Using Coordination Classes to Interpret Conceptual Change in Astronomical Thinking

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Abstract: This paper illustrates methods for determining how students learned by "tracing" their visuo-motor activities while relating them to changes in understanding about Earth-sun relationships. The conceptual change model of coordination classes is outlined by defining and explaining p-prims and units of change measurement called readout strategies and causal nets as applied in this context. An example from the analysis is provided using one student from the data corpus to show the connections between student learning and activity during the augmented reality exercise. A summary is given of the results of the iterative videotape analysis for this single student, making the respective connections to the astronomy learning activity. A summary of the analysis follows for the entire student sample, along with a section addressing the larger picture of how students' coordination classes changed as a result of their activity.

Keywords: coordination class, conceptual change, augmented reality, learning activity

Introduction

Students traditionally have difficulty learning Earth-sun relationships. Although many have investigated why this is the case, the fact remains that traditional 2D methods of instruction have drawbacks when presenting 3D spatial content (Schneps, 1988). What if, as a student, you were able to interact with complex phenomena in a "cognitively familiar" way? What if, as an instructor, you were able to present spatial concepts in what the student perceives as three dimensions? This research project investigated augmented reality (AR), an interface technology that allows both of these possibilities to occur. AR augments the real environment with virtual 3D objects. It allows the user to manipulate the orientation and position of virtual 3D objects through a first-person view of the environment. It normally consists of a display (worn as a visor in this case), a tracking system, and accompanying hardware and software. Students manipulate the virtual objects by changing the position of a square piece of foam core (see Figure 1).

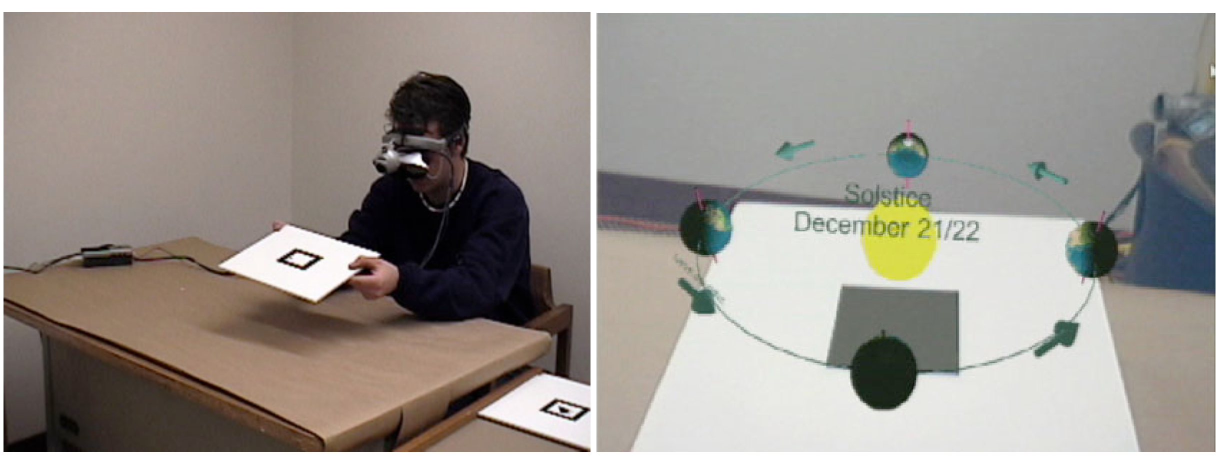

Figure 1: The picture on the left shows what the investigator sees when a student interacts with AR. The picture on the right shows 1st person viewing perspective, the same as that of the student participating in the AR exercise.

Using previous work as instructional design resources, a learning activity was designed and implemented to teach students the reasons for the seasons (e.g., Barab et al.,2000). The learning activity included students' interaction with six virtual models. The investigator instructed students to ask questions while they explored the virtual content.

