On The Relationship Between Visuospatial Knowledge And Learning Electricity: Comparative Case Studies of Students Using 2D And 3D Emergent, Computational Learning Environments

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Section 1: Introduction

Spatial Dynamics and Learning Electricity (with Agents)

Representing and understanding three-dimensional structures is a central concern for mathematics and science education (Wu & Shah, 1993; Bodner et al., 1986; Yang, et al., 1987; Siemankowski and McKnight, 1971; Miller, 1984; Ferguson, 1992; Bryant & Squire, 2001). The growing body of evidence cited above suggests that spatial visualization is a central skill in mathematical and scientific cognition, and educators are coming to see that understanding three-dimensional structures is important for students (Eisenberg, et al., 2002; Wu & Shah, 2003).

Historically, one of the most difficult and pervasive problems in mathematics and science education involves creating understandable representations of three-dimensional structures. As Eisenberg *et al.*, (2002) wrote:

> "Finding an effective way to communicate (say) the arrangement of a complex molecule, or the shape of a galaxy, or the placement of various functional areas in the human brain, or the geometry of a complex set such as the Lorenz attractor, can tax the ability of even the best graphic designer or science illustrator."

Over the last few years, designing and instructional use of 2D and 3D computational learning environments, with a particular emphasis on visualization, has taken a central focus for learning scientists. For example, in the domain of physics, the *Technology-enabled active learning (TEAL)* project at MIT (Dori & Belcher, 2005) uses 2D and 3D simulations of charged particles and electric field lines to illustrate relevant concepts of electric potential and electrostatic forces, and in the domain of geography, Edelson's (2002) *My World GIS* uses 2D geographical visualizations that provide a powerful way for learners to make visible the patterns and trends that lie hidden in complex geographical and environmental data. In the domain of chemistry, Stieff & Wilensky (2003; Stieff & McCombs, 2006) used *Connected Chemistry*, a curriculum based on multi-agent based NetLogo (Wilenksy, 1999) models that primarily rely on 2D and 3D visualizations of subatomic particles and their interactions to represent relevant concepts such as total gaseous pressure (i.e., pressure exerted by a gas on the on the walls of the container within which it is contained) as *emergent phenomena* – i.e., macro-level phenomena such as pressure emerge from simple interactions between gaseous molecules. However, studies of student learning using the aforementioned learning environments have so far effectively focused on identifying the process and nature of conceptual understanding of students before, during and after their interaction with the learning environments - without an explicit focus on spatial knowledge of the learners.

On the other hand, most investigations of spatial knowledge in the context of physical phenomena have so far dealt with static representations and/or environments (Marcus et al., 2000; Bennett, 1969; Smith, 1964; Hagerty & Sims, 1994; Bennett, 1969). In reality, however, many physical phenomena can be best described as dynamic – that is, having one or more components that move relative to other components. For example, those phenomena identified by Eisenberg (2002) above as requiring or eliciting three-dimensional thinking (a complex molecule, galaxy, or the human brain for instance) all have important *dynamic* processes that are central to their purpose. Dynamic spatial reasoning has been identified as an entity distinct from static spatial reasoning (Hunt, Pellegrino, Frick, Farr & Alderton, 1988). This suggests that in order to understand how students make sense of phenomena that is *spatially dynamic*, we should investigate their sensemaking processes in the context of those spatially dynamic events.

We believe that Electricity, when represented as a *spatially dynamic,* emergent (Holland, 1998; Wilensky & Resnick, 1999) phenomenon provides us a suitable context in which we can explore students' knowledge construction process from the perspective of their visuospatial knowledge. In this study, we investigate the relationship between visuospatial knowledge and learning electricity by studying different groups of students interacting with 2D and 3D versions of the same computational model (Ohm's Law; Sengupta & Wilensky, 2006) that model electric current (through a wire connected across two battery terminals) as an emergent, spatially dynamic phenomenon. By the term "emergent", we mean that current in a wire is modeled as a phenomenon that emerges due to a series of interactions, such as collisions and repulsions between individual agents (such as electrons and nuclei within the wire, and positive and negative charges in the battery terminals connected to the wire). Both the interactions between these individual agents, as well as the resulting emergent phenomenon, can be described as *spatially dynamic.* This paper then attempts to understand the affordances of an added spatial dimension in this model by investigating how established components of visuospatial thinking – perspective, salience, and relationships – serve to help participants make sense of dynamic (i.e., moving and changing) spatial systems as represented by a 3d model projected on a 2d screen.

Moreover, electricity is a well-researched topic in cognitive science as well as science education – both in the context of students' misconceptions, and instructional design. Students' misconceptions at all levels (middle school, high school, college) have been well documented by researchers all over the world (for a complete bibliography see Pfund & Duit, 1992) and there is a broad agreement among several researchers that "levels of knowledge" (Wilensky & Resnick, 1999) plays a crucial role in a deep understanding of the key concepts in electricity such as current, voltage and resistance (Bagno & Eylon, 1990; White & Frederiksen, 1998; Sengupta & Wilensky, 2006). These researchers suggest that students' misconceptions in the domain of electricity arise from the inability of students to relate the micro-level objects and their interactions (i.e., electrons and atoms, and forces of interaction between them) to the macro-level, observable phenomena such as current and voltage. The model used in this study is part of a NetLogo based curriculum, NIELS (NetLogo Investigations In Electromagnetism: Sengupta & Wilensky, 2005, 2006) which is a suite of such models that was designed to address these issues. Models in the NIELS curriculum have been implemented successfully both in undergraduate and middle school classrooms (Sengupta & Wilensky, 2006, in progress). Learners in these classrooms after interacting with NIELS models showed evidence of thinking in levels in their understanding of the relevant concepts such as current, resistance and voltage. In this pilot study, we dive into the visuospatial aspects of the learner's online thinking about these phenomena (i.e., current and resistance) during and immediately after their interactions with the model(s) *in terms of how they process* *and understand the visuospatial information represented in the model(s).* In particular, we explore how learners notice and focus on the different levels of the systemic behavior based on the visuospatial information in the models and present a comparative study of students who interacted with the model in 3D with those who interacted with the model in 2D, and attempt to understand the relative affordances of the dimensionality of the model(s) in this context.

