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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, is poorly understood. In this paper, we report 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, 2013, Kirsh and Maglio, 1994). Further, actions could be a way of promoting integration of MERs (Chandrasekharan, 2009). Tangible interfaces, based on theories of embodied cognition, have been used for learning (Marshall, 2007). But there is no consensus on how representations should be combined on them 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 with the 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 an analysis methodology for characterizing the development of RC using eye tracking data. Our specific research question (RQ) was: "How can eye tracking data and the analysis methodology give us more insight into the mechanism of integration which results in development of RC?"

2. Design of Interface

We chose the concept of oscillation of a simple pendulum as the medium to examine the development of RC because of ease of understanding for a 7th grade student and we didn't want the complexity of the concept to interfere with the learners' integration of representations.

The design of the interface evolved through three iterations and the principle guiding our design was manipulability and sense of control, which seeks to promote integration of MERs. Thus the main feature of our design is the full manipulation of the interface, including the equation components; this introduces students to the controller role of the equation, meaning that they understand that changing the values in the equation can change the way the physical system behaves, a feature not seen in simulation models such as Netlogo (Wilensky, 1999) and PhET (Perkins et al, 2006). Table 1 has the list of design principles from distributed and embodied/enactive cognition theory (Kirsh, 2013, Kirsh and Maglio, 1994, Chandrasekharan, 2009) and their operationalization.

We began by deciding the action sequence that would support embodiment and the features/interactions that are needed on the interface for this action sequence. Based on this an initial interface was developed as shown in Figure 1. Next, we evaluated the initial interface against literature and theory, and modified the action sequence. In order to incorporate structured feedback to the learner during manipulation (as feedback is necessary to complete any action), we ensured that the pendulum, equation and graph appear sequentially and to ensure too much is not happening at the same time, we removed the manipulation from the graph. The modified interface is shown in Figure 1.

In the final iteration, we decided the learning objectives (LOs) of the interface, which guided the development of the tasks. Our LOs for this interface were that the student should develop (i) a dynamic understanding of equations, (ii) an understanding of equations as controllers and (iii) an integrated internal representation, consisting of the physical system, equation and graph.

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.
The features of the world are used directly for cognitive operations, hence the interface should have all the features needed for integration of representations.	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	The exploration on the interface is guided by tasks which the

integration of features.	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. This interaction is meant to mimic the interaction with a real pendulum. The parameters in the equation can be changed using vertical sliders - moving up indicates increase in parameter, moving down indicates decrease. This is because it is known 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.
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 and the external representation.

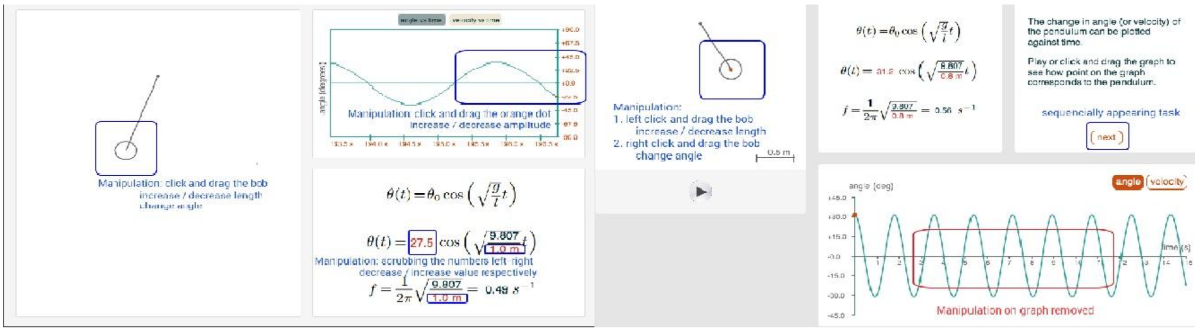

Figure 1. First iteration of interface design (L). All 3 components (pendulum, graph and equation) are manipulable. The second iteration of the interface (R) only pendulum and equation manipulable.