Method

We followed a qualitative approach to understand how students learned through their interactions with virtual content through the AR interface. This approach involved analyzing student interactions through videotaped recordings of their AR activities. To analyze the specific interactions and how they related to students' learning, we identified and followed visual and physical actions of students. We paid special attention to verbal and gestural communications as the students experienced the virtual content through the augmented reality interface. By replaying the videotape we inductively generated statements about patterns from multiple sets of observations. After multiple viewings of multiple subjects, we noted that changes in perspective while viewing the models generated specific questions and physical movements from the students. For example, students developed a series of rapid movements between two viewing perspectives to compare the amount of light the Earth receives at a single point along its orbital path.

Following multiple instances, we generated a specific code that described the students' activities and what may have precipitated their onset. By generating multiple codes in this fashion, we formed categories or trends. By tracing specific student actions and building codes over multiple sets of students, we inductively created a system of connections. Did students learn about Earth-sun relationships? What kinds of things did they learn? How did students learn? Our inductive approach for analyzing students' use of AR to learn Earth-sun experiences allowed us to answer these research questions.

P-prims and coordination classes: An overview

The issue of what a "concept" is, specifically in accordance with what counts as conceptual change for student learning, has traditionally been fraught with inconsistencies and vagueness. DiSessa and Sherin (1988) provided an overview of the issue, "What counts as a concept?" in educational and psychological literature as well as an argument for a need to more fully define the components of what makes a concept to establish common ground for researchers who write about conceptual change. In their attempt to find an answer to this question they defined a particular kind of concept called a coordination class, in part consisting of smaller knowledge components called p-prims.

Part of the work dedicated to researching how people learn involves a form of knowledge analysis, which Sherin (2001) contended flows from a general assumption that any single "answer" of a problem (such as in physics) will be generated by the activation of an ensemble of knowledge elements. Therefore, analyzing learning from a primitive level makes sense by capturing small changes in when and how existing elements are employed. These simple-structured knowledge elements, which diSessa (1993) called phenomenological primitives (or p-prims), "form the base level of intuitive explanations of physical phenomena" (Sherin, 2001, p. 503). P-prims are connected through networks in which the activation of certain p-prims makes the activation of others either more likely or less likely. Learning constitutes the changes in circumstances that create the activation of certain p-prims. Both diSessa and Sherin wrote of p-prims and their activation with specific reference to understanding physics problems. In this study, we extend their ideas to astronomical relationships. Coordination classes emerge over time as a conglomerate of numerous elements that may determine a "class of information across many contexts" (diSessa, 2002, p. 25). Coordination classes may be thought of as a measuring stick for developmental leaps in naive thought development of scientific concepts. They supply inferences that link observation to understanding, defining a model of an entire system for an expert's organization of knowledge.

Earth-Sun Relationship P-prims and Coordination Classes

We have identified a number of small pieces of information involved in learning Earth-sun relationships as falling under diSessa's definition as being "p-prims." Each of the identified Earth-sun p-prims have some abstract components to them and are difficult to describe with text and language. They are relatively independent and can be used individually. Each identified p-prim can be considered specific, depending on context, and can be recognized individually among different people. For the purposes of this research, we are not arguing that the identified Earth-sun relationship p-prims are the only p-prims that should be considered for this topic. Further, we are not arguing that the ones we use constitute an exhaustive list. Our aim with this paper is to recognize that certain small pieces of information exist for astronomical relationships, and that they can be identified as--and are consistent with--a structural component of a coordination class as characterized by diSessa. A sample listing of the knowledge elements identified as p-prims involved with learning about Earth-sun relationships, identified by two astronomy experts as consistent with diSessa's form and definition of p-prims, is given in Table 1.

Table 1: A selection of identified Earth-sun relationship p-prims used for the AR exercise.