Isotropic and Anisotrpoic Systems

Our particular research question at the center of this study, on the other hand, is a part of a broader agenda, which is to understand *if* and *how* 2D and 3D representations of multi-agent-based models of scientific phenomena afford different types of learning experiences for learners. We argue that such differences, if they exist, might be due to either of (or a combination of) the following reasons: a) the 3D representations might afford a different set of *visuospatial perspectives* that is absent in the equivalent 2D representations; and b) agents might exhibit new behaviors in a 3D model that are not explicit, or, are absent in the equivalent 2D representations. We perceive this study as a small step in answering these questions, with special attention to the first issue: that is, we are concerned with how students think about *the same phenomenon* presented in 2D versus 3D, rather than how new aspects of some phenomenon might be presented with an added dimension.

The model we use in this study, Ohm's Law (Sengupta & Wilensky, 2006), represents a particular class of phenomena in *which an added degree of freedom in the 3D representation does not change the individual agent's behavior or the emergent behavior of the system compared to the 2D representation* of the same phenomena. The topological space inside the wire is *isotropic*, i.e., electrons are subjected to the same forces or rules in every direction, and as a result exhibit the same behavior in all directions within the wire. In other words, there is no difference in how an electron behaves along the x, y, or z axes in terms of collisions. When the wire is subjected to a Voltage, the Voltage causes a net drift on the electrons towards the battery-positive (that is, in the x-direction). In this case, there is a difference in electrons' behavior between axes, but the behavior of the electrons in the x and z axes is identical. By including or omitting the z direction in the model, we are not including or omitting information about the behavior of the model itself. In other words, the behavior of the system is independent of the direction from which it is viewed. On the other hand, a large number of physical and mathematical systems are *anisotropic* in nature. Anisotropy is the quality of exhibiting different properties or properties with different values when measured along axes in different directions. For example, consider distance from point A to B as represented on a 2D map. The scale legend on the map might imply that the distance between A and B is 1 mile. However, if A and B represent the apex and base of a mountain, the actual distance one must travel to get from one point to another is influenced by the third dimension (altitude), and the distance between A and B would be in fact greater than one mile. Thus, in this case, an added dimension in representing the altitude of the system would therefore change the value of the distance between the two points. In our study, because no new behaviors or different properties of the system are manifested in the 3D representation of the Ohm's Law model compared to its 2D representation, we believe that this will allow us to investigate the cognitive and perceptual effects on learners due to their interaction with 2D versus 3D models in a way that reduces other such confounding factors.

Plan of this paper

The rest of this paper is structured as follows. In section 2, we first revisit the literature in cognitive psychology and psycholinguistics concerned with visuospatial thinking, and situate the relevant theoretical constructs in the context of the general nature of the physical phenomena represented in the Ohm's Law model. We argue that visuospatial perspectives are embedded in the model in the form of two types of landmarks – Locally Anchored Landmarks and Globally Anchored Landmarks (see Section 2.2 for detailed discussion) – and that learners readily use these two forms of landmarks in their process of making sense of the phenomena represented in the model. We randomly assigned our participants into one of three groups – A, B and C. Participants in Group A interacted only with the 2D Ohm's Law model (Fig. 3A), whereas participants in Group B interacted with the 3D Ohm's Law model in the survey mode (Fig. 3B), and participants in group C interacted with the 3D Ohm's Law model in the "Dive In" mode (Fig. 3C). Participants were interviewed and videotaped during their interactions with the model. Before and after their interactions with the models, participants were asked to explain their understanding of electrical current, resistance and voltage, as well as the relationship between them. The main results of this pilot study are that a) participants' use of visuospatial perspectives, primarily manifested in terms of Globally and Locally Anchored Landmarks, was independent of the dimensionality of model with which they interacted; and b) there was no difference between the three experimental groups in the accuracy of understanding of electrical current and resistance after their interactions with the models.

Section 2: Theoretical Framework

Motivation For This Study: Visuospatial Thinking & Learning Physics

Research in cognitive neuroscience and working memory suggests that there are two different components of "visuospatial ability" - visual imagery, and spatial imagery (Kosslyn, 1995; Hagerty & Waller, 2005; although spatial imagery can further be split into two distinct areas, static and dynamic spatial imagery; Hunt et al, 1988). Primarily, visual imagery refers to a representation of the appearance of an object, including features such as its shape, color or brightness. Spatial imagery, on the other hand, refers to a representation of the spatial relationship between parts or the movement of an object or system of objects, and is not limited to visual modality (i.e., one could have an auditory or haptic spatial image – see Hunt et al., 1988).

Over the past three decades, there have been quite a few studies that have probed the relationship between visuospatial ability in the context of diagrammatic representations in problem solving, and learning in the domain of physics. For example, researchers have investigated the role of 2D diagrammatic representations in the assembly instructions for electronic resistors in a series and parallel to each other (Marcus et al., 2000), and the role of spatial abilities in mechanical reasoning (Bennett, 1969; Smith, 1964; Hagerty & Sims, 1994; Bennett, 1969). Marcus *et al* (2000) compared the effectiveness of purely textual instructions to purely diagrammatic ones in assembly of simple electrical circuits. Their results revealed that diagrams were particularly helpful in more complicated assembly instructions. Mental animation, which according to Hagerty (1992) is the ability to infer behavior of any mechanical system, such as a system of pulleys, from its configuration, has also been investigated. Studies suggest that mental animation is a spatial visualization process, and that parts of a mechanical system are mentally animated individually due to the visualization constraints of working memory (Hegarty, 1992; Hegarty & Steinhoff, 1997).

