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Students Learning Paths in Developing Micro-Macro Thinking: Productive Actions for Exploration in MIC-O-MAP Learning Environment

Anura KENKRE* **& Sahana MURTHY**

Inter-Disciplinary Program in Educational Technology, Indian Institute of Technology Bombay, India

*anura.kenkre@iitb.ac.in

Abstract: MIC-O-MAP is a technology enhanced learning environment designed for developing micro-macro thinking skills in science and engineering topics at the tertiary level. Micro-macro thinking involves the analysis of dynamic microscopic and establishing co-relations to the outcomes that are measurable in the real or macroscopic world. Different students undertake multiple paths while interacting with MIC-O-MAP learning environment in an attempt to undertake the tasks of making predictions in the macro world, justifying them by establishing a micro to macro link. The focus of this study is to investigate how different students' interactions in MIC-O-MAP leads to *productive actions,* i.e actions that are effective in their learning of micro-macro thinking. A grounded theory approach has been adopted for analyzing the screen capture recordings of students as they explore MIC-O-MAP, along with semi structured interviews in order to infer these actions.

Keywords: micro-macro thinking, MIC-O-MAP, productive actions

1. Introduction

Science and engineering graduates are expected to not only learn domain knowledge but also develop scientific skills such as formulating questions, designing and conducting experiments, collecting, representing and analyzing data, modeling, creating and testing hypotheses (Crowley, et.al., 2001). Learning how to relate microscopic models to macroscopic phenomena, here referred to as micro-macro thinking, is an important skill to be developed as it will help to bridge the gap between theory and experiment. Making such connections has been found to be problematic for students (for example, Eilam, 2004; Gilbert & Treagust, 2009). Substantial effort has been put in by researchers in developing technology enhanced learning (TEL) environments to address student learning of scientific thinking skills, some examples being: WISE, WiMVT, Model-It, Sim Quest, Modeling Space, nQuire, Inquiry Island, virtual environments such as Co-Labs, Go-Labs etc (Slotta, 2004; Sun, & Looi, 2013; Fretz, et.al., 2002; Van Joolingen & De Jong, 2003; Avouris, et.al., 2003; Mulholland, et.al., 2012; White, et.al., 2002; van Joolingen, et.al., 2005; Govaerts, et.al., 2013). Several of these efforts have reported successful outcomes.

We define 'micro-macro thinking' as the ability to establish a link between theoretical variables in a micro-world and its corresponding manipulable variables in a macro-world in order to predict the functionality of the system. The invisible processes/interactions on going at a microscopic level are referred to as a micro world and a real world tangible device/component is referred to as a macro world. In order to develop this skill of micro-macro thinking, it is important to develop the skills of making observations, predictions, testing predictions against experimental outcomes and revising predictions. Many of the TEL environments above have included the presence of a facilitator such as a teacher who guides the learning path of students to various extents. Using a design-based research approach, we have designed and developed a TEL environment MIC-O-MAP (MICroscopic-Observations-Macroscopic Predictions) to be used in self-learning mode with its focus on developing micro-macro thinking in science and engineering topics at the tertiary level.

Student-centered learning environments emphasize constructing personal meaning by relating new knowledge to existing conceptions and technology promotes access to these resources and tools that facilitate construction (Hannafin, & Land, 1997). A complex interaction then prevails among prior knowledge, perception of events, intents, actions, observations, and reflections attendant to on-going thoughts and actions (Land & Hannafin, 1996). Technology-enhanced student-centered systems thus rely on the learner to generate and implement individual learning plans. Prior studies with MIC-O-MAP have shown that even though students develop micro-macro thinking skills there exist differences in the learning paths of high and low scoring students. (Kenkre & Murthy, 2014). However, what is still unknown is *how* students develop micro-macro thinking skills as navigate through MIC-O-MAP. Thus the focus of this current study is to identify productive actions of students as they explore the learning environment and interact with various features and activities in it. By 'productive action', we mean those learner behaviors and interactions with MIC-O-MAP that can be correlated to the learning of micro-macro thinking.