General Organizational Categories	Identified Earth-Sun Relationship P-prims
Earth revolves around the sun	1. one revolution is equivalent to one year
	2. it is a cyclical process
	3. the Earth moves along its orbital path approximately 1/365 of the way
	4. the orbital path is approximately circular
Earth rotates	1. the rotation is about an axis, approximately 22.5 degrees
	2. the Earth, as a spheroid, is always half lit
	3. one rotation is approximately equivalent to one day
	4. it is a cyclical process
	5. the Earth rotates approximately 365 times for every 1 revolution around the sun
Earth's relative position in space relative to the sun	1. the Earth maintains a consistent axis angle as it moves along the orbital path

The hypothesis behind the characterization of a coordination class is that one is able to explain how one "sees something" in the world, whether it is an object, process, event, or idea (diSessa & Sherin, 1998). Using the coordination class approach helped us identify how students "see" Earth-sun relationships without relying on their ability to define vocabulary terms of the field, and is independent of their ability to translate 3D mental images to 2D text and diagrams. This was relevant because students often have difficulty explaining their understanding of spatial relationships using language and writing. In this exercise, we used videotape to capture students' changes in understanding regardless of how well they are able to articulate "expert" language of the topic. At the same time, using the coordination class approach was consistent with how other research in the virtual reality field has made distinctions for "when" learning has occurred (e.g., Dede, 1995; Winn & Windschitl, 2002). DiSessa's use and characterization of coordination classes are purposefully loose in the sense that he believes they may "look" quite different depending on their context. Students with naïve beliefs about certain topics may have coordination classes just like experts, only less developed. In his research he argues that the physics idea of "force" is a good candidate as a coordination class because it is a system with a range of complexity, it has a range of applicability in that students will need to coordinate readout strategies and causal net inferences, and it has been traditionally a difficult topic to learn. The main topic areas of study in this experiment about Earth-sun relationships echo these three suggested requirements for being qualified as a coordination class. Therefore, using their approach of coordination classes was an appropriate way in this research to define students' understandings of rotation/revolution, solstice/equinox, and seasonal variation of light/temperature.

Identifying a change in students' understanding

DiSessa (2002) explained that the first of two structural components of coordination classes include a set of readout strategies which exist as "the set of methods by which any relevant information is gleaned from the world" (p. 16). Readout strategies help develop new ways to see information in the environment, information that might then be put to use as part of a new organization for a coordination class. DiSessa described the second structural component of coordination classes as a causal net. A causal net is "…the collection of possible inferences that can be drawn from available information" (diSessa, 2002, pp. 16-17). Evidence of students' causal net, or the way in which small pieces of information are assembled—or are related to—other pieces, emerged during the AR activity as students physically and visually explored the virtual objects. Evidence of their causal net also manifested itself during the post-test interview as students paused to think about how new answers to questions built upon their previous answers; they often found new understandings about "what was happening" that produced no conflicts with "what they already knew."

"…We can be more refined in describing the process of change in acquiring a coordination class. In particular, the separate changes in readout strategies and in the causal net constitute parameters of conceptual change" (diSessa & Sherin, 1988, p. 1177). With the idea of coordination classes as a basis for changes in understanding, we identified specific changes during the AR activity by highlighting when students use familiar readout strategies in new ways (new organizations) or created new readout strategies. Similarly, we noted instances of conceptual change by identifying when students used old causal nets in new ways or when they created new causal nets. To illustrate how we used coordination classes as a basis for changes in understanding, we provide the following episode that follows closely the AR exercise of one freshman student.

Student Example

In the transcript excerpts, the actor is denoted in the far-left column; “Ali” refers to the “Allison,” the student, and “Inv” refers to the investigator. The center column contains the transcripts of the conversation between actors. Descriptive comments about the activity are in the far-right column, along with text describing the physical movement and visual perspective of the student. At times in this analysis, the nonverbal comments indicate physical movements and pauses that are related to readout strategies which will be discussed throughout Allison’s example. We offer one student as an example of the kind of analysis we performed on 15 students’ activities during their exercise. Her example is also indicative of a step in how we eventually arrived at inferences for the data corpus.

Allison’s AR Exercise

Allison had already examined Model #1, a simple model of a rotating and revolving Earth object around a sun object, when she was given Model #2. This model consisted of four Earth objects in different places around a sun object (see Figure 2). Other objects, such as a ring that represented the Earth’s path around the sun, plus numerous annotations also existed in Model #2. After viewing the Earth object representing December Solstice on its lit side, she focused upward to the annotation, verbally referring to the model near the bottom of her field of view.

