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How does representational competence develop? Explorations using a fully controllable interface and eye-tracking

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Abstract: Representational competence (RC), defined as "the ability to simultaneously process and integrate multiple external representations (MERs) in a domain", is a marker of expertise in science and engineering. However, the cognitive mechanisms underlying this ability, and how this ability develops in learners, are poorly understood. In this paper, we present a fully manipulable interface, designed to help school students develop RC, and a pilot eye and mouse tracking study, which sought to develop a detailed understanding of how students interacted with our interface. We developed an analysis methodology for eye and mouse tracking data that characterizes the interaction process in analytical terms, and operationalizes the process of MER integration. We present preliminary results of applying our analysis methodology to student data obtained in our pilot study.

Keywords: multiple external representations, representational competence, distributed cognition, embodied cognition, equations, graphs

1. Introduction and Related Work

Representational competence (RC) is defined as "the ability to simultaneously process and integrate multiple external representations (MERs) in that domain" (Pande and Chandrasekharan, 2014). MERs are used extensively in science and engineering, and students have difficulties in learning owing to problems in working with MERs (Pande and Chandrasekharan, 2014 has a review). Students understand and are able to use and generate graphs and equations independently (Sherin, 2001; Hammer, Sherin and Kolpakowski, 1991). However students often have difficulty understanding how the two representations are related and can be used together (Kozma and Russell, 1997; Knuth, 2000). This indicates that there is a clear need for development of RC among students.

Computer interfaces with MERs have been widely used for the improving conceptual, phenomenon and procedural understanding in science and engineering (Rutten, van Joolingen and van der Veen, 2012). Despite this, the effectiveness of available computer interfaces for learning has been mixed (Ainsworth, 2006; Rutten, van Joolingen and van der Veen, 2012; Bodemer et al, 2004). One possible reason for this is that interface design is currently guided by information processing theories of cognition, wherein the role of the interface is to decrease the learner's cognitive load, particularly working memory load (Ainsworth, 2006; van der Meij and de Jong, 2006). However, emerging theories, such as distributed and embodied cognition (Glenberg, Witt and Metcalfe, 2013), postulate that external representations play more roles than decreasing cognitive load (Kirsh, 2010; Kirsh and Maglio, 1994). Further, actions could be a way of promoting integration of MERs (Chandrasekharan, 2009). Tangible interfaces, based on embodied cognition theories, have been used for learning (Marshall, 2007). But there is no consensus on how such representations should be combined for effective integration, the benefits of various approaches, or the cognitive effects of combining representations (Marshall, 2007).

Finally, there is a dearth of research which focuses directly on the development and assessment of RC using computer interfaces. Examples are Johri and Lohani (2011), Stieff, Hegarty and Deslongchamps (2011) and Wilder and Brinkerhoff (2007), and these are also based on working memory load design principles. Approaching the RC development problem from new theories of cognition could help in developing better interaction designs that facilitate MER integration.

In this paper, we report on the design of such a computer interface. We applied insights from embodied and enactive theories of cognition, particularly common coding and tool use (Maravita and Iriki, 2004) and theories of how building and manipulation of external models could lead to conceptual change and discovery (Chandrasekharan, 2009) to identify interaction features that will result in the integration of MERs and the development of RC.

The interface is designed for self-learning by a grade 7 student, and includes specific tasks that encourage exploration. We developed a stable initial prototype of the interface and performed a pilot study to understand the interaction process in detail. We recorded student eye movements and mouse clicks using an eye-tracker with the goal of developing a way to capture the RC development process. Our specific research question (RQ) was: "How can eye tracking data analysis give us more insight into the process and mechanism of MER integration?"In this paper, we report preliminary results of our ongoing work towards answering this RQ.

2. Design of the Interface

We chose the concept of oscillation of a simple pendulum as the medium to examine the development of RC. This is because the concept is easy to understand for a 7^{th} grade student, and we didn't want conceptual complexity to interfere with the learners' integration of representations.