The current study is takes a grounded theory approach and analyzes screen recordings of learners' interaction with MIC-O-MAP as well as the responses from follow-up semi-structured interviews. Findings from this study provide possible reasons for how a particular navigation path and learner interactions may lead to development of micro-macro thinking skill. Thus our study may provide guidelines for prospective designers of TEL environments on how to promote productive actions to maximize learning benefit of such TEL environments.

2. Background and Related Work

The practice of science and engineering requires students to establish a link between two levels. The macroscopic level comprises the tangible and visible and the microscopic level often comprises an invisible particulate level, such as the electrons, molecules, or atoms (Johnstone, 1982). Research shows that students have difficulty transferring from a macroscopic level of representation to the microscopic level (Gabel, 1998). It is important to have in-depth knowledge of the problematic features of micro–macro thinking and to understand what it is that is to be communicated to students and how this is best communicated to them (van Berkel, Pilot & Bulte, 2009).

Instructional interventions which target students' scientific thinking skills include WISE (Web-based Science Environment) which provides an Internet-based platform for middle and high school science activities (Slotta, 2004). Web-based inquirer with modeling and visualization technology (WiMVT) is based on the POE (Predict-Observe-Explain) principle (Sun & Looi, 2013). Model-It argues that students go through an inquiry cycle in the phases of Planning, searching, synthesis, analysis, explaining and evaluation (Fretz, et.al., 2002). Undergoing a similar inquiry cycle is proposed by nQuire and Inquiry Island (Mulholland, et.al., 2012; White, et.al., 2002). Learning Environments such as Co-Lab and Go-Lab also suggest similar phases of learning wherein students create hypotheses, evaluate them through experiments and then reflect on them, possibly repeating the cycle (van Joolingen, et.al., 2005; Govaerts, et.al., 2013). SimQuest promotes discovery learning and suggest following the WHAT-IF format (Van Joolingen & De Jong, 2003).

In these existing interventions, the teacher plays an important role by facilitating the process, giving prompts or grading the student‘s efforts at a later stage, such as in MARS (Raghavan & Glaser, 1995). Most of these solutions are focused on middle and high school science curriculum, while ISLE curriculum (Etkina & Van Heuvelen, 2007), which is mainly classroom-based has addressed high-school and introductory college courses.

In addition to large-N studies evaluating the effectiveness of TEL environments, researchers have conducted interaction analysis to identify how and why learners' interactions with the TEL environments and with peers have led to effective learning (for example, several chapters Puntambekar, Erkens, Hmelo-Silver, 2009 analyze interactions in CSCL environments).

3. MIC-O-MAP Technology Enhanced Learning Environment.

3.1 Development Methodology-Design Based Research (DBR)

We have used a design-based research methodology for the design and development of the MICroscopic Observations MAcrosocpic Prediction (MIC-O-MAP) learning environment. Design Based Research (DBR) is defined as a systematic but flexible methodology aimed to improve educational practices through iterative analysis, design, development, and implementation, based on collaboration among researchers and practitioners in real-world settings, and leading to contextually-sensitive design principles and theories (Cobb, 2003; van den Akker, Gravemeijer, McKenney, & Nieveen, 2006). The framework for the design of this MIC-O-MAP learning environment is based on theories from self regulated learning (Winne, 2001; Zimmerman & Schunk, 2001), question prompts (Ge & Land, 2004), scaffolding (Azevedo & Hadwin, 2005; Reiser, 2004) and formative assessment with feedback (Wiggins, 1989; Nicol & Macfarlane-Dick, 2006). We first conducted an exhaustive literature review in order to identify the features to be incorporated into the learning environment. Based on the experiments and the analysis of the data extracted from them, we refined and improvised the pedagogical features of our learning environment.

3.2 Features and Learning Activities in MIC-O-MAP

We have designed a technology enhanced learning environment MIC-O-MAP (MICroscopic-Observations-MAcroscopic Predictions) for the development of students' micro-macro thinking skill. We have developed modules in MIC-O-MAP for topics such as PN junctions, semi-conductors, photo-diodes, thermistors and so on, which are part of a first or second year curriculum both for Physics majors and for Electrical Engineering majors.