…and then there's also a solstice, December 21st and 22nd which would be winter solstice …	Here she turns the card 180 degrees back so that the June solstice is in the bottom of her field of view, then slowly turns the card 90 degrees so that the “Autumnal Equinox” annotation is in view.
…but it looks like they are the same distance from the sun. …	

Lines 280-281 show that Allison recognized a conflict with what she was seeing and what she previously had thought. Her previous notion, that the Earth’s orbit looked like an exaggerated ellipse, needed revision because it did not match with what she was seeing. She noticed here that all four Earth models were roughly equidistant from the sun model. She realized her previous understanding of the Earth’s path around the sun needed to be reorganized so that it matched with what she was seeing.

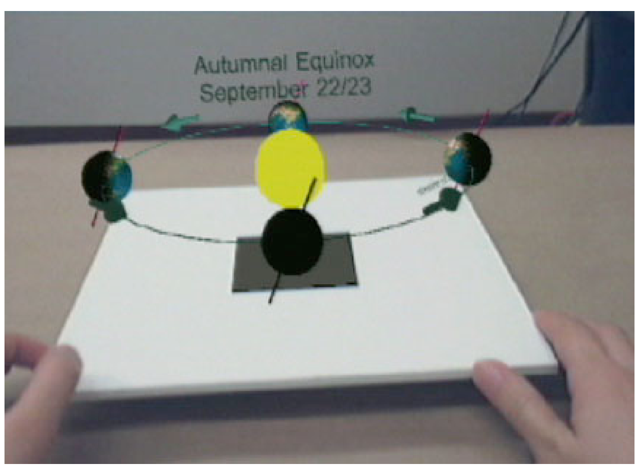

Figure 2: Allison's inspection of Model #2. She notices that each Earth object represents a different point on Earth’s orbital path, and the axis tilt of each Earth is “always the same angle.”

DiSessa described a causal net as “a collection of inferences” drawn from the available information. Evidence of Allison’s causal net, or the way in which small pieces of information are related to other pieces, was described by her as she physically and visually explored the virtual objects. Allison built and modified her causal net during the AR activity by recognizing differences in what she was seeing with her previous understanding. By gaining relative 3D information about the position of the virtual objects, she then associated the “December” Earth with wintertime from her own experience, and realized it was not further away from the sun object than the other Earth objects. Allison, in this sense, changed her understanding of how the Earth moves around the sun by modifying her causal net.

Later in the exercise Allison explored Model #4. This model had a large rotating Earth object with arrows representing the direction and angle of sunlight. An annotation was “attached” to Seattle which rotated with the Earth (see Figure 3). This model represented Earth at autumnal equinox. Allison explained the difference of how Seattle moves with respect to the lit portion of the Earth.

Inv:	So you noted that Seattle doesn't spend as long in the light as it did during the June solstice. Can you estimate anything about how long it stays in the light versus in the dark or –	
Ali:	Okay, if I count it, I can count to six about like one, two, three, four, five, six before it gets around and Seattle is in the sun for about two and then it's in the dark for about four. …	Allison creates a strategy to see how much daytime versus nighttime Seattle is getting by counting the seconds. Her estimation was slightly off (should be 3 seconds and 3 seconds).

She had kept the card on the table, with a point of view from the sun, the entire time. She was having trouble noticing the exact angle of the axis, which was not represented in this model as a “stick” like in Model #2, instead, she directed her attention to what actions the “Seattle” marker was doing.

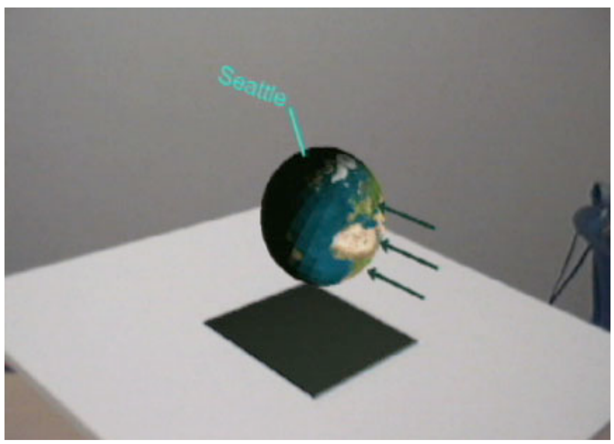

Figure 3: Model #4 where Allison investigated how much time Seattle spends in daylight.

