FIRE: Exploring Visual Cueing to Facilitate Problem Solving in Physics

PROJECT DESCRIPTION

Goals and Hypotheses

This project serves two overlapping goals. (1) To foster novel interdisciplinary research at the interface of cognitive psychology, specifically visual cognition and physics education. (2) To provide opportunities for a physics education researcher (P.I. Rebello - mentee) and his group to learn the theory and methods of cognitive psychology, specifically visual cognition, from an expert (Co-P.I. Loschky – mentor) and apply these theories and methods to ongoing physics education research (PER).

Problem solving is a major area in PER and an area of expertise of the P.I. (e.g., Rebello et. al., 2007). Although problem solving has deep cognitive underpinnings, and numerous physics problems have strong visuospatial components, most research in physics problem solving has not drawn from research in visual cognition. Recently, some researchers have begun to use eye movement data to gain deeper insights into how students read solved example problems (Smith, Mestre & Ross, 2010) or to compare the differences between novices and experts on problem solving tasks (Fiel and Mestre, 2007; Rosengrant, Thomson & Mzhoughi, 2009). But, overall eye-tracking is a relatively new tool in the PER arsenal.

Eye-tracking has long been used to gain insights into student cognition while reading text (for a review, see Rayner, 1998). Recently, eye-tracking has also served as a useful tool to gain insights into learning with graphics. Mayer (2010) provides a review of key studies that have used eye-tracking to investigate how eye fixation times in relevant areas of a diagram and performance on cognitive tasks may depend upon the learners' prior knowledge (*knowledge effect*), as well as the use of visual cues (*signaling/cueing effect*) and audio narration (*modality effect*) accompanying the graphic.

The proposed research investigates two of these effects (*knowledge* and *cueing*) in the context of solving introductory physics problems with diagrams. Further, we explore the applicability of visual cueing to improve introductory physics students' problem solving skills. Toward that end, we propose studies testing each of the hypotheses below:

Hypothesis 1: (*knowledge* effect) On conceptual physics problems that require the use of a diagram, the eye movements of experts differ significantly from the eye movements of novices.

Hypothesis 2: (*cueing* effect) On such physics problems, appropriate visual cueing to change the eye movements of novices can improve their problem solving performance.

In this proposal, we first discuss with relevant literature in the field. Next, we describe results from two pilot studies. Later, we describe in detail the design of each of our proposed studies. Finally, we present the professional development plan for the P.I. and management and evaluation plans for the project.

Brief Review of Relevant Literature

Role of Prior Knowledge*:* Most physics problems involve the use of information presented as text as well as diagrams. Thus, learning to solve physics problems involves coordinating information provided in multiple modalities with prior knowledge. The cognitive theory of multimedia learning (Mayer, 2001) identifies three distinct processes -- *selection*, *organization* and *integration,* (SOI) involved in learning with information presented in multiple modalities. *Selection* is the process of attending to certain pieces of sensory information from each modality. *Organization* is using the selected information in each modality to create a coherent internal representation in that modality. *Integration* is combining internal representations from different modalities with activated prior knowledge. All three processes are influenced by prior knowledge.

Selection occurs because the brain can process only a limited amount of information at a time. For instance, when a learner attempts to solve a problem involving text and an image, their brain can only process some of the information received by their retina, and thus various parts of the visual information compete for the learner's attention (Desimone & Duncan, 1995). Importantly, attentional processes in the brain are limited in space and time, and thus the learner is generally only aware of that part of the retinal information that has been attended to and entered short-term memory (Triesman & Gelade, 1980; Irwin & Gordon, 1998; Simons & Chabris, 1999).

Attention prioritization of visual information is governed by two types of processes: top down and bottom up. Top down processes dominate in expert learners who possess adequate domain knowledge to enable them to focus on the thematically relevant parts of an image that are critical for correctly solving the problem. Studies have shown that top down processes dominate in determining where experts look while performing visual tasks in various fields such as art, (Antes and Kristjanson, 1991) chess (Charness, 2001) and meteorology (Lowe, 1999).

Bottom up influences on attention are faster and more primitive than top down influences on attention (Itti & Koch, 2000). They tend to dominate in novice learners who lack prior knowledge that may help them decide which parts of an image are thematically relevant. Such learners tend to focus on parts of the image that are more perceptually salient (i.e., noticeable), rather than thematically relevant (Foulsham, 2008; Lowe, 2003). Thus, important differences in the eye movements of experts who possess the necessary domain knowledge and novices who do not possess such knowledge, can be seen by tracking their eye movements while they carry out tasks (e.g., Tai, Loehr & Brigham, 2006; Fiel & Mestre, 2007; Rosengrant, Thomson & Mzhoughi, 2009).

Role of Visual Cueing: Based on Mayer's (2001) theory of multimedia learning, de Koning et. al. (2009) propose a framework which suggests that cueing, if designed appropriately, can be used to facilitate in all three processes involved in learning and problem solving: *selection*, *organization* and *integration*.

Cueing Selection: Selection of relevant information is the first step in learning or problem solving. Research (Schnotz & Lowe, 2008) has shown that in general visuospatial or temporal contrasts can cue attention. In other words, moving objects with unusual colors, contrasts and shapes are most effective in attracting the learners' attention. For instance, de Koning et. al. (2007; 2010) found that spotlight cues produced by reducing the luminance of all parts of an animation except the section being cued caused learners to fixate longer and more frequently in cued areas. Similarly, Grant and Spivey (2003) found for learners who solved Duncker's (1945) tumor problem, the movement of a critical part of a diagram increased fixation times around that part of the diagram and also facilitate problem solving. Based on these results, Grant and Spivey (2003) proposed an implicit eye-movement-to-cognition link such that eye movement can influence spatial reasoning. Thomas and Lleras (2007) followed up on Grant and Spivey's study (2003) and sought to determine the nature of the eye-movement-to-cognition link. They manipulated eye movements of learners solving Dunker's (1945) tumor problem in four different conditions by having them follow a string of characters with their eyes. Importantly, learners whose eye movements were manipulated along multiple paths to the tumor, therefore embodying the correct solution, were more likely to solve the problem correctly. More recently, Boucheix and Lowe (2010) compared the use of arrow cues with spreading color cues in different conditions. They found that learners in the spreading color cue condition fixated longer on the thematically relevant areas of the diagram. All of these studies converge on the consensus that cueing attention through the use of contrast, colors and motion can potentially be effective in facilitating the learner to attend to the thematically relevant parts of the problem, which in turn can improve their problem solving performance. We utilize these ideas to develop the cues in our proposed research.

