Enacted Misconceptions: Using Embodied Interactive Simulations to Examine Emerging Understandings of Science Concepts

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Abstract: In this paper we describe an approach to examining and potentially diagnosing middle school students' misconceptions and emerging understanding about science concepts using immersive and interactive simulations. There are varying views in the literature on the nature of science misconceptions and the role they ought to play in learning interventions, but we focus here on their manifestation in physical activity as opposed to their detection via standardized inventories. We describe a novel framing of incorrect and emerging notions of science, and we illustrate this framing with descriptions of students' embodied interactions in an immersive digital simulation of planetary astronomy. Through live observation and video analysis we identified 9 misconceptions that were made visible through the student's bodily activity rather than through verbal accounts. We conclude with a discussion of how these same diagnostic environments may be used for instruction and remediation.

Introduction

Recent developments in interactive and immersive digital environments have opened new opportunities not only for instruction, but also for understanding and diagnosing students' misconceptions and developing ideas. Commonly thought to arise out of everyday experience in the physical world, misconceptions are qualitative intuitions or pre-conceptions that are resistant to change, even when confronted with traditional forms of instruction. While there are many viewpoints in the literature on the precise nature and origins of science misconceptions (e.g., naïve theories, knowledge fragments, etc.) the methods employed to identify student misconceptions and primitive understandings of physical phenomena has consistently relied on clinical interviews and subsequently developed paper-based inventories with schematic representations and multiple-choice questions. While we acknowledge that these instruments have provided valuable insights into facets of students' scientific reasoning, we believe they may be limited in their ability to detect the kinds of flawed conceptions and primitive ideas that are revealed not through students writing and spoken words, but through their actions in the physical world. A reliance on concept inventories for probing student misconceptions continues despite the emergence of interactive technologies that make it possible for learners to "act out" their knowledge—which includes misconceptions and emerging ideas—and make qualitative real-time predictions of the behavior of a physical system (e.g., Dede, Salzman & Loftin, 1996).

In this paper we put forth the notion of "enacted misconceptions" and we discuss the potential to use interactive technologies to make explicit the intuitive and developing ideas about science as revealed through a learner's bodily actions. This approach is based on recent advances in understanding the role of embodiment in conceptual development and learning. We explicate this framing by describing a set of specific enacted misconceptions that were revealed by middle school students using a full-body immersive simulation of how objects move in space. Finally, we discuss the potential for using the same kinds of interactive environments utilized for diagnostic purposes as a means of instruction and building up correct intuitions.

The Embodied Origins (and Expressions) of Science Misconceptions

Research on conceptual development in science over the last several decades has vigorously investigated the causes underlying students' consistent and robust errors with common science problems. They are variously described as common sense beliefs (Halloun & Hestenes, 1985), preconceptions (Clement, 1982), or as an 'intuitive sense of mechanism' (diSessa, 1993). As for the source of these intuitions or preconceptions, researcher frequently point to the influence of everyday experience in the physical world. For example, at the source of students' idea that "motion implies force" are everyday observations that objects stop moving unless a force is applied to them. The absence of an observable agent causing the counterforce (e.g., friction) likely accounts for students' difficulty in appreciating Newton's First Law.

Experiences giving rise to faulty intuitions are normally thought to be detached observations of everyday situations (e.g., watching a ball roll across the floor). Less attention has been given to the possibility that personal bodily sensations and experiences may be the basis for faulty conceptions about the physical world. For example, people traveling in a car that steers sharply will feel "pushed" against the door, potentially leading to the (incorrect) notion that centripetal force is directed outward from the center of curvature. Not only is it likely that these ideas about force *originate* from body-based actions in the world, it is also possible that these ideas are primarily *expressed* through embodied interactions. Thus, individuals in a sharply turning car may very well report consistently that the force is outward, but people looking at a diagram of circular motion are likely to vary widely in their interpretation of the system's forces (though perhaps with still very few people stating correctly that the force is directed inward). The point is that while most significant learning theories, including the Piagetian model, place prominence upon people's physical actions in the environment, knowledge is still typically inferred from whatever abstract and symbolic representation can be articulated verbally.