After a few moments of counting and discussion…

Inv:	What can you say about the angle at which the Earth's light or the sun's light hits the Earth?	
Ali:	On this one the light is hitting the Earth at a lower angle than it was during the June solstice. …	This is correct, she notices that the arrows in this model are striking the Earth at points nearer the equator than in the previous model.
	…In June it seemed like it hit more of the northern region and now it's hitting more of the southern region.	This is correct, an extrapolation of her earlier comment.

Allison created a new readout strategy to gather new information. To determine how long Seattle spent in light versus dark, she developed a strategy to count the seconds of time the Seattle object was in the light. This was a strategy she would repeat for the next model, comparing the amount of time that points on the Earth in the Northern Hemisphere were receiving sunlight with the amount of time that points on the Earth in the Southern Hemisphere received. DiSessa and Sherin (1988) described the building of new readout strategies and the modification of old readout strategies as one way of marking learning. "…The separate changes in readout strategies and in the causal net constitute parameters of conceptual change" (p. 1177).

As her exercise progressed, Allison displayed a comfort with her strategies for inspection of the model by making quick, sharp movements to move the card to exactly the position she wanted before she began her inspections. Take any familiar, small, hand-held object as an example. If you wanted to read the other side of a can of cola, you would quickly pick it up and turn it 180 degrees to see what you wanted. Similarly, Allison showed a comfort with her new strategy and with the virtual objects by being able to move the objects into an advantageous position without conscious thought of her physical actions. She utilized a complex readout strategy to glean information from the objects in her environment that she had not previously, and used it repeatedly for different areas within the model. In this way, she built a readout strategy different that used previously, one that was more effective and "transparent" to her conscious thought. This change in readout strategy was evidence of conceptual change according to the model of coordination classes we have described.

Allison Summary

Allison developed strategies in order to get information she needed to explore the virtual objects. For example, Allison pulled the card toward her for up-close inspection of virtual objects. She made repeated efforts to keep the pattern square in her view at all times in order to keep the virtual objects from "disappearing." She pushed the card away to inspect one or more of the virtual objects at the same time. She focused her inspections on the continents of the rotating Earth objects to determine which parts of the Earth received more light. Allison's technique with Model #2 was to examine the two Earths at solstice, turn the card 90 degrees, and compare them with the two Earths at equinox (see Figure 2). She repeated this strategy for all four Earth models. This strategy became especially useful when she needed to examine which part of the Earth spent more time in the light for each of solstice and equinox. By turning the card in a way that she could inspect the angle of the Earth's tilt during solstice and equinox, she was able to see the consistency of the Earth's tilt as it orbited the sun. Overall, she chose a wide variety of angles and positions for the inspection of the models. She consistently changed her view to find the most advantageous visual inspection perspective. She reused reliable strategies to revisit similar features, such as axis tilt. During the activity, she built on her newly acquired knowledge and cemented her understanding through her physical actions and explanations. In this way, she used her previous answers to solve the current question. Allison's identified inferences changed as a result of her activity.

There were many inferences Allison expressed that can be traced to events within her AR activity. She expressed that the Earth's orbit is approximately circular and not an exaggerated ellipse through her inspection of the Earths in Model #2. In a related inference, she said the Earth at equinox and solstice is relatively equidistant from the sun. The sequential experience that drove this change in understanding was when she associated the Earth representing December Solstice with the length of day from her own experiences, and verbally acknowledged that the Earth object was a similar distance from the sun object as the other Earth objects. In more complex modifications to her causal net, Allison noted that the cyclical nature of how the Earth receives sunlight is due to its angle of rotation. Tracing her AR activity, this inference can be associated with her quick, comfortable, and complex strategy of inspecting the Earth objects of Model #2 in seasonal sequence. Allison then organized new understandings about Earth's orbital path by combining new information of how the Earth is tilted and her re-consideration of the angle of the Earth at each equinox. Eventually, she inferred the Earth's axis angle remains at a consistent angle as the Earth orbits the sun. She modified her causal net with this inference by returning to a strategy of inspecting the angle of each Earth object in Model #2 and noting the axis angle of each relative to the sun.

