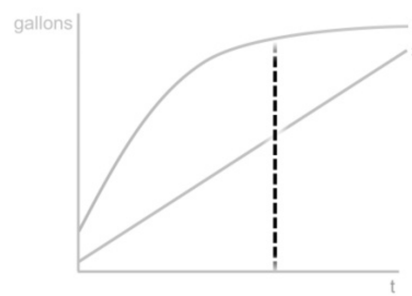
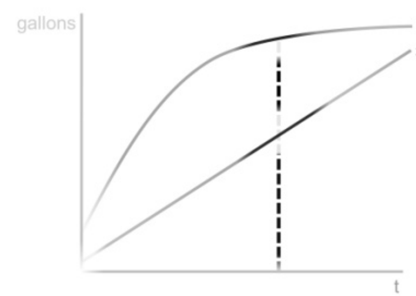
I	v = 5 m/s v = 3 m/s	v = 5 m/s v = 3 m/s	v = 5 m/s v = 3 m/s
J	d t	d t	d t
K	Ball A t = 0 s t = 1 s t = 2 s t = 3 s t = 4 s Ball B t = 0 s t = 1 s t = 2 s t = 3 s t = 4 s	Ball A t = 0 s t = 1 s t = 2 s t = 3 s t = 4 s Ball B t = 0 s t = 1 s t = 2 s t = 3 s t = 4 s	Ball A t = 0 s t = 1 s t = 2 s t = 3 s t = 4 s Ball B t = 0 s t = 1 s t = 2 s t = 3 s t = 4 s

L	d 1 2 t	d 1 2 t	d 1 2 t
M			
N	gallons 1 2 t	gallons 1 2 t	gallons 1 2 t

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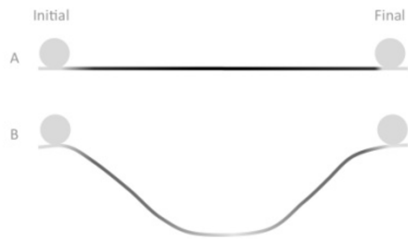
<td>
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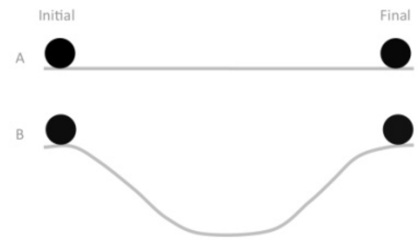
<td>
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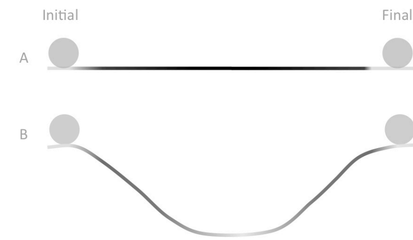
<td>
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Table C.2 Problem statements used in this study as well as definitions of "novice-like" and "expert-like" area.

Problem Statement	Problem Label	Novice-like Area	Expert-like Area
The motion of two objects is represented in the graph. When are the objects moving with the same speed?	A	Point where lines cross on graph.	Point where lines have same slope.
When is the speed of the object shown in the graph zero?	B	Point where line crosses x-axis.	Point where slope of line is zero.
How does the final speed of cart A compare to the final speed of cart B, if the mass of the carts is the same and they both start at rest? (Frictional effects can be ignored)	C	Roller coaster track (shape of track)	Roller coaster carts (height of carts)
Rank the changes in potential energy during the skiers descent down each slope from greatest to least.	D	Shape of each slope	Height of each slope
Sally slides down a straight slide and Carl slides down a curved slide. If Sally and Carl start at rest at the top of their respective slides, how do their speeds compare at the bottom of the slides? (Sally and Carl weigh the same amount)	E	Shape of slides	Height of slides
Between which pair of parallel plates is the electric field greater?	F	Potential at point between plates	Difference in potential on plates
Which pendulum takes longer to swing back and forth once?	G	Mass	Length
Blocks made of the same material are placed on opposites sides of the see-saw. Which was will the see-saw tip?	H	Only attending to mass	Attending to mass and lever arm
Which block has a larger acceleration when the hit?	I	Speed of blocks	Mass of blocks
At which point on the graph is the object turning around (moving away and then coming back)	J	Point where slope changes from increasing to decreasing	Point where line crosses x-axis
Two balls roll along the path show. 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?	K	Time when balls are at same position	Interval where balls have rolled same distance in one second.
The motion of a car is represented in the graph. At what time is the car moving faster?	L	Point with larger distance value (higher on the y-axis)	Point when slope of line is greater
Which trajectory (path) has a longer time of flight?	M	Wider trajectory	Taller trajectory
The graph represents two tanks being filled by water over time by separate water hoses. Which tank is filling faster at the time indicated on the graph?	N	Line with greater value on the y-axis at the indicated point	Line with greater slope at the point indicated

If both balls have the same mass and same initial speed, which ball arrives at the final position first? Friction can be ignored.	O	Shape of the track	Relative height at initial and final position of balls