Expert-novice differences have also been studied in the context of visuospatial thinking: Larkin & McDermott (1981) studied expert-novice differences in interpretation of diagrammatic representations of problems in physics, and argued that experts' mental representation of problems are closely aligned with domain specific, canonical, physics principles, whereas novices attend to the more superficial attributes of the objects represented in the diagrams. diSessa (1993) and Sherin (1996) present a complimentary perspective and argue that the building blocks of our intuitive reasoning about physical phenomena are small pieces of phenomenologically acquired knowledge elements, some of which are domain general – and that the difference between experts and novices are in the pattern of activation of these knowledge elements.

None of these studies, however, focus on the role of learners' spatial knowledge structures as it directly relates to how they might learn about phenomena within the domain of physics in general, and electricity, in particular. In this paper, we report a comparative pilot study of the relationship between visuospatial thinking and conceptual understanding of electricity between three groups of undergraduate students who interacted with 2D or 3D multi-agent based computational models of electricity. We investigate how *dimensionality* and *dynamicism* are understood and utilized by students in the context of electricity, and how various modes of mental representation of spatial knowledge are correlated with learning outcomes.

Mental Representation of Visuospatial Knowledge

Since the 1970's, spatial knowledge has received much attention in cognitive psychology and psycho-linguistics. Cognitive psychologists have typically studied spatial knowledge in the context of various types of spatial tasks such as learning an unfamiliar region through navigation or from a map, estimating distances between locations along a route or as the crow flies, reading and interpreting a map, etc. (Farell & Potash, 1979; Kozlowski & Bryant, 1977; Thorndyke, 1980; Uttal [xxx]). Thorndyke et al. (1980, 1981, 1983) identified different types of spatial knowledge (or perspectives) and their functions in common spatial tasks. These types of knowledge differ in the aspects of the environment that they represent, the primary sources from which they are acquired, and the tasks in which are most useful. Among researchers in the field of visuospatial cognition of maps and spatial navigation in general, there is a broad agreement about the types of spatial knowledge, or how they are represented in our memory. Spatial knowledge can be mentally represented in three forms (or perspectives) that Thorndyke et al. identified: *landmark*, *route* and *survey* (Thorndyke, 1980; Parush & Berman, 2004). *Route* knowledge (also known as procedural knowledge) is a sequential procedural description of the route between points in the environment, along with actions (i.e. turning) and locations where those actions take place. Survey knowledge or analog representation is a more simultaneous, image-like representation of the entire geographic area, including the layout of all elements and the spatial relationships among them. Landmark knowledge is the visual representation of *salient* objects in the environment, either man-made or other features. As Tversky (2000) points out, in any actual environment, certain elements are more prominent than others, "perhaps because of perceptual salience, perhaps because of functional significance". These privileged elements, typically called *landmarks serve as cognitive reference points* for many less distinguished elements (e.g., Couclelis *et al.*, 1987; Shanon, 1983). They then come to organize the space around them, defining *neighborhoods.*

In the field of psycholinguistics, the representation of spatial knowledge describing motion of any type in spoken and sign language in terms of the observer's *frames of reference* has been a topic of much synergistic interest. As Levinson (2002) and Talmy[1] (1983) have shown, most natural language descriptions of space are Liebinizian rather than Newtonian – i.e., they describe the motion of one thing with respect to other things. Thus, in spatial scenes, something (usually termed a "figure") is generally located with respect to something else (known as "ground" or "landmark"). If a figure's location changes, its motion can be described in terms of its distance, angle, or direction relative to the ground. Such angular or directional specifications of location require some form of coordinate system or *reference frames*. As Levinson (2000) points out, there are three main types of such reference frames: intrinsic, relative and absolute:

> "One way to specify an angle is to name is to name a facet of the ground and indicate that the figure lies on axis extended from the facet, as in "The statue is in front of the cathedral". We call this the **intrinsic frame** of reference, since it relies on a prior assessment of intrinsic or inherent parts and facets to objects. Another way to specify an angle is to use the viewer's own bodily coordinates, …[w]e call this the **extrinsic frame of reference.** A third way to specify angles is to use fixed bearings – independent of the scene – to specify a direction from the ground or landmark, as in "the coast is north of the mountain ridge". We call this the **absolute frame of reference**, because the names and directions of the fixed bearings are fixed once and for all. Although there are many variants of these kinds of coordinate systems or frames of reference, these three types (intrinsic, relative, absolute) seem to exhaust the major types used in language."

From a learning scientist's perspective, we believe that the research described in this section so far has important consequences for understanding learners' sense making processes through interaction with a 2D or 3D learning environments *in terms of how they process and understand the visuospatial information contained within the environment.* In the following section, we attempt to situate the theoretical ideas discussed so far in the specific context of the NetLogo models used for this study.

Towards a Specific Theoretical Framework for Analyzing Visuospatial Knowledge in Multi Agent-based Models: Agent-Salience and Anchored Frames

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[1] Talmy (1983, 1985) influentially proposed a typology to understand how motion is represented (coded) in languages, a detailed description of which is outside the purview of this paper.

In the context of dynamic, emergent systems such as electricity, we argue that there are two important aspects of visualization: a) identifying how elements or objects of interest are moving and interacting with relation to the environment or world in which they are featured/embedded, and b) identifying how elements or objects of interest are moving and interacting with relation to each other. For example, in the Ohm's Law model, noticing that all electrons are moving towards the battery positive and away from the battery-negative (see Figure 1) makes explicit that electrons are pushed away from the battery negative and attracted towards the battery positive – a combined push-pull mechanism that is responsible for generating current within the wire. This provides students with a sense of mechanism for understanding electric current. Similarly, observing the behavior of an individual electron with respect to other electrons makes explicit the rules that the random walk behavior of the electrons due to random collisions with the nuclei distributed through out the wire, in addition to the steady velocity of the electrons towards the battery positive. This will provide students a sense of mechanism for understanding electrical resistance.