Cueing Organization: The next step in learning or problem solving is organization of the selected information. Cues such as outlines and headings are widely used to organize textual information and facilitate easy memorization (e.g. Lorch & Lorch, 1995, 1996). However, organizational cues with graphics and visualizations are less prevalent. In the case of graphics, organization cues might include showing an exploded view of the constituent parts of an object and their spatial relations (Tversky, et. al.,

2002) or increasing the salience of specific parts of a graph to assist the learner to recognize trends and associations and construct a mental representation of the phenomena (Shah, et. al, 1999). Alternatively, the use of structural graphical organizers to help students make better sense of information conveyed in graphs has also been found to be helpful (Mautone & Mayer, 2007). Based upon the idea of analogical encoding (Gick & Holyoak, 1983) these cues facilitate the learning of unfamiliar content by first presenting familiar content using a graphical representation that has the same structural relationships as unfamiliar content. More recently, Canham and Hegarty (2010) have facilitated learners' understanding of weather maps by removing extraneous information, which is not by itself a cue but nevertheless assists in organization. A particular challenge to organizing information occurs when a static graphic is attempting to display a dynamic event. The use of numbers and arrows (Tversky, et. al., 2008) or spreading color cues (Boucheix & Lowe, 2010) that represent a chain of temporally spaced events can facilitate the learner to organize this information into an internal representation. Overall, much work is needed in the area of cueing for organization. The proposed research will explore this issue further.

Cueing Integration: The final step in learning or problem solving is integrating information from different modalities with one's prior knowledge. Two kinds of integration processes are important to learning and problem solving: relating elements within a single representation and relating elements across different representations. Cueing learners to relate elements within a single representation is especially important if the elements that they need to integrate are widely spatially separated (Lowe, 1989) or when the problem is ill structured or complex and schema construction necessitates high cognitive load. An example of such a problem is one in which the learner is required to infer dynamic information from a static picture (Hegarty, 1992). In such cases, the use of arrows and lines to cue causal relations has been found to be effective. Overall, cues that make implicit causal or functional relations between elements more explicit can potentially improve learning. We will explore the use of these kinds of cues in our project.

Cueing learners to relate elements across different representations or modalities is especially relevant in the context of physics problem solving where students have to coordinate graphs and pictures with text to create an operational situational mental model (Johnson-Laird, 1983) in order to solve the problem. Some of the cueing techniques that have been used to help learners connect elements across representations involve simultaneous flashing (Craig, et. al., 2002) and color coding (Kalyuga, et. al, 1999). The results of these kinds of cueing have not consistently shown promise on transfer tasks (e.g. Jamet, et. al., 2008). Similarly, the use of concrete graphical organizers that include diagrams or pictures of the quantities that are being graphed enabled learners to integrate the information with prior knowledge which led to more causal statements but not necessarily more relational statements (Mautone & Mayer, 2007). Overall, research on cueing learners to relate elements across representations is inconclusive. More studies are needed.

Table 1 below provides a brief summary of visual cueing in selection, organization and integration.

Cueing >	**Selection**	**Organization**	**Integration**	
Reason for cueing	To enable learners to attend to the thematically relevant parts of the information.	To enable learners to create an internal model based on the information.	To enable learners to create relations connecting elements… within a single representation	between different representations
Possible conditions when needed	• Distracting perceptually salient information • Movement is key to solution of problem	• High cognitive load • Complex system with constituent parts • Static graphic meant to display dynamic event	• Comparing elements • Dynamic info from static representation	• Coordinating info from graphs, pictures and text • Elements are abstract
Examples of cueing methods used	• Contrast, background fading • Bright colored shapes • Moving shapes	• Structural graph organizers • Exploded view of system • Numbers and arrows • Spreading color	• Arrows • Lines	• Concrete graph organizers • Flashing in sync • Color coding

In summary, we find that while cueing selection has been widely studied in the literature and found to be successful in several studies, cueing organization or integration has not yet been adequately explored. In this project we explore all three of these cueing processes in the context of physics problem solving.

Why Visual Cueing with Physics Problems?

Physics problems often involve conditions listed in Table 1. Thus, they are amenable to cueing selection, organization, and integration that occurs in the context of solving physics problems. For instance,
Cueing Selection: Physics problems may have perceptually salient elements that activate incorrect prior knowledge. In Fig. 1, the track is perceptually salient and learners may incorrectly attend to its shape.
Cueing Organization: Physics problems may use static pictures to represent dynamic events. In Fig. 1 below, the initial and final locations of the cart are drawn, but the movement is not shown.
Cueing Integration: Physics problems may require integration of elements within a representation (e.g. initial and final heights of carts in Fig. 1) or between representations (e.g. question text and diagram).

We conducted two pilot studies. Pilot 1 tested the *knowledge effect* hypothesis. Pilot 2 tested the *cueing effect* hypothesis only for *cueing selection* and not the other kinds of cueing.

Description of Pilot Studies

Pilot 1 (Carmichael et. al, 2010) Hypothesis: Learners who correctly answer a physics problem involving a diagram should have longer dwell times in the thematically relevant areas of interest (TR-AOIs) than participants who incorrectly answer the problem. Conversely, participants who incorrectly answer a problem should have longer dwell times in perceptually salient areas of interest (PS-AOIs) than participants who correctly answer the problem.
The eye movements of 22 participants solving 10 multiple choice conceptual physics problems were recorded using an Eye Link 1000 eye tracker in Loschky's Visual Cognition Lab. The TR-AOI in each problem, which was decided by three content experts, contained the thematically related visuospatial component that one needed to attend to in order to correctly solve the problem. Conversely, the PS-AOI contained the most noticeable perceptual feature in the problem, which was not necessarily thematically relevant. For example, the problem in Fig. 1 asks learners to compare the final speeds of the two roller coasters on the left and right. In the problem (see Fig. 1), the PS-AOI includes the track, which is perceptually salient, but irrelevant to the correct solution. Conversely, the TR-AOI includes the thematically relevant horizontal eye paths of an individual comparing the vertical heights of initial and final roller coaster, which allow one to correctly answer the problem—namely that the two roller coasters have the same final speed.