To summarize the analysis layered throughout Allison's example:

- She made changes in her understanding of rotation/revolution and solstice/equinox that more closely matched that of an expert.
- She gained an understanding of seasonal conditions that correspond with the Earth's position during different times of the year that she did not express in her pre-test interview.
- She made connections between these newly acquired ideas and the corresponding phenomena of direct light and amount of daytime/nighttime.
- She reorganized her understanding that integrated new information by combining it with previous experiences into something that made sense to her.
- She continued to modify her understanding the longer she explored the models.

Findings from the Data Corpus

Allison was only one specific case from this study. However, there are instances within her activity as discussed in her analysis that are representative of the other students' AR experiences. Some readout strategies found across the student sample were more visual and physical in nature. These included simple left, right, up, and down movements of the virtual objects to change viewing perspectives. Other readout strategies found across the student example were pulling the card closer for detailed inspection of a virtual object, and pushing the card further away for a goal of inspecting one-or-more virtual objects at the same time. Rotating the card was common when students wanted to inspect the consistent axis angle of the Earth objects. Keeping the card (models) steady over a period of time was a common strategy employed by students to compare the relative movements of virtual objects with each other, such as the orbital movement of the Earth relative to the sun.

Students used a strategy of inspecting the continents on the rotating virtual objects to determine which parts of the Earth received more light. A common variation of this strategy was inspecting the model from the sun's perspective to concentrate on the detail of the entire lit portion of the Earth object to examine the continents and how they rotate with respect to the model arrow objects. A combination of movements followed by a pause, and repeating this combination movement-pause pattern, was a strategy students used to inspect, gesture, and verbally describe a virtual object to communicate and understanding to another person. Other readout strategies also involved visual and physical activity, but were often more complex by combining a number of movements with more cognitive strategies. An example is the way students chose to use a repeating complex combination of movements with pauses to determine how each Earth model represented information about seasonal variation. For example, the majority of students who participated in the AR exercise developed a strategy of counting how long Seattle was in the light to determine the length of day/night at different times of the year. They then used this information to help develop their understanding of the Earth's tilt during different times of the year. Students also used different readout strategies with the cards at different times, such as slower movements with Model #3, #4, and #5 and quicker movements for Model #2. These inferences acquired by students as a result of their AR activity represent a modification to students' causal net. The students gathered information, creating a change in the number of possible inferences about aspects of Earth-sun relationships. The way these aspects were organized reflected how well a student's understanding matched that of an expert, substantiated in such sub-topics as "how the Earth rotates," "what is happening at June Solstice," and "why it is winter in Australia while it is summer in Seattle."

Students expressed a number of inferences they acquired during their AR activity. For example, 13 of the 15 students described the idea of Earth's rotation on an axis and that the Earth revolves around the sun. However, all the students confirmed these inferences during their AR activity, specifically during their inspection of Model #1. Students inferred the approximate circular shape of Earth's orbit and that the Earth's angle remains consistent for each of the four positions of solstice and equinox through their inspection of Model #2. Students inferred that each Earth represented a seasonal significance through their inspection of Model #2, and occasionally other students would make the connection through their inspections of Models #3, #4, and #5. When specifically asked, only 2 of the students expressed an understanding of the seasonal connection between solstice and equinox before their exercise, while 13 expressed the connection afterward. Students re-inspection of Model #2 led to an inference about the "big picture" for the position of the Earth as it revolves around the sun. Another inference was that seasonal variation of light and temperature is due to the way the Earth moves relative to the sun, combined with its consistent angle of rotation.