What does this mean for the theoretical constructs (landmarks, frame of reference, etc.) described in the previous section? In the first case, when one notices an individual electron (or a group of electrons) moving away from the battery-negative toward the battery-positive terminal, the electron (or the group of electrons) whose motion is being observed is the "figure", and the battery-terminals are the "ground". These battery terminals are "fixed" in space. We term such grounds or landmarks (i.e., that do not change their temporal position with respect to the locally dynamic individual agents or *figures*) *Globally Anchored Landmarks (GAL).* In other words, such grounds designate (or, are embedded in) a reference frame that is fixed in space with respect to the individual agents that exhibit temporally dynamic behavior. However, in the second case, when one notices the behavior of an electron relative only to a few other (say, 4 - 5) electrons in its immediate vicinity, the ground is that immediate surrounding collection of electrons that is locally dynamic in nature. Such landmarks are characterized by a *proximally connected* region in space that *moves with the individual electron,* within which a few dynamic, individual agents interact between themselves. These neighborhoods are *locally anchored* – i.e., they are static with respect the *figure* agents (or electrons) in terms of the behaviors that all electrons exhibit, but are dynamic with respect to the globally anchored landmarks or behaviors that are exhibited differently by different electrons. We term such landmarks *Locally Anchored Landmarks* (LAL). Figure 3 (3A, 3B & 3C) shows examples of these landmarks in the 2D and 3D Ohm's Law models used in this study. Within the context of a locally anchored landmark, learners might notice the collective behavior of a few electrons in that neighborhood, or they might observe the behavior of a single *salient electron* in the collection. This salience could be due to either or both of the physical and functional attributes of the electrons – i.e., differences in color, or differences in the behavior of an electron with respect to its immediate neighbors. It is also interesting to note that both LAL and GAL are situated in an *intrinsic frame of reference* since they rely on a prior assessment of intrinsic or inherent parts and facets (electrons and battery terminals) of the wire/circuit displayed in the model. Figures 1a and 1b below provides a schematic of the attributes and functionality of these two types of landmarks.

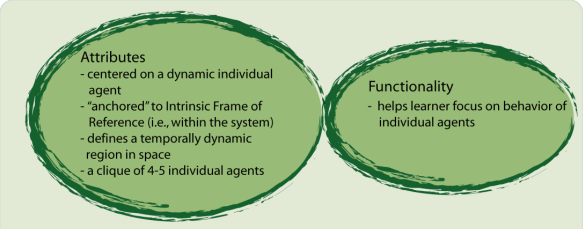

Fig. 1a: Locally Anchored Landmarks

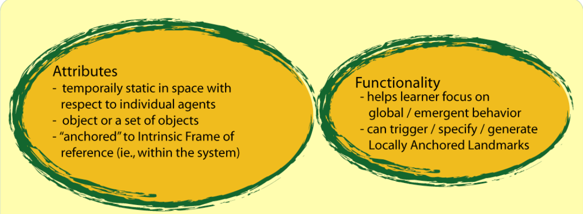

Fig. 1b: Globally Anchored Landmarks

The primary goal of this study is to investigate the differences in roles, if any, that these two types of landmarks play in process of knowledge construction when learners interact with the Ohm's Law model in 2D and 3D.

Section 3: The Learning Environment: NIELS

In our study, learners interacted with computational models that are part of the NIELS curriculum authored in the Netlogo modeling language (Wilensky, 1999). Each model in the NIELS curriculum was coded both as 2D and 3D representations of the relevant phenomena. Models in NIELS represent phenomena in the domain of electricity (such as current, voltage and resistance) as *emergent phenomena*, resulting from simple interactions between a number of agents on a micro- or individual- level.[2] This allows students to treat each individual agent (electron), or, small groups of electrons as a small unit of a larger physical system. In terms of Hagerty (1992), they can mentally "animate" these units to understand and/or predict the behavior of the overall system.

One model in the NIELS curriculum was used for this study: Ohm's Law (Sengupta & Wilensky, 2005b),. This model includes several navigation aides and scaffolds that allow users to further explore and interact with the models. For example, users can change the color of the agent(s) (i.e., electron(s)) that they are observing to be different from that of the other electrons, so that they could unambiguously follow its (their) motion. They can also highlight a small radius around an electron observe the behavior of a few surrounding electrons. Learners can situate themselves at any point within or outside of the wire in the 3D model, whereas they can only situate themselves on the surface of the wire in the 2D model.

The model is based on Drude's theory of free electrons, in which electrons in the conduction band of the atoms, which the resistor made up of, act as free gaseous particles in absence of an Electric field. The collide with the nuclei of the constituent atoms

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[2] By levels, we do not mean a classic hierarchy or chain of command, like the levels of officers in the army. Rather, we are talking about the levels of description that can be used to characterize a system with lots of interacting parts (Wilensky & Resnick, 1999).

throughout the wire, and in between collisions, their behavior can be described as a random-walk. When an electric field is applied across the resistor, an additional drift is superimposed on these electrons in the direction of the positive battery terminal. The distance between two successive collisions is called the mean-free path and is used in this model as a representation of resistance. Thus, the emergent behavior in this model is current that obeys Ohm's Law (Drude's theory is only valid for Ohmic conductors). Voltage and Collision-rate of the electrons with the nuclei in the wire are modeled as variables with which the students can interact in the form of sliders (see Figure 4).

In this model, electrons wrap around horizontally – i.e, after entering the battery positive, electrons reappear at the battery negative. This represents an important notion that the charges leaving the battery-negative are regenerated at the battery positive in a closed circuit in order to maintain a constant potential difference. Thus, the battery is represented as a source of *charges* – and charges in one terminal of the battery "compensate" the other. Students are thus prompted to think of the charges as "objects", interactions between which give rise to the emergent phenomenon of current.