Figure 1 given below shows screen-shots of the important features of MIC-O-MAP in the topic of semi-conductors- PN junctions. This topic requires students to understand the working of the material on a microscopic level, such as motion of electrons, and apply this to predict macroscopic level outcomes seen in a lab experiment, such as voltage-current characteristics measured by meters.

Figure 1: Left to right- Simulation of microscopic model along with Prediction questions and pedagogical agent, Justification Box, Experimental Results for comparison and judgment, Scaffolding questions with customized feedback. Note taking & pedagogical agent present in each screen window.

Students are provided with the microscopic model of a phenomenon and are asked to interact with it with the help of variable manipulation. Macroscopic outcomes in a graphical format are presented to the learner simultaneously and they are asked to predict the graphical outcome on the basis of their observations in the microscopic model. Students are expected to link the micro-world observations to the macro-world graphical outcomes and phrase a justification for their choice of answer. Once the student has committed to an answer they are provided with the experimental outcome from a real world laboratory and they are asked to test their prediction by comparison of graphs and revise if required. At any point of time is the student needs assistance, then they are provided with scaffolding questions pointing them to key areas of the microscopic simulation that they might have missed.

3.3 Learning with MIC-O-MAP: Prior Studies

In previous studies we found that MIC-O-MAP helps in students' learning of micro-macro thinking skills (Kenkre, Murthy & Mavnkurve, 2014). We adopted a quasi-experimental research design (N=73) with first year undergraduate science and engineering programs from various colleges under Mumbai University, India as participants. The experimental group learnt with MIC-O-MAP for the topic of semiconductor PN junctions whereas the control group was given a simulation of the same microscopic phenomenon but without the scaffolds and prompts. We found that the experimental group scored significantly better on the post-test on micro-macro thinking, leading to the conclusion that MIC-O-MAP was effective in developing students' micro-macro thinking skills.

While students from experimental group studied the material, their screen activities were captured by My Screen Recorder software, screen-recording software. Post the study, all these screen capturers were analyzed and later coded in accordance with the interaction pattern observed. To understand possible reasons for the different time spent by students, we had compared the interaction behavior of students from the low and high scoring groups respectively. It was found that high scorers on an average try to establish a strong micro to macro link and then on the basis of this make an informed decision about the macroscopic graphical outcome (Kenkre & Murthy, 2014).

4. Research Method

The research questions being addressed in this paper is:

1) What are productive actions of learners as they explore the features and learning activities in rich, open-ended TEL environments?
2) How do these productive actions help learners acquire macro-micro thinking skills?

We addressed this research question using in-depth qualitative analysis of learners' interaction with MIC-O-MAP learning environment, combined with semi-structured interviews. Overall, the analysis followed a grounded approach (Strauss & Corbin, 1998) wherein interleaved transcripts of students' interactions and interviews were coded such that the codes and categories emerged from data, while guided by the above research question. Such a methodology is well suited to answer our research questions, since our goal is to gain insight into the processes by which student learning happens, and how interaction with the features of the TEL environment support these learning processes.

4.1 Participants and Procedure

Participants were students from the first year undergraduate science and engineering programs from various colleges under Mumbai University, India. In order to understand various student behaviors for this study, purposive sampling was conducted in the experimental group to obtain 10 participants who scored high on post-test after interacting with MIC-O-MAP.

A total time period of one hour was allotted to the students for learning the topic. The topic being learnt using the learning environment was P-N Junctions (forward biased) from the subject of physics. Students were asked to explore the learning environment, MIC-O-MAP, and attempt every learning activity in it (as described in Section 3.2). While they were learning the topic with MIC-O-MAP, their interactions were recorded using a screen capture software. At the end of the learning session, the recording was replayed to the students and semi-structured interviews were conducted. Questions were asked to elicit the connection of students' interactions in MIC-O-MAP to the learning objectives, i.e. their ability to establish and articulate the connections between micro- and macro-worlds).