In order for these 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, so that the three representations are integrated.

Another significant change in this iteration was that the left and right "scrubbing" action to change the equation parameters was replaced by vertical sliders, as it is known that small magnitudes are associated with lower space and larger magnitudes with upper space (Fischer, 2012). These interactions distinguish our interface from other variable manipulation simulations, e.g. PhET (Perkins et al, 2006), in which the mode by which values are changed (slider, input box or multiple options) is not relevant. Our interface is designed to make the learners do actions which mimic the behaviour of the system so that it can be 'enacted' - the learning is through a form of participation with the system.

After adding the tasks to the interface and making the final interaction changes, the interface was ready for piloting. A link to the final prototype used in the current study will be made available in the camera-ready version if this paper is accepted. A screenshot is shown in Figure 2.

3. Methodology

We performed a pilot study with the broad research goal of developing an analysis methodology to characterize what it means for the thinking skill of RC to be developed by interacting with our interface. Our specific RQ was, "How can eye and mouse tracking data and the analysis methodology give us more insight into the mechanism of integration which results in development of RC?"

Our sample consisted of twelve (6 female) 7^{th} grade school students from two urban schools in Mumbai. The sampling was based on convenience.

Each student was shown the interface and allowed to work independently with it for as long as he/she wished, proceeding through the screens and tasks by clicking the “Next” button. The experimenter intervened only when students had a question and provided appropriate hints. When the student indicated that the tasks were completed or that they wished to quit, they were interviewed regarding their background, their impressions of the interface and administered an assessment task.

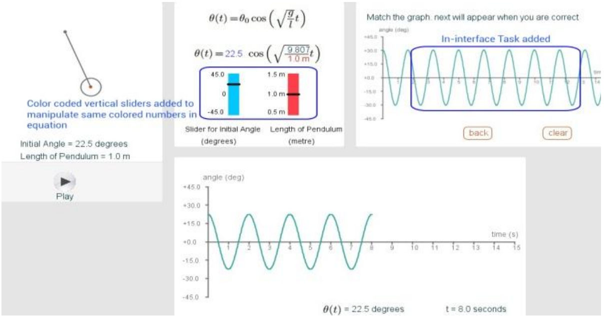

Figure 2. Final interface with sliders and tasks

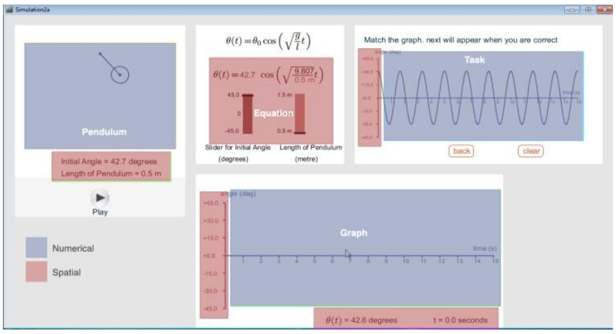

Figure 3. AOIs used for the analysis.

Our data sources were,

1. Eye Tracker: Students’ eye movements were recorded using a Tobii X2-60 (static) eye-tracker, in order to capture how their loci of attention shifted as they explored the interface. This data could help decipher the dynamic process involved in integration.
2. Assessment task: The assessment task attempted to evaluate the extent to which students are able to imagine and mentally simulate the movement that they observed on the interface. The task consists of 6 questions, 3 multiple choice questions which ask students to imagine the position of the pendulum from the graph, and 3 marking questions which ask 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. So we must 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.[1] The data was analyzed at multiple levels of abstraction as shown in Figure 4.