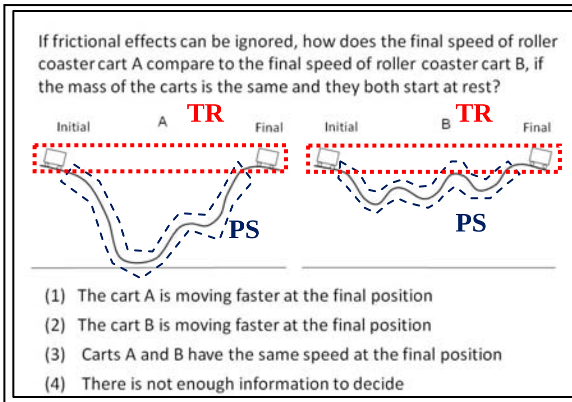

Fig. 1. TR-AOIs and PS-AOIs in a problem

We found (Fig. 2) that the average percent dwell time in the TR-AOI was significantly greater for participants who correctly answered a problem (34.2% vs. 19.4%, $p < 0.05$). Conversely, the average percent dwell time in the PS-AOI was significantly greater for participants who incorrectly answered a problem (28.6% vs. 14.2%, $p < 0.05$).

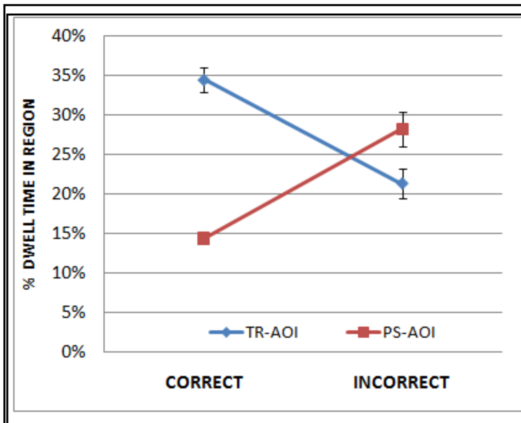

Fig. 2. Percent dwell time in the two AOIs. The error bars are the standard error.

Pilot 2 (Stevens, et. al, 2011) Hypothesis: Selection cueing based on eye movements of learners who correctly answer a problem facilitate correct solution of an isomorphic transfer problem.

To establish that our participants had the necessary basic knowledge of the physics concepts we administered a test of seven written questions. Fifteen participants answered the written questions correctly, thus indicating their knowledge of physics concepts were divided into two groups: cued (N=8) and non-cued (N=7). Both groups solved an initial problem from Pilot 1 (Carmichael et al., 2010). If a student answered the initial problem incorrectly, she was given an isomorphic scaffolding problem.

Students in the cued group follow colored shapes overlaid on the scaffolding problem as they moved across the screen in one-second intervals. The motion of these colored shapes was based on results of Pilot 1, and embodied the solution to the problem. An example of a cued problem is shown in Fig. 3. To avoid simply giving students the correct answer, cueing did not only occur near the area with the correct solution, but across several areas relevant to the correct conceptual understanding of the problem. We attempted to implicitly cue students to attend to the thematically relevant parts of the image without indicating the answer.

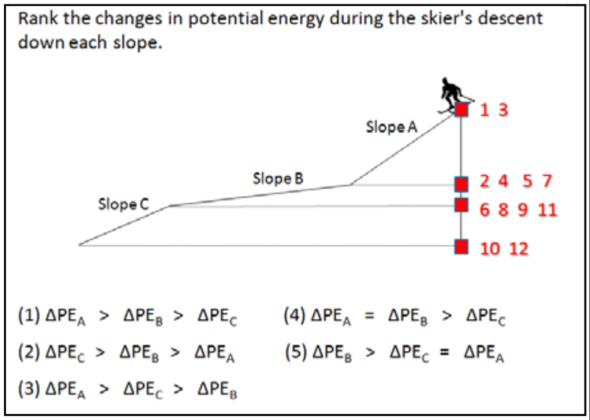

Fig. 3. Example of visual cues provided in Pilot 2. The highlighted square shape moves in the sequence of the numbers shown.

Students in the non-cued group solved the same problems without any visual cueing. If the student answered a scaffolding problem correctly they were presented with the transfer problem; otherwise, they were presented with another scaffolding problem, until a maximum of three scaffolding problems, after which a transfer problem was presented. Students' eye movements were compared between the groups.

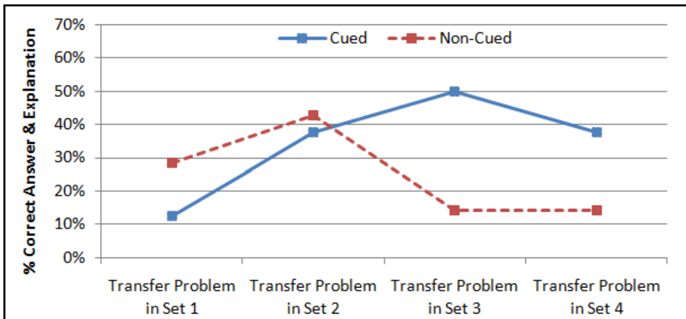

Fig. 4. Percentage of Pilot 2 participants who provided a correct answer and explanation for each transfer problem.

Our results (Fig. 4) showed a trend such that on average students who were cued were more likely than the non-cued students (35% vs. 24%) to answer the transfer problem correctly, but this effect occurred in later problem sets indicating that effectiveness of cueing might improve with time. Further, a larger number of students in the cued group (6 of 8), compared to the non-cued group (3 of 7) proceeded to answer the scaffolding problems correctly before proceeding to the transfer problem. Our results (Fig. 5) also showed a trend that students who were provided with visual cues to solve the problems were on average more likely (1.6 vs. 1.2 times per student per problem) to change their verbal explanations to be more conceptually correct. Finally, our eye tracking data showed that cued students were more likely to mimic the eye movements they had made in the cueing sequences on subsequent non-cued problems.

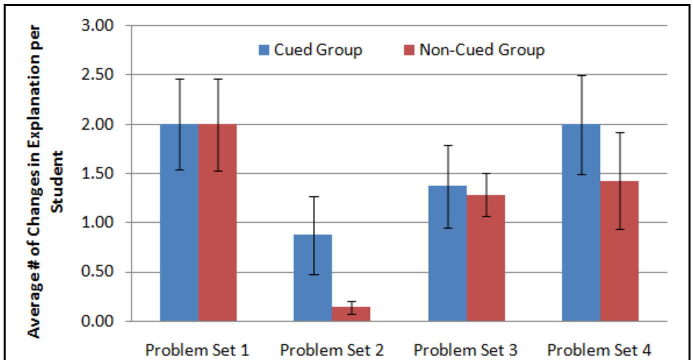

Fig. 5. Average number of changes in explanation per student per problem set. Error bars are standard error.

Both pilot studies show promise. The pilot studies also provided the PI and his group valuable experience in this field and a knowledge base on which to build the proposed studies described below.