4.2 Data Sources and Instruments

Students' on-screen activities were captured by My Screen Recorder software. Post the study, all these screen capturers were analyzed and later coded in accordance with the interaction pattern observed. This is known as Clickstream Analysis i.e. analyzing the record of screens or pages that user clicks on and sees, as they use a site or software product.

Semi-structured interviews were conducted right after students' interactions with the learning environment in order to gather an understanding into the thought process behind the choice of a particular learning path. Semi structured interviews contained questions such as, "Can you elaborate why you have opted to go back to this feature?", "In what manner is this feature helpful for finishing this task?", "Can you explain how are you phrasing this justification your prediction? Can you detail out how you managed to establish the micro-macro link?". Post recording the interview, the process of data analysis was undertaken, wherein the interview was transcribed, coded and categories were extracted out from the data. This helped in getting an insight into the experience of the user while interacting with the learning environment.

4.3 Data Analysis

The recordings of the screen captures and interviews were transcribed leading to a complete interleaved transcript of interviews and screen captures of each of the 10 students, amounting to 5-6 pages worth data per student. Focusing on the screen capture recording, we took note of which feature was viewed in order, one after another. Analysis of this provided us with the navigation path taken by students as they interact with MIC-O-MAP. The unit of analysis was one question by the interviewer and a corresponding answer by the student. Codes were allotted to each unit of analysis depending upon what was being reported- usability, purpose of visit and time spent. Initially new codes were allotted till saturation of these codes was reached, after 4-5 students transcript. Two raters coded the transcripts. Inter-rater reliability for the raters was calculated and the value of Cohen's Kappa was found to be 0.839 ($p<0.001$).

Students reported the usage of a particular feature of MIC-O-MAP for various learning goals. The interviewer at the same time took notes of the actual actions of the students while interacting with the learning environment in the recordings. Analysis of a mapping between the codes allocated and the navigation path taken by students gave rise to the productive actions when students learn with rich technology enhanced environments such as MIC-O-MAP.

5. Findings: Learner Actions and Learning Paths in MIC-O-MAP

We first present three illustrative cases of learner actions and behaviors as they interact with MIC-O-MAP. The first two cases reported here are those students who developed the micro-macro thinking skill whereas the last case is of a student who did not develop this skill inspite working with the same environment of MIC-O-MAP. An indication of the development of micro-macro thinking skill is their scores on the post tests. Also the interview transcript analysis for these chosen students were representative of productive action to be undertaken by learner while using MIC-O-MAP. The specific learning paths of the first two learners are different, yet each of these learners was seen to display productive underlying actions to develop micro-macro thinking. One case representative of a typical path undertaken by low scorers is also presented in end. The key point to be noted is that the last student who is a low scoring student, does not perform the productive actions undertaken by the high scoring students. This stands out as a crucial evidence for establishing a correlation between the productive actions performed by the learner and development of micro-macro thinking skill.

5.1 Case 1-High Scoring Student

Student-1 begins by interacting with the simulation of the micro-world and almost immediately goes to the prediction task. In the prediction task, in which he has to choose one correct graph out of four shown graphs, his cursor moves over and pauses on the graph in each option, however he does not commit to the prediction. He then goes back to the simulation of the micro-world and makes more minute and careful observations. After this, he commits to one graph. He then tries to phrase a justification, comes back to take a look at other options in prediction task, does not change initial answer and continues phrasing the justification. Then he comes to the testing phase, notices that the prediction is incorrect and goes to scaffolding questions. He reads all the options and feedback, deliberately moving and pausing between the words, indicating careful reading. He once again goes back and watches each and every part of the previous screen (as indicated by the cursor movement and corroborated in the interview). He repeats the action of going back and forth between the simulation of the micro-world, the prediction question and the scaffolding questions. This brings him to the summary phase where he writes a correct description of how the different representations are linked to each other. He also reads assumptions listed before stopping.