Section 4: Methods

Our participants were nine junior undergraduate students majoring in psychology and education at a large Midwestern university. They had not taken any college-level physics course, although all of them had taken introductory physics in their respective high schools. The participants were divided into three groups: participants in Group 1 interacted with 2D NIELS models, Group 2 interacted with 3D NIELS models starting with a survey perspective, and Group 3 interacted with 3D NIELS models starting with an immersive route perspective. Views of the circuits, as visible to students in each group, are depicted in Fig. 2. Prior to their introduction to the models, participants were administered an oral pre-test, in which they were asked to provide qualitative explanations of electric current, voltage and resistance, as well as the relationship between them. During their interaction with the models, the participants were asked to perform specific activities that involved changing the rules of interaction between individual agents (e.g., amount of attraction/repulsion between the electrons and charges in the two battery terminals; freedom of electrons to move around randomly, etc.) and observe how both the global behavior, such as current, and the local behavior, electronic motion, changes. Throughout the interview, participants were asked to think aloud and describe what they were observing on the screen. After they interacted with the models, an oral post-test was administered, in which participants were asked the same qualitative questions as in the pre-test. During the interviews, participants were asked not to use symbolic representations such as equations (e.g., Ohm's Law: $V = IR$), although, they were allowed to use the NIELS model(s) they interacted with while answering questions in the post-tests.

After the pre-interviews, all participants were handed out a information sheet that described in brief the main ideas of free electrons theory that was embodied in all the models – i.e., electrons in the outermost shell of metallic atoms are considered to be free from the nuclear attraction, and as such, behave like free gas molecules. However, these electrons also collide with the nuclei that are randomly placed in the wire, thereby, exhibiting random walk behavior. Participants in groups A and B were then introduced to the models in a survey mode as indicated in Fig. 1A and 1B below, respectively, whereas participants in group C were introduced to the 3D Ohm's law model in the "Dive In" mode as shown in Fig. 1C. They were asked to interact with first, the Voltage slider, and then, the Collision-rate sliders. Around 10 minutes into the interview, participants were asked to "Watch" a single electron by using a subroutine that highlighted a small circular region of space around single electron, and they were asked to repeat their interactions with the sliders. After another 5 minutes, participants were asked to use another subroutine that changed the color of a few randomly selected electrons to make them salient with respect to other electrons, and once again, repeat their interaction with the Voltage and Collision-rate sliders. Throughout the interviews, the participants were asked to think aloud and describe what they observed in the model. The interviewer often asked follow up questions for further clarification. For example, if a student mentioned that "the electrons are moving faster when I increase the voltage", the interviewer would then ask if the participant was looking at all the electrons on screen at once, or whether he was focusing on a selected few. Participants were also asked to clarify how they determined electrons were moving in particular directions – i.e., whether they were observing electrons move with respect to other objects on the screen, etc.

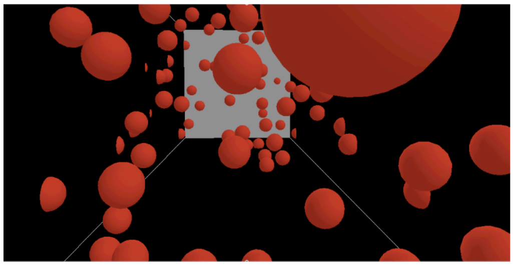

Fig. 2C: View of the circuit in the 3D Ohm's Law model in the "Dive In" mode

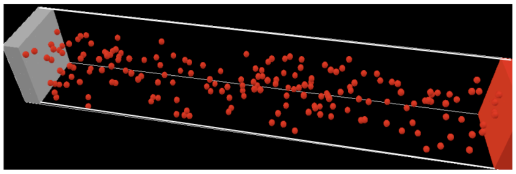

Fig. 2B: View of the circuit in the 3D Ohm's Law model in the "Survey" mode

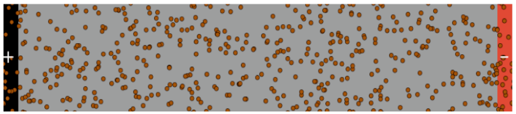

Fig. 2A: View of the circuit in the the 2D Ohm's Law model

Fig.2: Views of the Circuit for Participants in Groups A, B and C

The interviews were videotaped and later transcribed. Participants' responses were coded for different forms of landmarks, i.e., Locally Anchored Landmarks (LAL) and Globally Anchored Landmarks (GAL). To assess students' understanding of electric current, resistance and also, their relationship with Voltage in the pre- and post-tests, the participants' responses were coded in terms of levels of knowledge – i.e., explanations of the relevant phenomena at the micro-level, the macro-level, and a complementarity of both.

Section 5: Results

Locally Anchored and Globally Anchored Landmarks

As expected, we did observe that both Locally Anchored Landmarks and Globally Anchored Landmarks were employed by the participants in order to make sense of the phenomena modeled. For all of our participants, both locally and globally anchored landmarks played an important role in the making sense of the mechanistic aspects of electrical resistance and current. Specifically, a pattern in which students a) notice a small group of electrons or “clique”, b) identify and examine the behavior one electron within that clique, and c) identify and examine the behavior of the same electron with repect to the overall model was observed. For example, a student might first notice a “scattering” or random movement amongst several proximal electrons. She then focuses on a single electron within that group as a means of systematically analyzing this movement. Here, the *local* group of electrons *anchors* and situates that electrons’ movement. From this she can determine that random-walk behavior results for electrons colliding with nuclei within the wire, producing the phenomena referred to as resistance. Finally, she might note the movement of that same electron with reference to static components of the surrounding environment, such as the battery terminals and wire walls. These *global* components of the model *anchor* the electrons’ movement with respect to the world, so that larger phenomena such as drift from the battery-negative to the batter-positive terminal is evident. These different landmarks, and the sequence of landmark use described above, were observed in all interviews across conditions and student, and some students in fact explicitly mentioned the nature of Locally Anchored Landmarks and their difference from Globally Anchored ones.