Description of Proposed Studies

Study 1: Expert and Novice Learners' Eye Movements and Explanations

Hypothesis: (*knowledge* effect) On conceptual physics problems that require the use of a diagram, the eye movements of experts differ significantly from the eye movements of novices.

What is new in Study 1 vs. Pilot 1? Pilot 1 found statistically significant results, but could be improved upon by including a larger number of problems, and a larger number of participants with more clearly differentiated levels of expertise. Although the hypotheses of the two studies are similar, the proposed Study 1 is substantially different from Pilot 1 in the ways described in Table 2 below.

Characteristics of Pilot 1	**Modification in Proposed Study 1**
Materials: Ten multiple choice conceptual problems created by us.	We adapt problems from the FCI and other well known conceptual physics assessments. A total of 20 problems are first selected, but we narrow down the list to about 10 problems. Open-ended problems with a fixed answer time are used as per Mayer (2009). They are graded by using a pre-set rubric created by the P.I and physics GRA.
Participants: Convenience sample of 22 participants with mixed levels of ability.	Volunteers enrolled in algebra-based physics are given a brief paper and pencil test to assess their pre-knowledge of the concepts and 50 participants are chosen from among those who have a minimum pre-set score on the test. Twenty (20) experts are chosen from based on whether they are GTAs or faculty and have taught introductory physics recently.
Data Analysis: Comparing eye movements of those who got a problem correct versus those who did not. PS-AOIs selected by project team.	Data analysis focuses on comparing the expert eye movements to the novice eye movements in the areas of interest (TR-AOIs vs. PS-AOIs). A timed retrospective cued verbal report (van Gog, 2005) is collected from each participant. It is analyzed based on a pre-decided rubric for correctness and completion. We use Itti's (2000) algorithm on salience maps to select the perceptually salient areas on each problem.

Participants: The novices are 50 students enrolled in introductory algebra-based physics classes. The novices have adequate knowledge of the physics terminology used in the problems, but are far from experts. We recruit students in algebra-based college physics who have taken one semester of high school physics. Each novice is paid $10 for their participation in an hour-long session.

The 20 experts in the study are selected from a pool of physics graduate teaching assistants and faculty members who have taught an introductory physics course within the last year. This requirement assures that the introductory physics course content is fresh in their minds.

Materials: We develop a set of 20 conceptually based, multiple-choice problems in introductory physics, each of which includes a figure whose spatial structure is intimately connected to the problem's solution. Starting with problems in Pilot 1 that have shown strong differences in eye movements between correct and wrong solvers, we expand our pool by considering problems in well established physics conceptual assessments such as the Force Concept Inventory (Hestenes et. al., 1992), Energy and Momentum Conceptual Evaluation (Singh & Rosengrant, 2003) and others that have diagrams.

Procedure: At the beginning of an hour-long session, each participant is given a brief explanation of what to expect during the session and a calibration of the eye tracking system is completed. Next, they are instructed to silently answer each problem on a computer screen, while their eye movements are recorded, and indicate their answer using number keys on the keyboard. Finally, they are asked to provide a verbal cued retrospective report for which they see a recording of their eye movements on the problem and asked to explain their thought process either concurrently or after the recording (van Gog, 2005). They are free to pause, rewind or replay the recording. There is a time limit for answering the problem and retrospective verbal reports.

Analysis: Thematically relevant areas of interest (TR-AOI) of each physics problem are indicated by a panel of three physics professors who have taught an introductory physics course within the last year. Discrepancies within the panel are resolved through discussion until a common TR-AOI is agreed upon. The perceptually salient areas of interest (PS-AOI) are defined by their intensity and orientation based on Itti's (2000) work with salience maps. If the AOIs are spatially distributed, corresponding AOIs are combined to form an aggregate of AOIs (AAOIs).

The percentage of eye fixations in each type of AAOI is determined. An ANOVA with correctness of answer as the independent variable and percentage of fixations for both of the AAOI types as the dependent variables will be conducted for both the novices and experts. As per convention in most educational research, a significance level $\alpha = .05$ is used to determine statistically significant differences between participants. Hypothesis: Experts have statistically significantly longer dwell times in the TR-AAOIs than novices. Conversely, novices have statistically significantly longer dwell times in the PS-AAOIs than experts.

Validity threats: We identify the following potential validity threats and ways to minimize them.
(i) Participants: Although participants for our study are chosen from a pool of volunteers whose prior knowledge is tested, it is nevertheless a convenience sample and not statistically representative the class. We strive to include a diverse pool of participants, with gender (about 50% female and male) and ethnicity representative of the larger population enrolled in algebra-based physics. Unfortunately, we have to exclude learners who cannot use the eye-tracking system such as those with eye glasses or contact lenses above a certain power.
(ii) Problem tasks: It is likely that the problems that we select are not representative of typical problems in this physics course. We will present the slate of problems to a panel of three physics faculty who have recently taught algebra-based physics, to tell us if the problems are representative of problems used in the class and make modifications deemed necessary.
(iii) Equipment issues: As is true in any eye-tracking study, the act of using an eye tracker may change the problem solving behaviors of the participants. We use an S1 Mirametrix eye-tracker that does not need an obtrusive head rest or chin support. We are not using the Earthlink 1000 eye-tracker used in the pilot studies because that facility is heavily used and therefore we have budgeted funds ($5000) to purchase the S1 Mirametrix eye-tracker which will be housed in the Physics Department in closer proximity to our research participants.

Study 2: Attentional Cueing for Novices

Hypothesis: (*cueing* effect) On conceptual physics problems that require the use of a diagram, appropriate visual cueing to change the eye movements of novices can improve their problem solving performance.

What is new in Study 2 vs. Pilot 2? Pilot 2 data shows promising trends, but unlike Pilot 1 it did not reach statistical significance. We anticipate that Study 2 is more likely to do so, given a larger sample size and more carefully designed cues. Although the hypotheses of the two studies are similar, the proposed Study 2 is substantially different from Pilot 2 in the ways described in Table 3 below.

Characteristics of Pilot 2	Modification in Proposed Study 2
Materials: The cues for the problems were designed based on expert eye movements. There was no careful delineation of the cues.	We have designed our cues more carefully based on de Koning et. al (2009) framework as well as eye movement data from Study 1. There are three hierarchical levels of cues: *selection*, *organization* and *integration* (see below for details).
Participants: Convenience sample of 15 participants with mixed levels of ability.	Volunteers enrolled in algebra-based physics are given a brief paper and pencil test to assess their pre-knowledge of the concepts and 100 participants are chosen from among those who have a minimum pre-set score on the test.