Our learning objectives (LOs) for this interface were that the student should understand (i) the idea of equation and graph as dynamic entities (ii) the idea of equation as a controller of systems, and (iii) different numerical-spatial and dynamic-static transformations and develop an integrated internal representation, consisting of the physical system, equation and graph.

Our design, unlike simulation models with similar elements, such as Netlogo (Wilensky, 1999) and PhET (Perkins et al, 2006), is derived from basic research, particularly education research examining RC, and recent cognitive science theories and models, including distributed and embodied cognition, that investigate the cognitive roles played by different kinds of representations and their underlying cognitive/neural mechanisms (Marshall, 2007; Kirsh, 2010; Kirsh and Maglio, 1994; Chandrasekharan, 2009). One feature derived from basic cognition research is the full manipulation of the interface, which seeks to promote integration of MERs. This link is derived from an embodied cognition idea - that actions and manipulation, i.e. motor control, requires integrating multiple cognitive and perceptual inputs, and feedback loops. This suggests that actions and manipulations performed on MERs in an interface would trigger/prime the neural processes involved in integration of inputs; thus it would help in integrating the multiple representations as well. This line of thinking led to making the equation components manipulable. This also introduces the controller role of the equation, a feature not seen in other interactive visualizations.

In this design, students control and 'enact' the equation, and integration is hypothesized to result from this control feature. Thus the (eventual) testing of the development of RC based on our design would also involve testing this hypothesis, and by extension, the cognitive theory that underlies it. Applying these cognitive theories to our interface leads to features such as full learner manipulation of the pendulum via clicking and dragging, controlling the equation parameters using vertical sliders, and complete interconnection between the three modes. By contrast, a PhET pendulum simulation **Error! Reference source not found.** does not have the equation and graph, and there is only one interaction on the pendulum, while the other variable is manipulated via horizontal sliders. The design of the interface evolved through three iterations and was based on a set of design principles from distributed and embodied/enactive cognition theory (Kirsh, 2010, Kirsh and Maglio, 1994, Chandrasekharan, 2009) which are shown in Table 1, along with our operationalization of these principles. Other mappings are possible.

In order for the LOs to be met, students need to be able to do the following: (i) Map a physical system to a graph, (ii) Map a physical system to an equation and (iii) Map an equation to a graph. We designed a series of three tasks, requiring the student to manipulate the equation and pendulum to match a given graph. We hypothesized that these tasks were complex enough to result in extensive exploration and manipulation of the interface by the student, leading to the three representations being integrated.

Screenshots of the first two versions of the interface are shown in Figure 1, while a screenshot of the final version used in the pilot study is shown in Figure 2.

Table 1: Design principles and operationalization

Principle	Operationalization
External representations allow processing not possible/ difficult to do in the mind.	The interface plots the graph of the equation/motion of the pendulum for various lengths and initial angles of the pendulum.
Cognition emerges from ongoing interaction with the world.	The interface is fully manipulable, i.e., the learner can control the pendulum, equation and graph, to see how change in each affects the other elements.
Features of the world are used directly for cognitive operations. Hence the interface features should support integration directly.	The interface has the physical system, equation and graph, along with different numerical values. The dynamicity of elements, and their interconnections are made transparent, so that learners can integrate across spatial-numerical and dynamic-static modes.
The active self is critical for integration of features.	The exploration on the interface is guided by tasks which the learner must do.
Action patterns can activate concepts, hence actions and manipulations of the representations should be related to existing concepts.	The learner can interact with the pendulum by changing its length and initial angle by clicking and dragging the mouse. The parameters in the equation can be changed using vertical sliders - moving up/down increases/decreases parameter values. This is related to the finding that numbers are grounded by associating small magnitudes with lower space and larger magnitudes with upper space (Fischer, 2012). By contrast, a PhET pendulum simulation (Perkins et al, 2006) does not have the equation and graph, and there is only one interaction on the pendulum, while the other variable is manipulated via horizontal sliders. These interactions distinguish our interface from other variable manipulation simulations, wherein the mode by which values are changed (slider, input box or multiple options) is not relevant. Our interface seeks to make the learners do actions that mimic the behaviour of the system, so that the system can be 'enacted' - the learning is thus through a form of participation with the system.
The interface should allow coupling of internal and external representations.	The task requires student to match a given graph. Learners change the parameters of the pendulum/equation to generate the graph, and visually match the task graph to their graph. This develops learner's imagination and coupling between their internal model and the external representation.