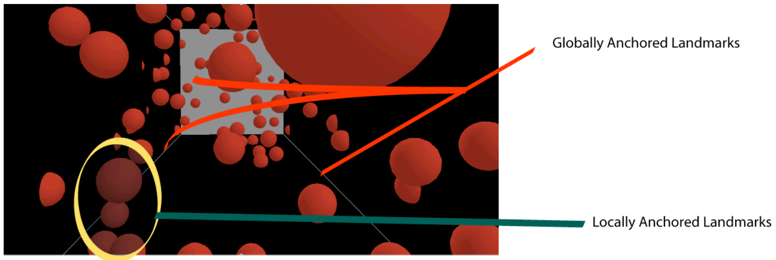

Fig. 3C: Landmarks in the 3D Ohm’s Law model in the “Dive In” mode

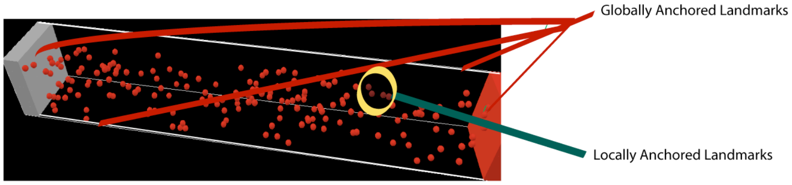

Fig. 3B: Landmarks in the the 3D Ohm’s Law model

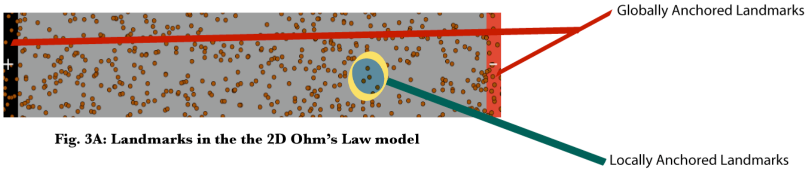

Fig. 3A: Landmarks in the the 2D Ohm’s Law model

We will now discuss a few examples that make explicit the role of these landmarks in the learners' process of knowledge construction during their interaction with the models across the three different experimental conditions. Consider for example, the following excerpt which is representative of participants in Group A who interacted with 2D model. In this excerpt one participant interacting with the 2D model is describing how he was able to determine that electrons were "scattering" due to some other objects in their trajectory:

Excerpt 1:

Pat: …[decreases the collision-rate].. and now the scatter is definitely less.. because they are not colliding with each other that much... they are just going more freely towards the left and.. they are not bouncing of each other in different directions

Interviewer: How are you observing that they are not scattering as much? I mean, how are you noticing them?

Pat: And then if I want to determine if all of them are scattering I look at an individual group and try to focus on that….

Interviewer: When you say a group, can you maybe show me a region? How many electrons...makes a group for you?

Pat: Um, when I look at one group, I would say the region I like, look at... would probably be about like this [draws 3/4 inch circle on screen with finger] size, that's a small group. Then I can see where they're going, whereas if you look at the whole thing, you sort of move to the left, you see they're obviously scattering but...

Here, the participant claims that in order to determine that all of the electrons are in fact "scattering", he must focus on a small region of space occupied by a *collection of proximal electrons* – a *clique* of 4-5 electrons - that act as a *locally anchored landmark*. As he follows the clique, he focuses on how the electrons move with respect to each other. With his focus set on the clique, he reduces the collision-rate slider, and thereby notices that the electrons tend to "scatter" less as he increases the collision-rate of the electrons with the nuclei. The effect of collision-rate with the nuclei on the motion of the individual agents - electrons - was thus made explicit to Pat.

Participants in Group B, who interacted with the 3D Ohm's Law model, also had similar experiences. The notion of a clique of electrons traveling together was a central component of their interactions with the model, and as the excerpt below shows, it played an important role in providing them with a sense of mechanism of electrical resistance. Here the participant, Bob, is describing what he observes after he reduced the value on the collision-rate slider:

Excerpt 3:

Bob: It almost seems like it is slowing down a little bit

Interviewer: ummhm.. what is slowing down?

Bob: [points to a group of electrons near the battery negative]... the electrons are slowing down … I mean they are moving a lot faster, they are not moving towards the positive end that faster..

Interviewer: Uhmmm..

Bob: Because they have to go around all these different obstacles.. they are hitting

8 the nuclei…. if you decrease the collision rate.. you are kind of removing all the
9 barriers …
10 Interviewer: when you are observing electrons move in particular directions, are you
11 observing these directions just by looking at the electrons or by looking at electrons
12 and something else?
13 Bob: I was just looking at them.. and I thought that they stuck with a cluster of the
14 same electrons.. it seems like it is like that for a little bit .. yeah.. then they break
15 away after a while .. and these other electrons then form another group.. so it seems
16 like there is some locus of clusters.. some members join the group, and some
17 members leave…

Here, Bob's responses are similar to that of Pat in Excerpt 1. Focusing on a group of a few electrons enabled him to observe the trajectory of individual agents, which in turn made explicit the effect of collisions on the electronic paths (*go around all these different obstacles… they are hitting the nuclei*). His responses in provide evidence of Locally Anchored Landmarks in the form of a temporally dynamic focus zone moving towards the battery positive (*…they stuck with a cluster of the same electrons…*) – even though its composition kept changing with time, he kept tracking the motion of the "focus zone".

The interviewer then noticed that Bob had mentioned two different directions in which the electrons were moving in lines 3-5, and decided to ask him to describe his method for judging the direction of motion of the electrons he was observing. The following conversation ensued:

1 Interviewer: and how do you observe how much an electron moves forward or
2 backward on the screen?
3 Bob: I don't really see it with respect to other electrons.. I see it with respect to the
4 starting point and the end point
5 Interviwer: What about the other directions?
6 Bob: Ummm.. is it closer to the top, or closer to the bottom...
7 Interviewer: You mean the white lines?
8 Bob: Umhmm.. the white lines..