Characteristics of Pilot 2	Modification in Proposed Study 2
Design: Between subject design with two groups: cued and non-cued. Each student was presented with only at most three practice problems.	Also a between subject design, but this time there are four groups: one non-cued group and three cued groups (see below for details). Each student is presented with at most six practice problems which gives them more practice with cueing and a greater likelihood that the cue will have an effect.

Participants: As in Study 1, the participants must know the relevant physics terminology and concepts. However, they must not be skilled at applying physics concepts to problems. If so, no improvement from the attentional cueing treatment can be expected. Conversely, if the participants are completely unfamiliar with physics concepts, they will not be able to activate appropriate prior knowledge and combine it with relevant information cued from the diagram. Thus, the ideal participants are selected from a pool of volunteers who have taken a high school physics class and are currently enrolled in an algebra-based physics class.

One hundred (100) participants are selected from this pool based upon their responses to a brief written survey that will assess their knowledge of physics terminology and application of concepts. To select participants based upon the criteria above, a window of minimum and maximum performance on the survey is determined apriori by researchers. Volunteers scoring in this window are invited to participate. Each participant is paid $10 for their participation in an hour-long session

Materials: Ten (10) physics problems that show the strongest expert-novice differences in Study 1 are used in Study 2 as a set of 'initial problems.' From each of these 10 'initial problems' we alter the perceptually salient feature to create six isomorphic 'practice problems' and the thematically relevant feature to create one isomorphic 'transfer problem' designed to assess whether the participant has the correct model of a physics concept applicable to a new situation. Fig. 6 shows an example of an initial problem, a practice problem and a transfer problem.

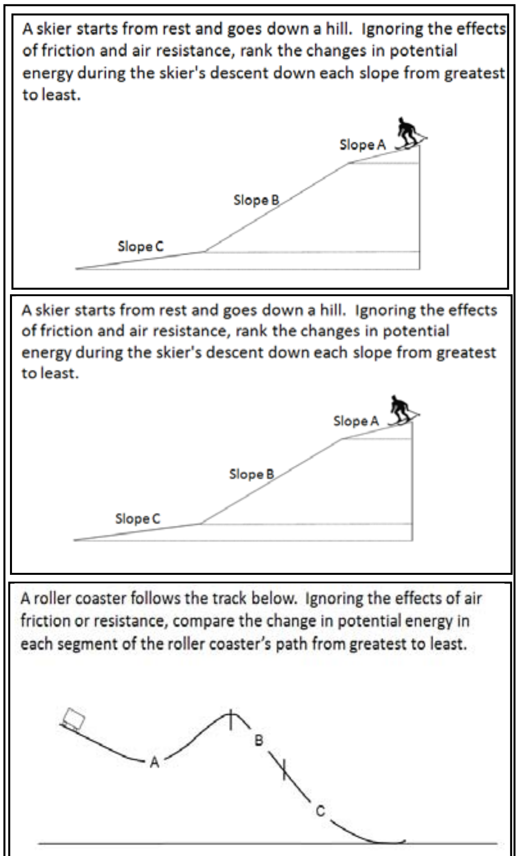

Fig. 6: Example of an initial problem (top) practice problem (middle), and transfer problem (bottom).

We create three kinds of visual cues based on eye movements of experts in Study 1 as well as guidance by de Koning et. al. (2009), which is summarized in Table 1. At this point, we cannot decide exactly what each cue type would look like, as this decision would need to be made only after we have analyzed the results of Study 1. Below are some possibilities:

(i) *Selection* cues: Spotlight cues (e.g. de Koning et. al., 2007; 2010) overlaid on the practice problem diagrams highlighting the TR-AOIs, moving object cues (Grant & Spivey, 2003; Thomas & Lleras, 2007; 2009) or a fading background.

(ii) *Organizational* cues: Spreading color cues that were used by Boucheix & Lowe, (2010) or use of numbers and arrows (Tversky, et. al., 2008).

(iii) *Integration* cues: Simultaneous flashing (Craig, et. al., 2002) and color coding (Kalyuga, et. al, 1999).

In each of the three categories, we do not confine ourselves to the cues listed above. As de Koning et. al. (2009) indicate, *organizational* and *integration* cues have not been adequately explored previously.

Design: Study 2 is a between subjects design with type of visual cue on practice problems as the independent variable. Participants are divided into four equal groups: (i) *selection* cued, (ii) *organization* cued, (iii) *integration* cued and (iv) non-cued (control). All groups follow a sequence shown in Fig. 7: View an 'initial' problem, indicate answer and verbal explanation. If the answer and explanation are correct and complete (based on a pre-determined rubric) they are shown a transfer problem. If not, they are presented a sequence of up to six practice problems followed by a transfer problem.

The control group gets no cues on any problem. The treatment groups view each problem for four seconds as per Thomas and Lleras (2007) without cues, and then are shown one of the three possible cues.

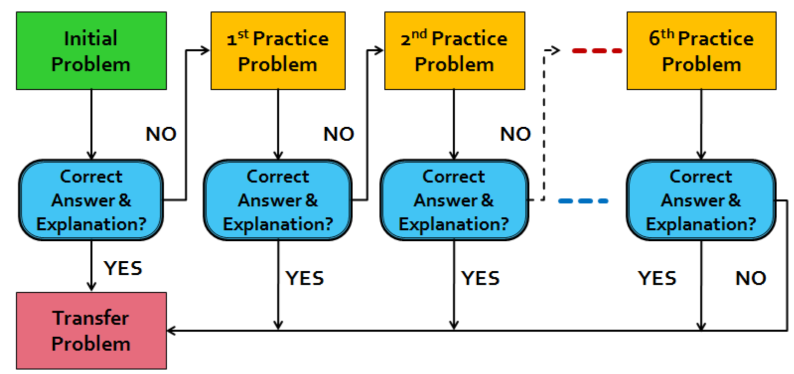

Fig. 7 Sequence of problems for Study 2.

Procedure: At the beginning of an hour-long session, each participant is given a brief explanation of what to expect during the session and a calibration of the eye tracking system is completed.

Next, they are instructed to silently answer each problem on a computer screen while their eye movements are recorded, indicate their answer using number keys on the keyboard and provide a verbal explanation to the researcher. The researcher rates the answer and explanation as per a predefined rubric to determine whether they are correct. Depending upon their answer and explanation to the initial problem they are directed to the problem sequence shown in Fig. 7, which is repeated for five selected problem sets from our original pool of 10 sets. In each set, the practice problems are counterbalanced to take into account ordering effects. Participants are given a maximum time (yet to be determined) for providing the answer and explanation to any of the problems. After answering the initial problem, the participants in all groups, before seeing the practice problems are told, "A few seconds after you begin viewing the problem, images *may* appear on the screen. Please watch these images and follow them with your eyes if they move until they disappear."