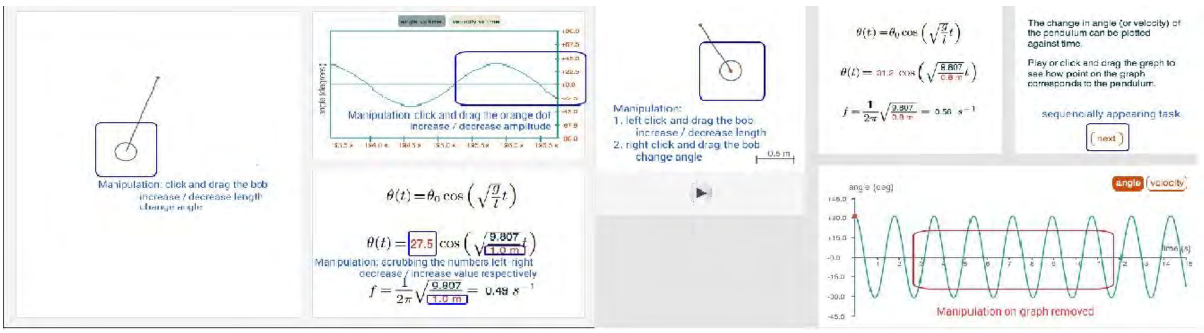

Figure 1. First version of interface (L). All 3 components (pendulum, graph and equation) are manipulable. The second version of the interface (R) only pendulum and equation manipulable.

3. Methodology

A pilot study was done with the broad research goal of developing an analysis methodology -- i.e. how to characterize interactions with our interface, and how to connect this to RC. Our specific RQ was, "How can eye tracking data give us more insight into the process and mechanism of MER integration?"

Our (convenient) sample consisted of twelve (6 female) 7th grade school students from two urban schools in Mumbai. Each student was allowed to work independently with the interface for as long as he/she wished, proceeding through the screens and tasks by clicking the "Next" button. When students had a question the experimenter provided appropriate hints. When the students indicated that the tasks were completed or that they wished to quit, they were interviewed regarding their background and their impressions of the interface. They were then administered an offline assessment task.

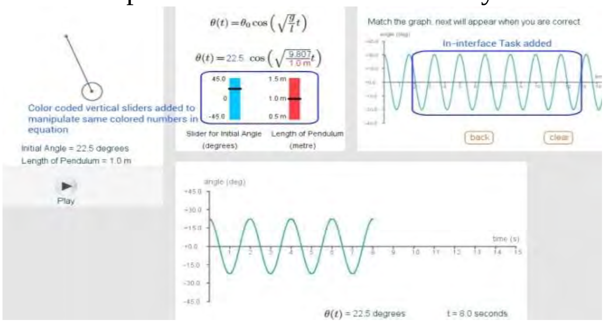

Figure 2. Final interface with sliders and tasks

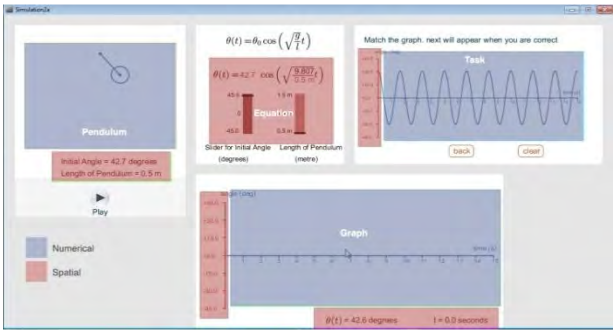

Figure 3. AOIs used for the analysis.

Our data sources were:

1. Eye Tracker: Eye movements recorded using a Tobii X2-60 (static) eye-tracker, capturing how students' loci of attention shifted as they explored the interface.
2. Assessment task: To evaluate the extent to which students are able to imagine and mentally simulate the movement that they observed on the interface. Consisted of 3 multiple choice questions, asking students to imagine the position of the pendulum from the graph, and 3 marking questions, asking students to mark points on the graph corresponding to the pendulum's position.