Here, Bob's responses in Line 3 makes explicit that he was indeed focusing on a single electron within a Locally Anchored Landmark when determining certain types of motion, but not others. However, this excerpt also provides evidence for the fact that globally anchored landmarks aided him to understand the behavior of a single electron due to the collision-rate, as well as the applied voltage. For example, in line 4, Bob mentioned that he "saw" the electron's horizontal motion with respect to Globally Anchored Landmarks, i.e., the battery terminals (*starting point and end point*), whereas, he noticed how much the electrons were moving up and down (due to the collisions they suffered with the nuclei) with respect to another set of Globally Anchored Landmarks – i.e., the top and bottom edges of the wire (*the white lines*). This was representative of all participants in our study.

In case of participants in Group C who interacted with the 3D model only in the "Dive In" mode, Globally Anchored Landmarks played an additional role - Locally Anchored Landmarks were triggered by the globally anchored landmarks such as the grey region in

Fig 3C depicting the battery positive, and the "horizontal floor" of the wire before the wire connects to the battery-positive. In the following excerpt the participant who interacted with the model only in the 3D "Dive In" mode is describing how she was able to understand the effect of collision-rate on the motion of electrons:

Excerpt 3:
1 Interviewer: What do you notice when you increase the collision rate?
2 Jenna: Ummmm…. they are moving faster towards each other ..
3 Interviewer: So when you say "they".. how do you notice the electrons? I mean are
4 you noticing all the electrons on the screen or are you noticing only a few electrons?
5 Jenna: well.. all the ones in the grey box… [points to 4-5 electrons on the screen]..

Here, the participant, Jenna, is also focusing on a local clique of electrons and tracking how electrons are moving within that clique *with respect to each other*, just like Pat and Bob in the previous two excerpts. However, as Jenna mentioned, the gray region in the GUI indicating the battery-positive terminal, a globally anchored landmark, triggered this locally anchored landmark by defining a spatial *zone* in the model within which she could observe the *clique* of electrons.

Role of Software Scaffolds: Highlighting and Coloring Electrons

As described in the methods section, in each experimental condition, participants were provided two types of scaffolds embedded within the model – the "Watch a single electron" function that highlighted a small region about the radius of an inch around an individual agent, and the "Color 10 Electrons" button that set the color of 10 randomly selected electrons throughout the wire to be different than the rest. Our hypothesis was that these scaffolds would define Locally Anchored Landmarks for the participants, and thereby, focus on one and/or a few electrons. However, in all the interviews that we conducted for this study participants noticed small clusters of electrons *prior* to the introduction of these scaffolds. For example, when one student in the 2D condition was asked to use the "Watch a single electron" function, he noted that the function was not useful to him since he was already using Locally-Anchored Landmarks.

1 Pat: I was kind of already doing it... I mean maybe it's good because some people
2 might not do that. Maybe some people would just look and think of the whole and
3 maybe they have trouble focusing on a certain region. I think that might help some
4 people. I don't know if it helps me, it might, but it couldn't hurt.

In other words, participants naturally observed Locally Anchored Landmarks without the aide of external scaffolds. However, all the participants mentioned that both these scaffolds enabled them to follow the trajectory of an electron for a longer time, whereas in absence of the scaffold, the changing composition of the Locally Anchored Landmarks (see lines 15-17 in Excerpt 3) sometimes made it difficult for them to follow the motion of an individual agent beyond a certain length of time. We therefore conclude that these scaffolds are examples of effective visualization aides, as they take advantage of, and help reinforce the participants' natural cognitive tendencies that play a key role in their sense making process during their interaction with the models.

Pre and Post-Interviews

Before and after their interaction with the models, participants were asked to provide mechanistic explanations of electrical current and electrical resistance, and how they are related to Voltage. None of the participants had taken any college level physics or chemistry courses, and they all had taken an introductory physics course in their high school. Their responses were coded for the reasoning at the micro-level, macro level, and whether they used both these forms of reasoning in a complementary manner. Their responses prior to the interview revealed the following:

a) Students often went back and forth between identifying current as an "object" that flows through the wire, and current being the flow of energy that is "carried by" objects. Students were also not able to correctly identify the objects that carried this energy – 80% of the participants mentioned that the carrier objects were atoms, whereas the remaining 20% mentioned that the carrier objects are "whatever matter is made up of" or the "building blocks of matter". All of them, however, explicitly mentioned their inability to recall "what current is made up of" from their high school physics class that they had taken years before the date of these interviews.
b) None of the participants had heard the term electrical resistance earlier, but tapped into the meaning of the term resistance and the general nature of their response was that electrical resistance "had to do something" with the material of the wire that blocked electricity. 12% of the students attributed resistance to be a property of the wire itself, whereas 50% of the students attributed resistance to be due to the material of the insulation coating on top of wires, and 28% of the students claimed that they had no idea of "how resistance works". We also found that students often went back and forth between describing resistance as a property of a substance, and a mechanism responsible for hindering electricity.
c) On being asked to explain the idea of Voltage, all of the participants associated it with a battery. However, when the interviewer probed further, they were unable to provide any account of a mechanism that might be responsible for the generation of voltage. On being asked how Voltage was related to electric current, 60% of the students also explained that they believed voltage to be the "power" of current, whereas the remaining 40% of the students were unable to provide any detail about the relationship between current and voltage.

These responses reveal that the participants' knowledge about electricity is primarily phenomenological in origin – i.e., acquired from the ubiquitous presence of electrical circuits and appliances (bulbs, wires, etc). In order to explain electrical resistance, they tapped into the semantic meaning of the term "resistance", and applied the meaning in the context of electricity. However, despite the ubiquitous presence of electricity in everyday life, we do not have access to the micro-level objects and mechanisms involved in the generation of electricity. This was reflected in the students' inability to explain the emergent processes of current and resistance in terms of individual level objects such as electrons and nuclei, and positive and negative charges in the battery terminals.