Contemporary research and theoretical developments in psychology and philosophy have challenged the symbolic view. Goldin-Meadow, Alibali, & Church (1993), for example, argue that children's body movements (and specifically gestures) play an important role in cognitive development and facilitating the process of learning (c.f., Abrahamson, Trninic, Gutierrez, Huth, & Lee, 2011; Antle, 2013). Theories of embodied cognition maintain that even complex concepts are derived via the perception of our bodies (Johnson, 1987). On the more radical side of embodied cognition theory, some researchers have argued that all cognition is essentially a process of activating simulations of bodily action (Barsalou, 1999).

If it is the case that cognition is inseparable from the actions and sensations of the body, then it makes sense that one would look to bodily behavior as a means of examining a person's understanding (or misunderstanding) of scientific phenomena such as principles of physics. In particular, it makes sense to create diagnostic environments grounded in the perspective of one's body (Gallagher, 2005; Lindgren, 2012). Advances in computer technology and specifically in the area of augmented and mixed reality make these kinds of immersive diagnostic environments possible.

Traditional Approaches to Examining Misconceptions

The diagnosis of students' misconceptions in physics primarily utilizes paper-based schematic representations (or web-based equivalents) often accompanied by explanatory or descriptive text. The examples describe or represent a situation requiring the application of the rules and principles of physics. For example, students may be asked to describe the forces acting on an object thrown upwards or, more often, select among 4-5 drawings representing the correct forces as arrows. Through examples of this kind, researchers and teachers gain insight into whether students hold naïve concepts of physics; in this particular case, students may select an answer containing 2 forces (one upwards and one downwards, this latter the force of gravity) while the only force acting on the object is the force of gravity. The foundational studies on physics misconceptions (McCloskey, Caramazza, & Green, 1980; Clement, 1982; Halloun & Hestenes, 1985) combined these representations with clinical interviews to elicit reasoning and explanations. From these studies, multiple-choice tests were developed based on common answers given to these questions (e.g., Force Concept Inventory (FCI); Hestenes, Wells, Swackhamer, 1992). Note, however, that even in their pre-multiple-choice origins, the misconceptions questions were rooted in students' verbal accounts of their reasoning while passively observing diagrammatic representations. We certainly do not deny that these traditional instruments have value in revealing errors in students' verbal processing of physics problems, but if one accepts the idea of misconceptions as a deeply intuitive misunderstanding expressed through behavior, then it is quite possible that these paper-based instruments are insufficient for fully characterizing student conceptions.

The impact of representational formats in students' performance on assessments is, as in a variety of other subjects, well known in physics learning. For example, Meltzer (2002) conducted research on the discrepancy between student performance with physics problems presented with sketches and text versus graphs and text. He found that answers designed to reveal student misunderstanding differed in relation to the formats used. The study suggested that students had acquired sophisticated strategies to interpret graphical representations in relation to specific questions, answering them often correctly; but interviews showed that students still did not have an intuitive understanding of physics governing the behavior of real-world objects. Hestenes (1996) emphasizes that the success of teaching of physics depends crucially on the representations being used, with multi-layered integrative models capturing the dynamic of the physical world being among the more successful ones. Likewise, success in assessments depends on the way in which knowledge is enacted, whether it is text, graphical representations or, indeed, computer-based dynamic simulations. Theoretical support of this position is provided by diSessa's (1993) notion of "knowledge in pieces." He proposes that students do not hold a systematic and consistent naïve theory of physics but rather a loose collection of notions about specific situations. This may mean that placing students in contexts in which they have not yet been tested may show a wider range and diversity of conceptions than normally uncovered by paper-based tests. Further, embedding students in action-based environments that more closely resemble the contexts in which this knowledge would be applied would presumably allow the diagnostic process to focus on the ideas and situational understandings that are most in need of further development and remediation. Indeed, part of the success of novel digital learning environments, and especially interactive desktop-based simulations (e.g., Adams et al., 2008), may derive from the ability of these systems to tap into learners' misconceptions not revealed by "static" multiple-choice questions, though clearly systematic studies are needed to investigate this possibility.