4. Analysis Approach

The goal of our analysis is to pull out interaction patterns from eye and mouse tracking data and explore what it means for a learner working with our interface to develop the thinking skill of RC. For this, we needed to identify patterns in the student interaction that could be markers for integration of MERs. To do so, areas of interest (AOIs) as depicted in Figure 3 were defined, and the eye fixation and mouse click co-ordinates in the respective AOIs were extracted from the eye-tracker. The data was analyzed at multiple levels of abstraction as shown in Figure 4.

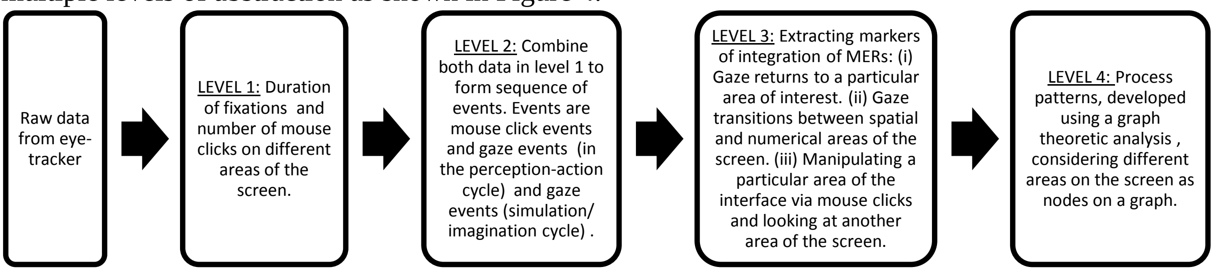

Figure 4: Levels of Analysis

The data obtained from the eye tracker includes eye fixation durations and number of mouse clicks on different areas of the screen (level 1 analysis). In level 2, we determine sequences of fixation events and mouse click events, and classify them into events occurring in the perception-action cycle, and events occurring in the simulation/imagination cycle. The perception-action cycle refers to students manipulating features on the screen (e.g. sliders), playing the simulation, and looking at the dynamic features of the screen (for e.g. the plotting graph). The simulation/imagination cycle (or thinking) happens when the simulation is paused and involves students looking at the static features on the screen (e.g. length/angle values and the graph).

In level 3 analysis, we define markers that signify integration, and abstract out the data further to calculate these markers. An example of a marker is returns, i.e. a learners' eye gaze returning to a particular area of interest after going elsewhere, as this indicates that the learner is retaining a particular feature in memory and returning to it. A second example is eye gaze transitions between a numerical area on the screen (e.g. the equation) and a spatial area on the screen (e.g. the graph) as this specifies integration between numerical and spatial modes. The third example is the learner manipulating a feature on the screen (e.g. pendulum) and looking at another area of the screen (e.g. graph) as this indicates the integration of two representations via the systematic variation offered by control. Once these markers are obtained, we define a goodness measure for these markers by comparing against marker values of experts, or marker values of learners who perform well on the assessment tasks.

The final stage of abstraction is to generate process patterns of how the learners interacted with the interface, using a graph theoretic framework, wherein the AOIs are the nodes and the transitions between the various AOIs are the weights of the branches. The duration of returns, and the sequence in which returns occurred, will also be added to this graph. These graphs will then be compared to the graphs of experts or learners who perform well on the assessment tasks to evaluate learner process. The comparison of graphs is a complex problem, and this is not implemented yet. Thus, results of the analysis at levels 2, 3 and 4 will answer our RQ, "How can eye tracking data analysis give us more insight into the process and mechanism of MER integration?" by allowing us to correlate interaction behaviours such as returns with MER integration (i.e. high performance on the assessment tasks).