Post-interview Questions	**Responses**	**Micro-level Objects**	**Interactions between micro-level objects**	**Emergent Phenomenon**
How would explain what is electrical current based on your interactions with the model?	Current is how fast the electrons are moving towards the positive end due to the voltage	Electrons	Force on electrons towards the positive end due to applied Voltage	Current
How would explain electrical resistance based on your interactions with the model?	Resistance is due to the collision-rate.. the nuclei cause the electrons to scatter around.. kind of gets in their way	Electrons, Nuclei	Collisions of electrons with the nuclei	Electrical resistance
How would explain the relationship between Voltage, electrical resistance and current interactions with the model?	Current is like the net impact of voltage…. and the impact depends on the collision-rate.. I mean if the collision-rate is higher, the impact of the voltage on the electrons will belower… they will take more time to get to the positive	Electrons, Nuclei	Force on electrons towards the battery-positive, Collisions between electrons and nuclei	Current, resistance

Table 1: Levels of Explanation in Interview Responses

The participants' responses to the same questions after their interaction with the models revealed significant shifts in terms of the "levels" (Wilensky & Resnick, 1999; Sengupta & Wilensky, 2006) in which they explained the phenomena of electrical current and resistance. Table 1 below shows sample responses and the coding scheme we used to identify the "levels" of explanations in them. All the participants in each group were able to identify the individual micro-level agents and the rules of their interactions responsible for the emergence of electrical current and resistance – electrons, whose net motion towards the battery positive due to an applied voltage gave rise to electric current; and the nuclei, whose presence in the wire caused the electrons to "scatter around" and thus give rise to resistance. No difference was found between participants in different groups in terms of accuracy of these responses.

Section 6: Discussions

Isotropic 2D and 3D Systems and Implications For Learning

Overall, there were few differences between participants' use of Locally-Anchored versus Globally-Anchored Landmarks in understanding 2D versus 3D models, and even fewer differences in the depth of understanding that those students came away with after interacting with the models. In fact, one could argue that the main results of this pilot study are that a) participants' use of visuospatial perspectives, primarily manifested in terms of Globally and Locally Anchored Landmarks, was independent of the dimensionality of model with which they interacted; and b) there was no difference between the three experimental groups in the accuracy of understanding of electrical current and resistance after their interactions with the models. However, as we have pointed out, there may be some differences in how students construct or utilize LAL or GAL, depending on perspective and dimensionality. For example, in case of one participant who interacted with the 3D model only in the "Dive In" mode, locally anchored landmarks, such as a small collection of electrons, were triggered (indeed, defined) by the globally anchored landmarks such as the grey region in Fig 3C depicting the battery positive.

However, it is important to interpret this result in light of our discussion in Section 1.2 – that this model is representative of *isotropic* physical systems, where an added dimension does not alter or modify the behavior (or provide new or different information about the behavior) of individual agents in the system, and/or the overall systemic behavior. Whether our main result would hold true for an multi-agent based model of an anisotropic physical system, is a question that needs to be investigated further. In fact, as we have discussed in section 1.2, we would argue that we are likely to find differences between learners interacting with 2D vs 3D models when these models depict anisotropic physical systems, and that these modes of interaction – how students determine and process differences in dimension in anisotropic systems – are a point of interest for future work.

Landmarks, Agent-Specific and Emergent Phenomena

It is important to note that our study examines how students interact with and make sense of emergent phenomena using an agent-based model. Because of this, students must concentrate on two distinct levels of behavior: the behavior of individual electrons (randomly walking while being pushed and pulled toward the batter-positive terminal), and the overall trends in behavior of those electrons when taken as a whole (an apparent migration of electrons through the wire). This, not surprisingly, maps particularly well to the concept of Locally Anchored and Globally Anchored Landmarks. It might be that, in order to make sense of behavior at a micro level, Locally Anchored Landmarks are more appropriate because they enable participants to isolate and evaluate agent behavior with less attention to the overall phenomena to which it might be contributing. Similarly, Globally Anchored Landmarks might be appropriate when one wants to understand the general trends exhibited by the model. Our results, as discussed in Section 3.3, provide preliminary support for the hypothesis that learners use these differential affordances when interacting with models: learners throughout the different experimental conditions employed Locally Anchored Landmarks to understand the effect of collision-rates on *individual* electronic trajectory. This, in turn, provided them with a sense of mechanism for understanding electrical resistance in terms of collisions between electrons and nuclei. Globally Anchored Landmarks, on the other hand, were employed by all participants to understand the impact of Voltage and Collision-rate on the *net* speed of the electrons towards the battery positive. This provided them with a sense of mechanism for understanding electrical current.

On the other hand, one could argue that we employ Locally-Anchored and Globally-Anchored Landmarks to understand *all* dynamic phenomena whether or not it is representing both micro- and macro-level events, and that it is the observation of these different types of landmarks that bring our attention to these different levels. Results indicate that participants' attention to LAL versus GAL was sporadic – that is, that participants frequently and quickly switched between the two approaches. If participants only paid attention to those types of landmarks that were more appropriate for a specific question or topic, we might instead expect focus to remain on one type of landmark or the other as they explore that topic. We suggest more work be done to disentangle exactly how Locally-Anchored and Globally-Anchored Landmarks relate to micro- and macro-level phenomena, as they might suggest that more attention be paid to how students might utilize LAL and GAL, as well as how one might inspire students to look at models using these different approaches.

Looking Forward

In Herbert Simon's terms, one can think of any designed artifact as an interface between an "inner" environment, the substance and organization of the artifact itself, and an outer environment, the surroundings in which it operates. The success of the design then depends on whether the inner environment is appropriate to the outer environment (Simon, 1965). In our case, the "inner" environment pertains to the various aspects related to the design of the NIELS 3D models, as well as the activities embedded in the models. The "outer" environment is the mind of the learner. We believe that visualization is an important aspect of the learner's cognitive processes, i.e., the "outer" environment of the design. We hope that studies such as this will continue, and that they will help us to better understand the learners' sense making process as *he/she* interacts with a 2D or 3D learning environment *in terms of how learners process and understand the visuospatial information contained within.* We believe this to be an important branch of research with important implications for the design of learning environments.

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