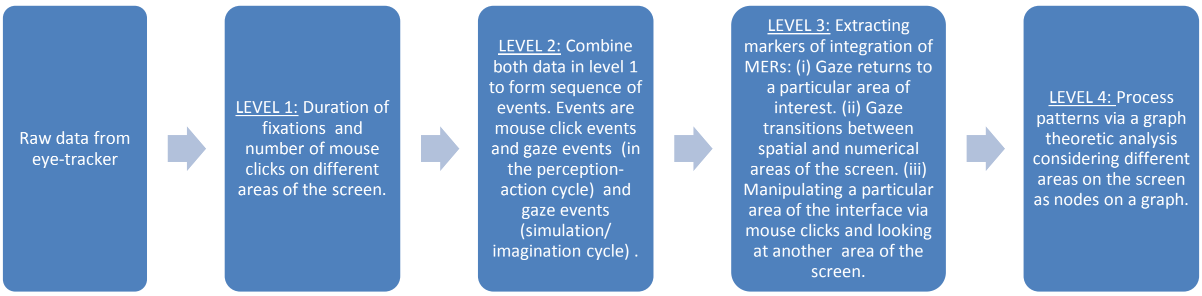

Figure 4: Levels of Analysis

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

[1] The statistical outputs do contain systematic errors to a certain degree arising out of calibration accuracy/precision differences among individuals and loss of gaze data points due to blinks, proximity to the laptop screen, rapid head-movements, or moving out of the eye-tracking zone, etc. However, such errors are consistent across all participants.

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 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 manipulating features on the screen (e.g. dragging the pendulum) and looking at the static features on the screen (e.g. length/angle values).

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 perception and action. Once these markers are obtained, we can define a goodness measure for these markers by comparing against the marker values of experts or against the marker values of learners who perform well on the assessment tasks.

The final stage of abstraction is to generate process patterns for the interaction of learners 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. These graphs can then be compared to the graphs of experts or learners who perform well on the assessment tasks to evaluate learner process.

5. Indicative results

For lack of space, in this paper we present indicative results by applying our analysis methodology to the data of one student who performed well on the assessment task. The data at level 1 of analysis, namely fixations has been reported elsewhere. In this paper, 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.

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, from Figure 4 we observe that this student looks from the spatial area of the graph to the spatial area of the task and returns 11 times. At present we don't have a comparison for these numbers, but in future work we will compare these numbers to the numbers of experts and those of a low performing student.

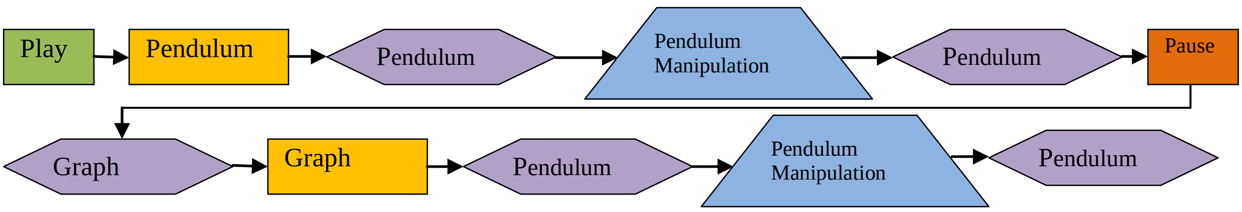

Figure 4: An example of a sequence of events for a good performing student

In the final level of analysis, the return data will be combined with duration of each return in order to create a rich graph theoretic representation of the students' interaction process which can then be compared to an experts' process and against a low performing student.