5. Indicative results

For lack of space, in this paper we present indicative results, applying our analysis methodology to the data of one student who performed well on the assessment task. This is ongoing work, and we have not completed the level 4 analysis, and correlated the results to assessment task performance, which would give us an answer to our RQ. The data at level 1 of analysis, namely fixations and mouse clicks, is reported elsewhere (Majumdar et al, 2014). Here we report analysis of the fixation data at levels 2 and 3. Figure 4 shows an example event sequence for the learner between two consecutive clicks on the play button and the legend is shown in Figure 7 (also see AOIs in Figure 3). The sequence of events between the play and the pause button are events in the perception/action cycle, while events after the pause button are in the imagination cycle. This sequence shows that the student transitions between spatial and numerical regions both in the action and imagination cycles.

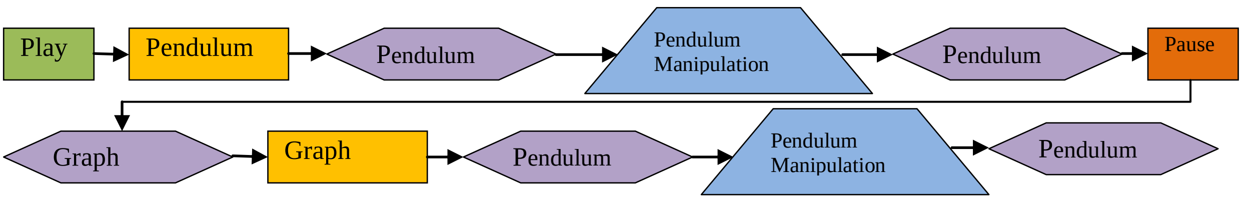

Figure 4: An example of a sequence of events for a good performing student

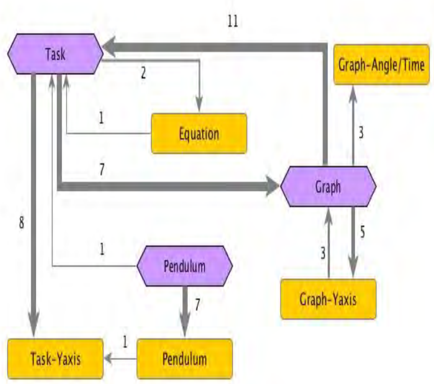

Figure 5: Numerical-Spatial Returns

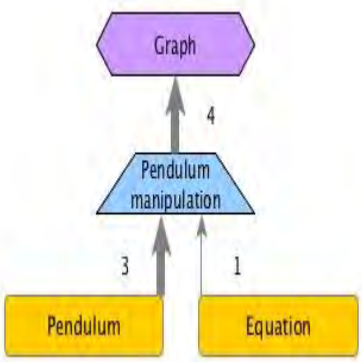

Figure 6: Click-gaze transitions

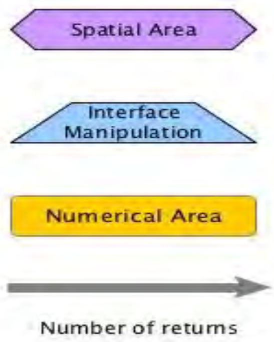

Figure 7: Legend for figures 4, 5 and 6

Next we present two markers of integration at level 3 of the analysis. The first is eye gaze transitions between numerical and spatial areas on the screen (Figure 5) and the second is the transitions between mouse clicks and eye gazes on different areas of the screen (Figure 6). In these figures, the thickness and numbers on the arrow from A to B indicates the number of A-> B-> A transitions made by the student. For instance, Figure 4 shows that this student looks from the spatial area of the graph to the spatial area of the task and returns 11 times. In the final level of analysis, the return data will be combined with duration of each return, to create a rich graph representation of the students' interaction process, which will then be compared to the processes of an expert and a low-performing student.

6. Conclusions and Future Work

In this paper, we presented the design of an embodied computer interface for the development of RC. We evaluated the interface in a pilot study, developed an analysis methodology for extracting process patterns (i.e. how students interacted with our interface) from eye and mouse tracking data and evaluating how these process patterns translate to MER integration. We also presented preliminary results using this analysis. Once complete, our methodology becomes a template for analyzing the process of how learners interact with a new design, using eye and mouse tracking and evaluating whether MER integration occurs using that design.

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