The Potential to Use Interactive Learning Technologies to Examine Misconceptions

Previous attempts to use novel and technology-enhanced learning environments to uncover incorrect ideas and intuitions about the physical world are sparse. Bates and Galloway (2010) surveyed recent uses of diagnostic methods in a mechanics courses and found that sketches depicting real-world objects combined with text and multiple choice questions remained the standard. This includes examples where simulations and other digital tools were used for learning and instruction, but when it came to assessing the presence and persistence of misconceptions, these studies still relied on traditional inventories and diagrammatic representations. This is to a large degree justified by the availability of a very large amount of data collected over decades relying on standard examples and therefore available for comparison. Though these data continue to confirm the internal validity of standardized tests (i.e., coherence of answers across test examples in relation to assumed deep-seated misconception), little has been done to examine how misconceptions might be changing or vary in their appearance given the availability of contemporary learning technologies. Unfortunately, the impact of learning technology is often seen as increasing student engagement and interest, not as an expanded context for application and assessment of critical concepts.

Unlike more passive and didactic instructional approaches, interactive learning technologies (e.g., computer simulations) focus on actions in realistic contexts, and they are designed to give learners opportunities to experience the effect of their actions (Dede, 1995; de Jong & van Joolingen, 1998; Lindgren & Schwartz, 2009). In addition to creating powerful learning interventions, these environments also permit researchers and instructors to observe students' real-time actions and choices that may reveal problematic intuitions and misconceptions about science. By placing the learner in a realistic environment, she may mobilize deep-seated intuitions, exposing them to experimentation and reflection, and making them amenable for change. It is important to note that an interactive technology environment for exposing primitive concepts does not need to be completely unstructured. Guidance through the use of the simulation or visualization technologies can still be provided, as long as there are built-in opportunities for learners to make choices and articulate predictions. As suggested earlier, we are particularly enthusiastic about the potential for revealing misconceptions with *embodied* interactive simulations, where learners not only take action within a digital environment, but they physically enact their understanding through gross gestures or full-body movement. In the next section we describe the design of one such embodied interactive environment.

The *MEteor* Simulation of Planetary Astronomy

The remainder of the paper examines a particular simulation environment and how we used it to identify several specific body-based misconceptions—what we have termed enacted misconceptions—pertaining to an understanding of how objects move in space. The *MEteor* simulation that we developed at our lab study is a large full-body simulation of planetary astronomy. Learners launch a virtual asteroid into a simulation of outer space (planets with gravitational forces, etc.), and run with the asteroid, predicting its trajectory in real time. The simulation consists of 4 different levels that require the learner to accomplish certain tasks, such as hitting a target with the asteroid that is located behind a planet, or putting their asteroid completely in orbit around a planet. The simulation was built in collaboration with physicists and physics educators to ensure accuracy of the science principles being represented.

The system is made interactive with laser-scanning technology that monitors the learner's movements across the floor display, and gives feedback on her success in following the asteroid. While the learner can move freely across the simulation, cuing mechanisms and feedback have been implemented to help guide the learner. For example, if the learner ever gets more than about 4 feet away from the asteroid it will disappear and the leaner will have to re-launch. Nonetheless, there is still ample room for learners to make inaccurate predictions and move in ways that are counter to core physics principles.