Given below is his corresponding navigation path:

SIM	PQ	SIM	PQ	SIM	PQ	SIM	PQ	SIM	PQ	JUS	PQ	JUS	RWA	SQ	PQ	SIM	PQ	SIM	PQ	JUS	RWA	SUM	ASM

Here, SIM- Simulation of the micro world, PQ- Prediction Questions, JUS- Justification of Prediction, RWA- Real World Answer, SQ- Scaffolding Questions, SUM- Summarization, ASM- Assumptions.

Summarized below is an excerpt from the interview transcript for Student-1:

Question by Researcher: Please share your entire experience while interacting with this module.
Answer by Student-1: Understanding improved using MIC-O-MAP as opposed to what is taught in class.
Q: Can you elaborate how you have made a choice of the graph?
A: I have followed whatever was suggested on top [*by the mentor agent in the system*]. It was told that we should observe what happens when the voltage is varied. That is why I clicked on the button indicating + and -. I interacted this for quite some time and saw how the electrons moved. Then I saw that four graph options are given and submit is written, it means that I should choose one of these. So I went ahead and chose one.
Q: On what basis did you chose a graph? You have selected option2, so what was your thought process behind this?
A: When I was playing with this, for starting few values of voltages not many electrons flow. Later they start increasing and move faster with each voltage value.
Q: You have clicked on the help button in after the task of testing your prediction.
A: Yes I was answering each question, combining the feedback with what I observed in the animation and then chose another graph and wrote my answer.

5.2 Case 2-High Scoring Student

Student-2 similarly begins by interacting with the simulation of micro-world, varies different voltages and observes the output electron motion for each value. She then comes to the prediction question task. When she realizes that a graph is to be predicted, she goes back and interacts with the simulation of micro-world for a longer time repeating the voltage values and observing onscreen action. After this she goes the scaffolding questions. Her cursor moves along each option of the scaffolding questions, and then she answers each question. She then goes back to the simulation of micro-world as per the suggestions in the feedback obtained in the scaffolding questions. Later she tries to attempt the prediction question once again and chooses one graph. In the justification task, she writes a detailed justification: "… as the voltage is increased step by step, the current increases but after the knee voltage is crossed, the current increased rapidly". Then she goes back to the simulation of micro-world and rapidly varies the voltage and checks what is happening. She returns to the justification task, and she writes an even more detailed justification. She tests her answer with the real world answer, when found correct proceeds to summary and assumptions.

Given below is her corresponding navigation path:

SIM	PQ	SIM	PQ	SIM	PQ	SQ	PQ	GLO	SIM	PQ	JUS	SIM	PQ	SIM	PQ	JUS	RWA	SUM	ASM	RWA	SUM

Summarized below is an excerpt from the interview transcript for case 2:
Question by Researcher: Can you share what you were thinking while the cursor is moving around?
Answer by Student-2: Yes I am trying to decide what I should be clicking on first. I have clicked on PN junction animation.
Q: Please explain why.
A: Because everything is dependent on this, including graphs.
Q: Now before choosing a graph you have clicked on help to predict graph.
A: Yes the graphs were voltage versus current and I am trying to see which one depicts the fact that current increases after a certain value.
Q: Can you elaborate that based on your choice of option how did you decide your answer of the graph?
A: Because I realized after reading the third point that when we increase the voltage of the external battery, that at certain voltage current increases. That's how I decided my choice of a graph.

5.3 Case 3- Low Scoring Student

Student 3 begins by interacting with the simulation presented in the micro-world. He proceeds to the prediction question but is unable to make a choice and returns to make more observations in the micro-world. He repeats the action of choosing one graph and going back to the simulation of the micro-word. He tries to proceed without making a prediction. When not allowed to proceed he commits to one choice of graph but is unable to phrase a justification. He goes back and forth between the scaffolding questions and the simulation in an attempt to copy the on screen text. Finally, post reaching the testing phase, notices that the prediction is incorrect but instead of attempting a revision proceeds to the summary and stops.

