A knowledge analytic comparison of cued primitives when students are explaining predicted and enacted motions

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Abstract: The Knowledge in Pieces theoretical perspective posits p-prims as an important knowledge element in intuitive reasoning. Because p-prims are a class of knowledge elements developed and abstracted from everyday physical experiences, it seems plausible that immediate physical experiences, both in terms of sensations and actual observations of motion, would cue knowledge in different ways than when those experiences are just discussed as hypotheticals. This paper presents two cases to show that immediate embodied experiences with everyday objects does change which p-prims are cued and how they are deployed by students to explain situations involving motion. These cases come from a corpus of videorecorded interviews with high school students who were asked to explain predicted and enacted motions that involved deliberate sensory engagement with their bodies. Findings suggest that a connection is indeed present, and learners' embodied experiences should be leveraged in future work to support conceptual change in science.

Keywords: conceptual change, embodied cognition, p-prims, knowledge in pieces, intuitive knowledge

Introduction

While there are still various frameworks actively used for analyzing students' intuitive knowledge, particularly in science, several learning scientists have found a "complex systems" approach to modeling knowledge to be especially fruitful (Smith, diSessa, & Roschelle, 1993). This approach, often associated with diSessa's "Knowledge in Pieces" (KiP) theoretical framework (diSessa, 1988) is especially apt for explaining why student reasoning exhibits discernable variability and change in response to changes in the immediate context (Sherin, Krakowski, & Lee, 2012). KiP posits that such dynamical knowledge and its interactions can be productively and precisely modeled as a diverse set of elements of varying form and content. These elements are activated under different situational circumstances to produce explanations, expectations, or predictions of natural phenomena. Conceptual change results from continual exposure to such situations and transforming what set of knowledge elements gets cued in the desired contexts.

My goal in this paper is, with a KiP orientation in mind, to demonstrate that deliberate introduction of embodied, kinesthetic, or sensory experience is an important feature for cuing knowledge elements. Consistent with growing interest among learning scientists (e.g., Hall & Nemirovsky, 2012; Lee, 2015) and cognitive psychologists generally (e.g., Barsalou, 1999), I take seriously the notion that embodied actions and experiences have detectable consequences on how students think and learn. As they do not map well onto existing knowledge representational schemes, they have been underrepresented in intuitive knowledge research. However, I expect that for students who are still developing technical understandings of physics, we should see notable changes in students' explanations when they begin to consider and integrate immediate embodied experiences in their reasoning. Stated by way of example, I hypothesize that describing principles about how an imagined object will move across a surface when a force is applied will yield different thinking than explaining what happens when one is doing the work of actually physically moving an object across a surface. A more robust understanding of whether and how student thinking responds to immediate embodied experience would better inform how we could design instruction that will reshape students' intuitions.

This paper has modest aims. Specifically, I focus on showing the phenomenon of explanation change when students experience specific motions. The descriptive analyses describe what knowledge elements are cued before and after those motions are enacted. In the next section, I briefly elaborate on the KiP perspective. This is necessary to provide a vocabulary for describing knowledge. Then I will describe the methodological approach I used, *knowledge analysis* (diSessa, Sherin, & Levin, 2016), and the data I obtained. Two cases of student reasoning about motion are presented. In both cases, the students cued new knowledge and articulated the importance of immediate embodied experience in shaping how they thought about the motions.

Knowledge in Pieces

"Knowledge in Pieces" (KiP) is used to describe a complex knowledge system consisting of diverse knowledge elements that are dynamically cued and activated to help people function in the world. While the underlying knowledge system posited in KiP has elements that are diverse in both form and content, one kind of knowledge element that has been identified and heavily discussed, particularly in physics understanding, is the *phenomenological primitive* or "p-prim" (diSessa, 1993). These elements are primitive in the sense that they are thought to behave like atomistic units of conceptual reasoning; they are a specification of structurally simple relational or causal schemas that are often treated as self-evident when invoked. For instance, if a physics novice were asked why standing farther from a bell makes the sound of the bell softer than if they were standing close to it, we would expect a response to be something to the effect of "because that's just what happens." In this case, the observation that the sound of a bell seems to diminish or soften as one stands farther away from it does not need nor does it have any further intuitive explanation. This is because sounds exhibit a behavior of *dying away* over time and space, where *dying away* is a p-prim that asserts the eventual diminishing and ending of some effect over time or space. This particular primitive is also applicable to a range of other common situations: standing farther from a heat source, observing the back-and-forth motion of an empty swing eventually coming to a stop, or a rolling ball eventually coming to a stop on a flat surface. Such origins are part of why p-prims are considered phenomonelogical. They are developed from everyday experiences and observations in the physical world. Other commonly noted p-prims include *Ohm's p-prim*, which schematizes a set of qualitative relationships connecting increased effort necessary to bring about a comparable effect in the face of increased resistance and *cancelling*, which is schematized as opposing influences that negate one another's influence. These primitives will appear later in my analyses.