Analysis: We make the following between-subject comparisons using an $\alpha = 0.05$ level of significance.

(i) Number of participants who correctly answer and explain each problem, specifically after seeing the same number of practice problems. Hypothesis: No differences on initial problem. Larger number of cued than non-cued participants correctly answer and explain any given practice or transfer problem, when controlling for the number of practice problems seen prior.

(ii) Average number of practice problems that participants need to solve before being able to provide correct answer and explanation. Hypothesis: Fewer practice problems necessary before providing a correct answer and explanation in the cued groups than the non-cued group.

(iii) Number of participants who change their explanation to be more conceptually correct after completing a certain number of practice problems. Hypothesis: More changes in explanation on practice problems in cued groups than control group. Cued participants are initially led by PS elements, but cueing leads them to attend to TR elements. So, cued participants are more likely than non-cued to change explanations to be conceptually correct as they move through the practice problems.

(iv) Eye movements on each problem -- initial, practice and transform, specifically the percentage of saccades that mimics the cues on the practice problems. Hypothesis: No differences on the initial problem. Eye movement pattern observed in the treatment groups on the transfer problem will contain similar eye movements to those demonstrated in the visual cues. Seeing visual cues in a similar pattern across several practice problems may induce students to mimic these movements on the transfer problem.

NOTE: In the analysis above, we did not mention the three kinds of cueing groups. We will analyze our data for these differences, but currently have no strong hypotheses about which cueing is most effective.

Validity threats: In addition to threats (i) – (iii) for Study 1, the following threats are identified.
(iv) Placebo effect: Students will be told that they will see moving shapes, and therefore, a placebo effect is possible. To minimize the placebo effect we provide this statement to all groups. The statement "images *may* appear…. " is worded so that it can be provided to both the cued and non-cued groups.
(v) Cue type: The different types of cues used in this study are based on literature. However, within these categories, several variations are possible. A careful study of cue variation is beyond the scope of this project. We will explore the possibility of modifying the cues in a future study.
(vi) Cue timing: As with cue type, in this study we do not not vary the timing of when the cue appears. Cues always appear four seconds after the problem is shown as per Thomas and Lleras (2007). We also do not alter the duration for which these cues are visible. Therefore, we do not completely investigate variations in cue timing. As with cue type, such a study will be explored beyond the scope of this project.
(vii) Transfer proximity: A single problem is clearly an inadequate measure of transfer. Whether the particular problem assesses near transfer or far transfer is also debatable. To improve our validity of the transfer measurement, after participants have provided an explanation for the transfer problem, they are probed further with 'what if' type questions to investigate whether they have a robust mental model for solving not just this particular transfer problem, but a larger category of problems that share the same deep structure.

Summary of Proposed Studies

The two studies described above enable us to first identify the differences between the eye movements of experts and novices on physics problems with a strong visuospatial element. Then based on our insights, in the second study we further explore and exploit the cognition-to-eye-movement link of influence of participants' cognition on these problems, and thereby their problem solving ability through the use of visual cues. While our problem set, the types and durations of the cues and the participants are limited in this study, we believe this research will extend the current body of knowledge on the use of visual cueing and its application to problem solving in STEM fields.

Professional Development Plan

Dr. Rebello (P.I.) and his group have begun collaborating with a cognitive psychologist and expert in visual cognition – Lester Loschky (co-P.I.) on the use of eye tracking and attentional cueing in physics education. These collaborations have led to two pilot studies described earlier and resulted in two peer reviewed publications. (Carmichael, et. al, 2010; Stevens, et. al. 2011).

The proposed project is a natural extension of these collaborations and an opportunity for Dr. Rebello and his group to further develop their knowledge and skills in the theory and methods used by cognitive psychologists and how these can be applied to PER. Specifically, the professional development goals for Dr. Rebello are to:

- ➢ learn the culture of the field of cognitive psychology, particularly visual cognition, as well as the cannons of the field and contemporary research issues,
- ➢ become knowledgeable about common avenues and standards for publishing research in cognitive psychology and become a critical reader of literature in the field,
- ➢ develop the knowledge and skills necessary to design valid and reliable experiments that utilize theory and methods in cognitive psychology,
- ➢ apply the above knowledge and skills to his ongoing work in PER and explore the possibilities offered by cognitive psychology to take this work in new directions.

To achieve these goals, Dr. Rebello will work closely under the mentorship of Dr. Loschky to

- ✓ design and implement the proposed studies as well as jointly mentor the graduate and undergraduate students on all aspects of the project,
- ✓ gain hands-on experiences with the use of the eye-tacking equipment, data collection and analysis,

- ✓ attend weekly meetings of the Visual Cognition Group led by Dr. Loschky and learn about other projects that this group is involved in,
- ✓ actively participate in the Applied Cognitive Science seminar course which is offered in the Psychology Department for learners of different backgrounds to learn more about this field,
- ✓ regularly attend the weekly Cognitive Psychology Brownbag and present the results of PER work completed on this project to this audience,
- ✓ jointly, with Dr. Loschky, prepare talks and papers for conferences such as the *Psychonomic Society, Cognitive Science Society, and Eye Tracking Research & Applications Sympoisum*, and to coauthor papers in peer-reviewed cognitive and educational psychology journals such as *Learning & Instruction* and *Journal of Educational Psychology,*
- ✓ network with other cognitive psychologists at these conferences with a goal to explore the possibilities of broader collaborations with these individuals in the future.

All of these efforts will prepare Dr. Rebello to embark on independent work in this area and to explore new ideas for further research that integrates cognitive psychology, specifically visual cognition and PER. Currently, much of PER does not draw from research on visual cueing or vision cognition. This project will pave the way for the field of PER in general to become more informed about the theories and methods of cognitive psychology, particularly vision cognition, and their applications.

Project Management Plan

Personnel: The qualifications, experience and roles of the project team are described below:

Dr. N. Sanjay Rebello (P.I.) Associate Professor of Physics has over 10 years experience in physics education research (PER). Research conducted by his group has focused on transfer of learning, problem solving, and the use visualizations in physics learning (e.g. Rebello, et. al. 2004, 2007, Gire et. al, 2010). The proposed project builds on his ongoing work with Dr. Loschky on attentional cueing described in the pilot studies. As P.I., Dr. Rebello will have overall responsibility for the management of the project. This includes collaborating with the co-PI in the overall administration of the project including (i) developing professional expertise in the area of cognitive psychology, especially as it applies to physics education research; (ii) guiding the development of interview protocols, materials and rubrics; and (iii) supervising the graduate, undergraduate students and project assistant in all aspects of their work.