Given below is his corresponding navigation path:

SIM	PQ	SIM	PQ	demo	PQ	JUS	PQ	JUS	SQ	JUS	SQ	SIM	JUS	RWA	SUM

Summarized below is an excerpt from the interview transcript for case 3:

Question by Researcher: Can you explain the reason behind alternating between the simulation and the prediction questions?

Answer by Student-3: I am trying to think which is the correct option from the four graphs presented.

Q: How did you arrive at your final choice of graph.

A: Actually I wanted to go ahead to the next task, which is why I picked one of the graphs.

Q: Okay, after making your choice how did you phrase the justification? You seem to viewing the features of scaffolding questions and the simulation.

A: I had not thought much before choosing the graph which is why I have copied the on screen text from the scaffolding questions to proceed.

Q: You seem to be choosing one of the options in order to proceed to the next task, am I right?

A: Yes, I wanted to see what is there next. My graph which I had chosen did not match with the real world answer so I went ahead to view the summary.

5.3 How do students develop micro-macro thinking while interacting with MIC-O-MAP?

On the surface level it seems like the paths taken by Student-1 and Student-2 are different. Student-1 attempted the task of making a prediction almost right after starting the activity, got the prediction wrong, and interacted with the micro-world simulation and scaffolding questions multiple times for revising his prediction as well as for phrasing a justification. In contrast, Student-2 spent a lot of time initially interacting with the simulation to make careful observations in the micro-world, then used a combination of the simulation results and scaffolding questions in order to make the prediction and improvise the justification. Student-2 got the prediction correct in the first attempt. However, each of these learners displayed common productive actions which we uncovered in our analysis. These actions were not noticed in the interaction undertaken by the low scoring student. Below we show some instances of our codes and analysis of the interleaved transcript for high scoring students. This was done to extract out productive actions of the high scoring students.

i) From the screen-captures, we found that visits to the simulation alternated with spending time on the prediction question and graphs of current-voltage readings (macro-world). During the interview, students corroborated that the reason for multiple visits and large time spent on the micro-world simulation was to reason through the predictions of the macro-world processes. For example, Student-2 reported that "*I clicked on PN junction animation. Because everything is dependent on this including graphs"* We gave a code of 'micro-macro together to improve prediction and reasoning'.

ii) The screen-captures showed that students alternated between the scaffolding questions that led them towards the reasoning behind the prediction and the micro-world simulation. The interviews provided quotes such as *"I wanted to see what is mentioned in Help to predict with respect to the graphs mentioned here […] the mentor (agent) suggested that we interact with the simulation while answering the scaffolding questions."* We gave a code of 'Simulation and scaffolding questions – to help reason and predict'. We infer that students use the scaffolding questions as prompts when they are unable to make a prediction and the types of scaffolding questions with links to the micro-world simulation are designed so that to be able to provide students guidelines for helping them solve the complex task.

iii) Screen-capture data showed that students revisited the micro-world simulation multiple times during the process of writing the justification for their prediction. After each interaction with the simulation, the justification was refined and improved. In the interviews students reported that "*I realized that when we increase the voltage of the external battery, that at certain voltage current sharply increases. That's why the graph is what I chose."* We infer that when students write a justification after making more careful observations to phrase it and later repeat this exercise to improvise or ensure that justification written is correct.

iv) The screen-captures showed that students spend time on the integrated summary which contains both the micro-world simulation and the macro-world processes. A code of ‘co-relating representations for sense making’ is given when students report that *“Yes this view of having all three together is much better, with the diagram and graph. I’m trying to write whatever I have understood till now. Having the three representations on top is useful so I can relate them to each other.”* We infer that co-relating the multiple representations in the summary task for sense making and improving their understanding of the topic.

Table 1 summarizes the productive actions of learners as they interact with MIC-O-MAP learning environment to establish micro-macro links, and connects the design of the learning environment that may have supported these actions.