Enacted Misconceptions of How Objects Move in Space

Fifty-seven students from local middle schools used the *MEteor* full-body simulation for about 15 minutes each, working independently through the objectives of the 4 different levels. Students were given basic instructions on how to interact with the simulation but were largely free to explore and move in ways that they felt would best accomplish the objectives (i.e., hitting a target). We rely on the analysis of students' behavior as visible in video recordings as well as our live observations and field notes when the study was being conducted. In our review, we observed fairly consistent behavior indicating incorrect and emerging ideas about how objects move in space. These misconceptions and primitive ideas are much more specific than the kinds of misconceptions typically diagnosed by traditional instruments, reinforcing Liu & McIsaac's (2005) argument that the manner in which naïve physics intuitions gets applied depends on the kinds of questions, prompts, situations, and objects they are exposed to. There is good reason to believe that participants possess these incorrect ideas because they are actively trying to make accurate predictions to succeed in a game-like environment (as opposed to inferring

Table 1. Enacted misconceptions that were observed from video analysis of middle school students using the *MEteor* simulation.

***MEteor* Level and Objective**	**Observed Behavior**	**Specific Misconceptions**
Level 1: Launching the asteroid at a distant target (no other objects present in the simulation)	Participants frequently slow down and occasionally speed up when traveling to the target.	1.1. Moving objects in space behave like objects moving on Earth, which typically slow down over time
Level 2: Launching the asteroid at a target with a large planet nearby	Participants almost always begin by launching the asteroid the same way they did in Level 1. Participants also typically fall behind the asteroid, i.e. fail to predict gravitational acceleration	2.1. Gravity doesn't have a significant effect on objects that are relatively far away 2.2. Objects being pulled by planets will move with a constant speed toward the planet
Level 3: Launching the asteroid at a target with a small planet directly in front of it	Participants typically start by launching the asteroid from the far sides of the simulation platform in hopes of hitting it at an angle Participants are often lagging behind the asteroid and sometimes not anticipating strong gravitational acceleration and bending Participants frequently move as though they expect the gravity to be much stronger, responding similarly to how they moved with the larger planet in Level 2	3.1. Gravitational forces exerted by planets will move objects in motion directly towards the planet 3.2. The mass of a planet (different sized planets of equal density) does not affect the magnitude of gravitational force
Level 4: Putting the asteroid into orbit	The most consistent problem was that participants did not launch the asteroid tangentially, or slowly enough When participants successfully got the planet into orbit, they often moved around the planet with constant speed Most participants also moved as though they expected the orbits to be circular	4.1. Objects traveling directly at a planet will get into orbit by being swept up by "orbital forces" surrounding a planet 4.2. Objects in orbit move at a constant speed around the planet 4.3. Orbits are circular 4.4. Orbits require inherent force to be maintained

these misconceptions from their verbalizations). This configuration leads the participants to mobilize their ideas and intuitions and make them visible.

Table 1 lists the misconceptions that we observed in *MEteor*. These are organized according to the simulation level in which the enacted misconception was typically exhibited, and they are accompanied by the behavioral observations that suggest the primitive understanding. Figure 1 shows participants exhibiting a couple of the misconceptions described in the table. To be sure, observations of some of the students' behavior are consistent with ideas tested in traditional inventory assessments. This includes the observation that students frequently launch the asteroid with a force that is not required to get the asteroid to the target, suggesting the common misconception that objects stop moving quickly because their internal force dies out. That said, applying the notion that students have an "impetus" theory of motion to this particular simulation context is not sufficient to explain the list of enacted misconceptions in Table 1—it does not explain for example why a child

Figure 1. Left: Student exhibiting enacted misconception 2.2. The student's body is moving at constant speed, but the asteroid depicted in the simulation is accurately responding to the force of gravity by accelerating and is about to crash into the planet. Right: Student is exhibiting enacted misconception 4.2. The asteroid depicted in the simulation has just sped up as it moves closer to the planet, but the student had assumed the orbiting asteroid would move at constant speed and almost falls over in an attempt to catch up to it.

does not slow down when they are enacting an asteroid's orbit around a planet and the asteroid is at a point in the orbit that is a further distance from the planet.