Characterizing the students' coordination classes

After an analysis of students' changes in readout strategies and the inferences they made to modify their causal net, it is helpful to consider how these measurements for learning have affected the students' coordination class. What does an individual student's coordination class look like? Reviewing diSessa's thoughts on this topic helps describe the development of students' coordination classes for Earth-sun relationships analyzed in this research. In a recent work he asserts that in order to deal with a new context, people may need to "construct a coordination strategy on the spot by problem solving" which relates very well to the guidance and task activities we use in our analysis (diSessa, 2003, p. 6). However, in his research he has yet to use his own defined devices for measuring learning—readout strategies and causal nets—in the way we have done as a means to show how students are learning. He has not shown us specifically what a less-developed coordination class looks like, nor what a well-developed coordination class looks like, for his students studying physics and large number theory topics. Why doesn't he show us the coordination class for his students?

DiSessa (2003) writes that tracking causal nets and readout strategies, and applying them to a singular coordination class, is a highly complex issue and may be inappropriate. Most likely, multiple coordination classes are evolving together at the same time. Think about coordination classes as overlapping circular regions in a Venn diagram, where elements are shared between coordination classes. Within each area there are elements of knowledge, p-prims, that are connected to each other in a relatively simple network (a less developed coordination class) or a complex network (a more developed coordination class). Each area may encompass a varying number of elements that also help determine the state of development of the knowledge structure. For this research we are not exclusive in discussing and attributing the evolution of students' understandings to one particular coordination class. Instead, we assert that a particular coordination class has been reorganized, expanded, and is likely one of many that is involved in the students' learning. The idea that coordination classes are not mutually exclusive and may influence the development of each other follows the three coordination classes in this research being seen as a metaphor of overlapping circles in a Venn diagram. It also follows that the identified Earth-sun p-prims used here are not exclusive to one coordination class, nor that we have identified an exhaustive list of p-prims within each coordination class.

Summary

In this paper we outlined our process of videotape analysis to examine students' conceptual change involving astronomy. The context involved students participating in a designed educational exercise using augmented reality; the topic was dynamic spatial relationships. We related how the structural components of coordination classes, causal nets and readout strategies, in their work with physics parallel similar events when learning about the Earth-sun relationships used in this study (diSessa, 2002; diSessa & Sherin, 1988). The resulting analysis provided us with a method and measure for students' conceptual change from participation in the AR exercise. This approach proved successful in that we were able to trace student learning through their activity with the virtual content, demarking events when students modified their causal net and created new readout strategies. These events thus provided evidence of when and how students learned. Students learned about rotation/revolution, solstice/equinox, and seasonal variation of light/temperature as a result from their AR activity. They learned by creating and modifying strategies for obtaining small pieces of information about dynamic spatial relationships. They learned by modifying the number of possible inferences made from this "new" information, and reorganizing the information forming more developed coordination classes. Students' understandings of Earth-sun relationships more closely matched that of an expert as a result guidance and task-related activities within the AR exercise.

References

Barab, S. A., Hay, K. E., Barnett, M., & Keating, T. (2000). Virtual Solar System project: Building understanding through model building. *Journal of Research in Science Teaching, 37*(7), 719-756.

Dede, C. (1995). The evolution of constructivist learning environments: Immersion in distributed, virtual worlds. *Educational Technology, 35*(5), 46-52.

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*, 165-255.

diSessa, A. A. (2002). Why "conceptual ecology" is a good idea. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 29-60). Dortrecht: Kluwer.

diSessa, A. A. (2003). Coordination and contextuality in conceptual change.

diSessa, A. A. & Sherin, B. L. (1988). What changes in conceptual change? *International Journal of Science Education, 20*(10), 1155-1191.

Schneps, M. H. (1988). *A private universe. An insightful lesson on how we learn*. [Film]. Santa Monica, CA: Pyramid Film & Video.

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

Winn, W. W. & Windschitl, M. (2002). *Strategies used by university students to learn aspects of physical oceanography in a virtual environment*. Paper presented at the American Educational Research Association, New Orleans, LA.

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