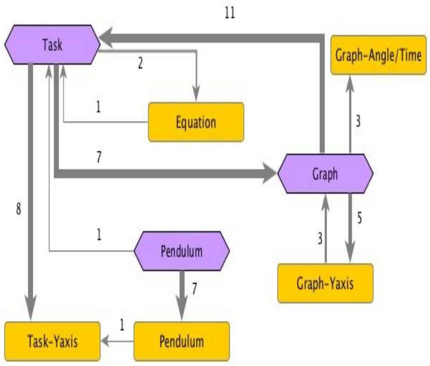

Figure 5: Numerical-Spatial Returns

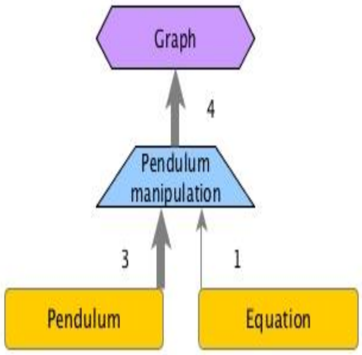

Figure 6: Click-gaze transitions

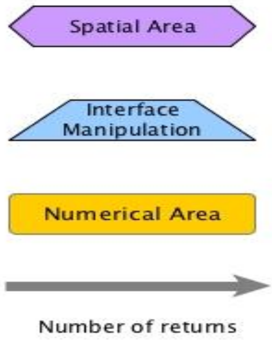

Figure 7: Legend for figures 4,5 and 6

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 patterns of student interactions that signify RC development from eye and mouse tracking data, and presented preliminary results using this analysis. Once complete our methodology becomes a template for any interaction design and analysis of interaction using eye and mouse tracking.

References

Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. Learning and Instruction, 16(3), 183-198.

Pande, P., & Chandrasekaran, S., A general account of representational competence, Unpublished.

Sherin, B. L. (2001). How students understand physics equations. Cognition and instruction, 19(4), 479-541.

Hammer, D., Sherin, B., & Kolpakowski, T. (1991). Inventing graphing: Meta-representational expertise in children. Journal of Mathematical Behavior, 10, 117-160.

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. Journal of research in science teaching, 34(9), 949-968.

Knuth, E. J. (2000). Student understanding of the Cartesian connection: An exploratory study. Journal for Research in Mathematics Education, 500-507.

Rutten, N., van Joolingen, W. R., & van der Veen, J. T. (2012). The learning effects of computer simulations in science education. Comp & Edu, 58(1), 136-153.

Bodemer, D., Ploetzner, R., Feuerlein, I., & Spada, H. (2004). The active integration of information during learning with dynamic and interactive visualisations. Learning and Instruction, 14(3), 325-341.

van der Meij, J., & de Jong, T. (2006). Supporting students' learning with multiple representations in a dynamic simulation-based learning environment. Learning and Instruction, 16(3), 199-212.

Johri, A., & Lohani, V. K. (2011). Framework for improving engineering representational literacy by using pen-based computing. Int. J. Engg Edu, 27(5), 958.

Stieff, M., Hegarty, M., & Deslongchamps, G. (2011). Identifying representational competence with multi-representational displays. Cogn & Instr, 29(1), 123-145.

Wilder, A., & Brinkerhoff, J. (2007). Supporting representational competence in high school biology with computer-based biomolecular visualizations. J. Comp. in Math. and Sci. Teaching, 26(1), 5-26.

Glenberg, A. M., Witt, J. K., & Metcalfe, J. (2013). From the Revolution to Embodiment 25 Years of Cognitive Psychology. Perspectives on psych sci, 8(5), 573-585.

Marshall, P. (2007). Do tangible interfaces enhance learning? In Proc 1st int conf on Tangible and embedded interaction (pp. 163-170). ACM.

Kirsh, D. (2013). Thinking with external representations. In Cognition Beyond the Brain (pp. 171-194). Springer London.

Kirsh, D., &Maglio, P. (1994). On distinguishing epistemic from pragmatic action. Cog Sci, 18(4), 513-549.

Chandrasekharan, S. (2009). Building to discover: a common coding model. Cog Sci, 33(6), 1059-1086.

Maravita, A., & Iriki, A. (2004). Tools for the body (schema). Trends in cognitive sciences, 8(2), 79-86.

Fischer, M. H. (2012). A hierarchical view of grounded, embodied, and situated numerical cognition. Cognitive processing, 13(1), 161-164.

Wilensky, U. (1999). Netlogo. Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, IL.

Perkins, K., Adams, W., Dubson, M., Finkelstein, N., Reid, S., Wieman, C., & LeMaster, R. (2006). PhET: Interactive simulations for teaching and learning physics. The Physics Teacher, 44(1), 18-23.