Dr. Lester Loschky (co-P.I.) Associate Professor of Psychology, has investigated both basic and applied topics related to the role of eye movements and attention in scene perception for the last decade. In the basic domain, he has investigated how our eye movements affect our memory for the objects in scenes and how people rapidly comprehend the "gist" of their surroundings. A key question he has looked at has been the role of peripheral vision in that process and how the limits of visual resolution in the visual periphery affect rapid scene comprehension. These questions stem from the fact that our visual experience is parceled out into discrete eye fixations in which both central and peripheral information contribute and also vie for attention. His research in the applied realm has thus investigated how vision, task performance and attention are affected by loss of peripheral image resolution in gaze-contingent multi-resolutional displays. Such displays push the technological envelope by using eye tracking to put high image resolution wherever the viewer is looking and lower resolution in their visual periphery. His research has been at the forefront of this area, which has applications to simulators, virtual reality, teleoperation and remote piloting. Dr. Loschky will be the P.I.'s mentor in the field of cognitive psychology. Dr. Loschky's responsibilities will include (i) advising the P.I. and graduate students on all aspects of the project; (ii) facilitating the professional development of Dr. Rebello in the field; and (iii) supervising group meetings of the Visual Cognition Laboratory.

Adrian Madsen nee' Carmichael (Physics GRA) is one of the graduate students working on the project. Her previous research has been on learning using physical and virtual manipulatives (Carmichael, et. al, 2010). She has already completed research on Pilot Study 1 and 2 (Carmichael, et. al. 2010; Stevens, et. al, 2011). Research completed on the proposed project will constitute Ms. Madsen's Ph.D. dissertation.

Adam Larson (Psychology GRA) is the other graduate student working on this project. His research is on the role of eye movements in scene and event perception. He has co-authored five peer-reviewed journal articles in the area of visual cognition, two of which are related to this project (Carmichael, Larson, et. al. 2010; Stevens, Carmichael, Larson, et al., 2011). He has been a critically important collaborator on both Pilot Study 1 and 2 and will remain so on this project. He will bring to bear his experience in scene and event perception as it bears on this project.

Advisory Board: An advisory board of two expert cognitive psychologists and one physics education researcher with experience in cognitive psychology, will provide external guidance, feedback and evaluation on the project activities. The board will meet with the project team toward the middle of the first and second years of the project. The team members and their qualifications are described below.

David Irwin Professor of Psychology, Univ. of Illinois, is an expert in the area of visual cognition and eye movements. His research has investigated how attention and eye movements influence what people remember from a single glance at a scene and how people combine information in visual short-term memory across eye movements. More recently he has been investigating the effects of eye movements on cognitive processing. Dr. Irwin's insights arising from his research in this area will be particularly useful to our project.

Brian Ross Professor of Psychology, Univ. of Illinois, has focused his research on how people learn new concepts in the course of problem solving, how they categorize problems and how the way in which the categories are used affects learning. More recently, he has collaborated with Dr. Jose Mestre on studies of visual cognition in physics education research (PER).

Jose Mestre Professor of Educational Psychology & Physics, Univ. of Illinois, has extensive experience in PER. His current work is at the interface of cognitive science, such as visual cognition and PER. Using techniques common in cognitive science such as eye tracking, his research has focused on details about how both experts and novices store, retrieve and apply knowledge. His most recent research is on the role of misconceptions in comprehending scientific text, visual processing of diagrams in problems and conceptual problem solving. Dr. Mestre's extensive experience in both PER and cognitive psychology will be invaluable to this project which also lies at the interface of these two disciplines.

Timeline: The timeline for the project is shown below. The requested start date is January 1, 2012 and the duration is 24 months.

Project Activities	**Spring 2012**	**Sum 2012**	**Fall 2012**	**Spring 2013**	**Sum 2013**	**Fall 2013**
Participate in Vision Cognition Group Mtg.	X	X	X	X	X	X
Participate in Cognitive Psych. Brown Bag	X		X	X		X
Plan Study 1	X	X				
Meet with Advisory Board		X				
Implement Study 1		X	X			
Analyze Study 1 & Plan Study 2			X	X		
Participate in Advanced Cog. Sci. Seminar			X			X
Prepare Publications on Study 1			X	X		
Meet with Advisory Board			X			
Implement Study 2				X	X	
Analyze Study 2					X	X
Prepare Publications on Study 2					X	X
Prepare Final Report						X

The plan above includes professional development and research activities. Participation in conferences is not included above because we have yet to decide on the specific conferences that we will attend.

Expected Measurable Outcomes

The goals, activities and measurable outcomes which serve as benchmarks of success for both research and professional development activities are described below.

Research

Goal	Activity	Measurable Outcome
Identify the differences in eye movements of experts and novices on physics problems with strong visuospatial elements.	Study 1: Measure the eye movements of experts and novices on a set of physics problems. Measure the differences in mean dwell times in thematically relevant and perceptually salient areas for both groups.	Determine whether there is a significant ($\alpha = 0.05$) difference between the dwell times in each area for each group.
On such problems, determine whether visual cueing can improve problem solving accuracy of novices.	Study 2: Comparison of four novice groups: three cued groups, one non-cued. Measure differences in problem solving accuracy and eye movements on the transfer problem.	Determine if there is a significant ($\alpha = 0.05$) difference between groups in change of problem solving accuracy and eye movements after practice problems.

Professional Development

Goal	Activity	Measurable Outcome
Learn the culture of cognitive psychology, particularly vision cognition, the cannons of the field and contemporary issues.	Participate in meetings of the Vision Cognition Group, Applied Cognitive Science Seminar and Cognitive Psychology Brownbag as well as network with other people in the field at conferences.	Read at least 30 canonical published works in the field of Cognitive Psychology.
Become knowledgeable about common avenues and standards for publishing in cognitive psychology and become a critical reader of that literature.		Jointly, with Dr. Loschky, prepare at least four talks at conferences such as *Psychonomics*, *Cognitive Science*, and two papers in a journal such as *Journal of Educational Psychology*.
Develop the knowledge and skills necessary to design valid and reliable experiments that utilize theory and methods in cognitive psychology.	Design and implement the studies and gain hands-on experiences with the use of the eye-tacking equipment, data collection and analysis.	Independently complete all steps in the design of valid and reliable experiments and analysis of the data from these two studies.
Apply the above knowledge and skills to his ongoing work in PER and explore the possibilities offered by cognitive psychology to take this work in new directions.	Network with other members of the cognitive psychology community at conferences and explore areas of collaboration.	Develop plans for at least one innovative research proposal at the interface of cognitive psychology and PER and build on the studies completed in the current project

Project Evaluation Plan

The Advisory Board consists of two expert cognitive psychologists (Drs. David Irwin and Brian Ross) and one expert physics education researcher who also works at the interface of cognitive psychology (Dr. Jose Mestre).