Table 1: Productive Actions of learners

Learner productive actions	How does the learner action help establish a micro-macro link?	MIC-O-MAP design supporting micro-macro link
When unable to make in informed prediction, learners undergo multiple rounds of interaction with all features of learning environment.	The various types of scaffolds are well designed to be able to provide students specific guidelines for helping them get unstuck. Scaffolds not just leading students to correct answer but to act like scientists and practice thinking skills.	Scaffolding questions aid in identifying key areas in the micro-world and use these observations in predicting the graph in the macro world.
In order to establish a micro-macro link while phrasing justification, learners manipulate variables in the micro-world simulation and establish correlation with graphical outcome in the macro-world.	When asked to write a justification for the macro-world prediction, students make more careful observations in the micro-world simulation, and later repeat this exercise multiple times to improvise or ensure that justification written is correct.	The pedagogical agent in MIC-O-MAP encourages learners to make careful observations in the micro-world simulation while constructing the justification for the macro-world prediction.
For a complete understanding of the topic, learners simultaneously interact with the dynamically linked multiple representations to summarize understanding.	Students correlate the multiple representations in the summary task for sense making and improving their understanding of the topic.	The summary section of MIC-O-MAP encourages learners to integrate various representations and write the summary of the physical process, after varying parameters and correlating multiple linked representations.

6. Discussion and Conclusion

We found that learners’ who develop strong micro-macro thinking skills use certain productive actions while interacting with various features of MIC-O-MAP. These productive actions enable learners to effectively use the rich features and scaffolds of the learning environment in order to achieve the learning objectives of establishing connections between the micro-world dynamics and the macro-world processes of physical phenomena. We highlight the connection between learners’ productive action and the design of MIC-O-MAP:

- Guided Investigation and wayfinding

When a learner is stuck in navigation or thought process enabling an informed choice of prediction, the constructive dialogue with the pedagogical agent aids in locating key areas to be observed in the simulation of the micro-world. A combination of these features is being used by learners for carrying out a scientific investigation in MIC-O-MAP and locating a path leading to the goal of micro-macro skill development.

- Accurate articulation and establishment of micro-macro link

Learners use the conceptual scaffolds for establishing or strengthening the micro-macro link after committing to a graphical prediction in the macro-world. This is done via a dialogue with the pedagogical agent who provides scaffolds. Learners use these scaffolds in order to analyze the graphical curves and observations in the micro-world and later link the two. This is done when they justify their commitment to a certain graphical outcome.

- Activities based on dynamic linked representation for holistic sense making

After interacting with various activities in the learning environment, a complete summary is written by learner post interacting with all representations present on the screen. While they do this they are able to understand the on-going process in the micro world and the tangible outcomes in the macro world. Establishment of this correlation is essential for their conceptual understanding as well as transfer of this knowledge in future learning.

One limitation of this study is that the analysis described in this paper only focuses on students who did develop micro-macro thinking skills, i.e. those who scored high on the post-test that included questions on relating micro- and macro- worlds in a new topic. Our rationale was to attempt to identify if there were any common behaviours and actions of such students which may have led to increased learning. We found such a common set, i.e. the productive actions. However, we have not checked if absence of these productive actions leads to a lack of development of micro-macro thinking skills. This is relegated to future work, in which we have begun to analyze screen-captures and interviews of students who scored low in the post test. Preliminary results indicate that such productive actions are missing among low-scoring students. Another limitation is that we performed the analysis in this study only on ten students, and for one topic in MIC-O-MAP. Increasing and diversifying the population as well as testing the inferences in multiple topics in MIC-O-MAP is required.

The contribution of this study is firstly the identification of the productive actions of learners as the attempt to make sense of complex learning in a rich, open-ended learning environment. Since learners are guided only by the pedagogical agent in the learning environment (and not by a facilitator or mentor), the task of the researcher designing such learning environments is challenging: it is not sufficient to include effective features in technology-enhanced learning environments, but it is important to ensure that learners in fact *use* these rich features in an effective manner. This study attempts to address this challenge by indicating how such self-learning environments and scaffolds within can be designed to promote productive actions by learners.

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