Of particular value with this simulation experience were the insights it gave to how children think about phenomena that cannot easily be observed or depicted in a diagram, such as the less-local effects of gravity. Observed behavior from level 3 of the simulation demonstrated that students often underestimate the impact of gravity not only on the asteroid's speed but also on the direction of its trajectory. The way that students typically angle their launches suggests that they are not initially taking into account that gravity's influence is persistent even at far distances. Equally interesting was how students seemed to reason about orbits. Many students would use the word "ellipse" to describe an orbit, but their bodies suggested that they believed orbits to be perfectly circular. Likewise, a participant would typically move as though they anticipated the asteroid to travel at a constant speed in its orbit, expressing surprise and sometimes nearly falling over as they scramble to catch up with the asteroid accelerating when it gets closer to the planet.

Especially problematic were participant's attempts to put the asteroid into orbit in the first place. This often entailed direct launches at the planet, perhaps suggesting that they believed there was some sort of invisible orbital field that would suck up the asteroid and put it into circular motion, like an object dropped into a draining sink. The enactments we observed in several of the levels suggested difficulty understanding the relationship between an object's initial velocity and gravitational forces exerted on the object; gravitational acceleration is a phenomenon that is difficult to observe on Earth since we typically can only see objects falling for short periods of time. While it may not be surprising that middle school students were challenged by these ideas, it is important to recognize that it would not be easy to pose a question on paper or even verbally to elicit these intuitions and misconceptions.

While the focus here has been on diagnostics and identifying the kinds of misconceptions that are only revealed through embodied interactions, there is clearly the potential to utilize these same interactive environments as a means to instruct and evolve primitive conceptions. Once an enacted misconception is identified, such as the tendency to represent an orbiting object with constant speed, targeted feedback administered in real time and exposure to varying contexts that highlight critical relationships can be designed into the simulation. Importantly, the context of diagnosis is not separated from the context of remediation, as often occurs in traditional instructional contexts. The enactment of misconceptions is not a symptom of faulty knowledge, it is itself an expression of knowledge, that when exposed and made visible provides opportunities for direct intervention and development.

There is great promise in using embodied and interactive simulations to examine primitive conceptions, but there are certainly limitations to this approach that must be considered as well. There are limitations, for example, on what actions the human body can perform such that it may be difficult to express accurate and complex ideas. It would be near impossible, for instance, for *MEteor* participants to have moved fast enough to represent the velocity with which an asteroid is capable of traveling around a planet (relative to its approaching velocity). The inability to recreate this pattern of motion with one's body certainly should not be taken as an indication that they do not understand the underlying physics. It is also important not to assume that correctly enacting a science phenomenon means that a person necessarily understands the causes of the phenomenon. Accurate performance can sometimes occur accidentally or is based on observations without appreciating underlying mechanisms. It is important, therefore, for interactive learning environments to elicit embodied performances that reflect deep understanding as opposed to surface-level descriptions of events.

Concluding Remarks

Recent models of cognition and learning have emphasized its embodied nature understood as the bodily enactment of thinking (Gallagher, 2005; Wilson, 2002). These views contend that there is a deep connection between thinking and bodily activity, and prescribed forms of physical movement may aid cognitive processes and increase the propensity for learning (Goldin-Meadow, 2005). In recent years increasing attention has been given to instructional environments and methods that incorporate body movements with the aim to help people build connections between their physical experiences and important principles and ideas in STEM domains (Abrahamson & Lindgren, in press; Goldin-Meadow, Cook, & Mitchell, 2009). Embodied learning is made especially relevant in relation to the development of immersive interactive environments that allow seeding of bodily activities (Lindgren & Johnson-Glenberg, 2013). However, while these systems show considerable promise to develop new forms of learning, less attention has been given to the possibility of using these systems to identify primitive and emerging conceptions. While the important role of interactivity in learning has being recognized and the use of interactive systems is being utilized in a range of STEM learning environments, often the impact of interactivity is conceptualized in relation to increased engagement, enjoyment, motivation and other indirect measures of learning. Now that immersive and interactive digital environments can confront learners with novel and highly contextualized scientific events, the possibility for access to different forms of knowledge than what is available in traditional diagnostics needs to be given serious consideration.

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