The Advisory Board meets with the project staff over two Skype conferences during the project – the first is during the planning of Study 1 and the second during the planning of Study 2. The Advisory Board examines plans for the two studies before the studies are implemented. Further at the end of the project, the Advisory Board will be provided the annual and final project reports before these reports are submitted to NSF, and will provide their input for these reports. Specifically, the Advisory Board provides formative feedback to the project staff regarding the degree to which the project objectives are being met by assessing: 1) the viability of the research studies to be completed by the project, 2) the progress in professional development of the P.I. and 3) the project's overall contributions to the body of knowledge at the interface of cognitive psychology and physics education research. The overarching questions below guide this effort.

- Describe how the project activities are advancing toward the research and professional development goals? What strategies and specific activities account for this progress?
- Are the methodology and results of the research studies valid and reliable?
- How has the project contributed to the knowledge base of visual cueing that can be utilized in physics problem solving?

Formative evaluation will be utilized to provide regular feedback to project leadership regarding progress. The summative evaluation will assess overall project success as documented through:

- Examining the project documentation and research activities of the project and aligning them with the goals and objectives of the project.
- Validating the research data and the outcomes of the developed studies.
- Examining potential for replication and extension of the studies.
- Assessing the contributions of the project to serve as a model for applying the theory and methods of cognitive psychology to physics education research.

The project team members work with the Advisory Board to coordinate the overall project evaluation. Input from the project team will be included in the annual and final reports submitted to NSF.

Project Dissemination Plan

Research from the project will be disseminated through talks and posters at conferences attended by researchers both in the cognitive psychology fields and science/physics education fields. These include *Psychonomics Society*, *Cognitive Science Society*, *Eye Tracking Research & Applications* as well as *Physics Educations Research Conference, National Association for Research in Science Teaching* and *American Educational Research Association*. The P.I. will definitely attend at least one conference in cognitive psychology each year.

Additionally we will also present our research in peer-reviewed journals in areas that overlap between the two fields. These would include *Journal of Educational Psychology,* and *Learning and Instruction*. We anticipate at least one journal article in each of these journals before the end of the project period. Finally, we will maintain an up-to-date website where our papers, talks and posters will be available to the general public.

Results of Prior NSF Support

We describe below results from our most recent NSF supported project in the area of problem solving, which is most relevant to proposed project.

REC 0816207 $999,955 09/01/2008 – 12/31/2011 P.I. Rebello

Investigating trajectories of learning & transfer of problem solving expertise from mathematics to physics to engineering

Main Findings: This project is a step in creating a knowledge base on the evolution of students' problem solving skills as they progress from mathematics to physics to engineering courses in the undergraduate curriculum. Our results indicate that in all three disciplines students are able to master procedural knowledge. However, they do not necessarily develop a deep conceptual understanding. This issue pervades all three disciplines.

In mathematics, the students have difficulty gaining conceptual understanding beyond the action and process levels of a mathematical concept. In other words, students, even after three semester of calculus do not develop an 'object' or 'schema' level understanding of mathematical concepts, as per the APOS framework (Dubinsky, 1992). Students may pass the courses by mastering the procedures without mastering the concepts of mathematics and learning how to transfer them to different situations (Bennett, Moore & Nguyen, 2011).

In physics, students can 'crunch through' the math, but they have difficulty with the physical interpretations of mathematical notations and operations. In particular, we see improvement in students' understandings of integral as an area underneath a curve, however few students display an understanding of integral as a process of accumulation (Nguyen, 2011a, 2011b). Similarly, students also struggle with the use of graphs in physics sense making (Gire, et. al, 2010).

When students move into engineering they appear to have a misdirected understanding of 'area under the curve,' properties of functions, time shifts and other concepts that they appear to have had a clear understanding of in their mathematics class (Chen, et. al., 2011).

One key issue is that students seem to be much more adept at applying graphical information to accumulation problems posed during mathematical interviews than they are during physics or engineering interviews. In particular, we have found problems that are mathematically identical where students can do the problem in the context of mathematics but are unable to solve the same problem when posed in the context of physics or engineering.

The issue however, is not that students have difficulty recalling concepts. Our interviews indicate that they can recall the mathematical concepts quite easily. The issue is deeper, they have difficulty activating the right conceptual resources within the contexts of the physics or engineering problem. In other words, they appear to have learned the math concepts insofar as applying them to problems in a math course, but later when they transition to a physics or engineering course, they need considerable scaffolding to do so. The use of attentional cueing, which is the topic of research in the proposed project can also be considered to be a form of scaffolding to help students activate the appropriate prior knowledge to solve the problem.

In addition to investigating students' difficulties with problem solving and transfer in these three courses, we have also investigated the use of instructional strategies to address students' difficulties with activating the mathematical concept in the context of physics and engineering.

In the focus group interviews in physics we have created several collections of problems and hints that show some preliminary success in helping students solve problems in multiple representations. Each collection combines abstract mathematical scaffolding, student evaluation of different lines of reasoning and student creation of complex problems. Using a treatment group, control group and pre-post quasi-experimental design we have shown robust improvements in students skills of transferring mathematical concepts to physics problems (Nguyen & Rebello, 2010). We have also developed online learning modules in engineering to help students with their conceptual difficulties. For the online learning modules in engineering, significant correlations between module scores, grades on written examinations and performance in previous mathematics courses have demonstrated variable clarity, but qualitative assessments of the technology-facilitated environment point to a clear increase in student learning and engagement (Chen & Warren, 2011).

Research Output & Human Capacity Development: Overall, the project has advanced the state of knowledge of conceptual difficulties that students face as they attempt to transfer their knowledge of mathematics to problem solving in physics and engineering. The project has led to 15 peer reviewed publications and 20 talks at conferences. Two graduate students will complete Ph.D.s in Mathematics Education and Physics Education based on their work completed on this project.