It is important to note that p-prims are not the only knowledge element posited within the KiP perspective. Others have identified "e-prims", a larger category of *explanatory primitives* that function similarly to p-prims but are not schematizations in the same way (e.g., "Gravity pulls things downward") (Kapon & diSessa, 2012); *symbolic forms*, which link aspects of external representations to conceptual schemas (e.g., equal sign understood as balance) (Sherin, 2001); *nominal facts*, which are accurate but relatively shallow, general assertions (e.g., "for every action there is an equal and opposite reaction") (diSessa, 1996); *narratives* such as potential energy converting to kinetic energy as a car moves up and down a roller coaster (diSessa, 1996); and several others. Several of these will also appear in the analyses below.

Embodiment and Embodied Cognition As Relevant to KiP

Embodied cognition serves as counterpoint to earlier models of cognition that have emphasized "disembodied" computational symbols for representing knowing and understanding. While there are several features and variations in what is considered to be embodied cognition (Wilson, 2002) and also some concern that embodiment need not be linked to cognition specifically, the common presuppositions are that we have bodies that have sensory and motor capabilities and that experiences in the world with those bodies fundamentally shape knowledge and action. Stated simply, bodily experiences matter for why we think in the ways that we do.

Of relevance to KiP and to p-prims is the posited basis of how p-prims are developed and identified. In diSessa's list of 15 heuristics for recognizing p-prims, he states "P-prims are likely to be abstracted in internally evident terms, especially early in development. Thus agency, muscle tension, and so on are likely to be represented in important base vocabulary for p-prims." (diSessa, 1993, pp. 122-123). This statement and others published elsewhere that tie sensory information to the formation of p-prims (e.g., Kapon & diSessa, 2012) suggest that while the p-prims are knowledge elements abstracted from everyday experience, they still have strong genetic ties to sensory experience. Forces, for example, come to be understood because we feel exertion and tension in our bodies. My proposal is that the connection extends beyond genesis. Rather, ties still exist that lead to cuing of p-prims during immediate sensory experiences.

One additional connection between KiP approaches and embodied approaches is in how information is extracted from readings of a situation immediately at hand. In proposing *coordination classes*, a KiP-based construct for more precisely characterizing the structure and composition of entities we colloquially call concepts, diSessa and Sherin (1998) also identify *readout strategies,* or what is now referred to as *extractions* (diSessa, Sherin, & Levin, 2016). These are "readings" of the present situation, such as visual appraisals of distance travelled used to infer speed or observations of reversal of motion to infer change in force. While visual appraisals have been most often featured in published research, I expect *extractions* can operate from other sensory modalities. For instance, we "readout" weight from pressure against one's hand or feel impacts against our body. Those should cascade to different knowledge being cued than before such information was extracted.

Methodological Approach

The primary method used was knowledge analysis (KA) of video-records (diSessa, 1993; Sherin, 2001). A recent and detailed articulation of the history of and central principles guiding KA appear in diSessa, Sherin, & Levin (2016). Briefly stated, it involves detailed and iterative review of curated video records to identify verbal or behavioral markers that could be taken as evidence of one or more cued knowledge elements as they are used, with the assumption of dynamic on-line reasoning is being recorded and that reasoning can be modeled. It bears resemblance to microgenetic analysis (e.g., Siegler & Crowley, 1991), but emphasizes articulation of specific knowledge elements and the relations between them.

Data Collection

For this study, 11 high school students (all in their junior or penultimate year of secondary education) who had already completed a year of high school physics participated. These students largely came from one public high school in the US that had an explicit STEM focus and a statewide reputation for excellence in STEM performance and STEM extracurricular activities (e.g., robotics clubs, science fair participation, etc.).

Three interview protocols exploring different physics topics were designed using everyday objects that the students likely had encountered in their lives at some point (i.e., athletic balls, toy trains, and a bicycle). The overarching interview structure was for students to predict and explain an object's motion, to enact and experience that motion, and finally to immediately explain why those motions appeared the ways that they did. Interviews were done after school at a university campus. All interviews were videorecorded and lasted between 30 and 60 minutes each. There was some participant attrition over time. In total, 24 interviews were collected. The two interview protocols relevant to the cases in this paper are summarized below.

Interview 1: Projectile motion with athletic balls

For this interview, the students met with the interviewer in a university gymnasium that was used for a variety of indoor sports (such as basketball, volleyball, and badminton). As such, there were a large number of lines painted on the ground, which were used as reference points in conversations later. Several athletic balls were provided and visible to the student. The task for the student was to explain what forces would be involved when each of the balls were thrown underhand "as hard and as far" as the student could throw them across the gymnasium. The three athletic balls most relevant to the case below and the order in which they were presented include: baseball (diameter = 2.9 in, weight = 143 g), tennis ball (diameter = 2.6 in, weight = 57 g), and a yellow foam ball (diameter = 2.9 in, weight = 47 g).

Interview 2: Collisions with a toy train

The second interview involved multiple collision situations for a toy train that was released from the top of a wooden track (Figure 1). Two are most relevant for the case below. For one, a brick was placed in the middle of the track and the interviewer asked what would happen when the train was released and what forces would be involved, with a specific focus on the moment that the train and the brick were interacting with one another. For the other, they were asked to imagine their flat hand was placed with the palm facing the train and to explain what would happen and why when the hand and train interacted. After these were discussed as predictions with explanations, the activities were all enacted with the train being actually released.

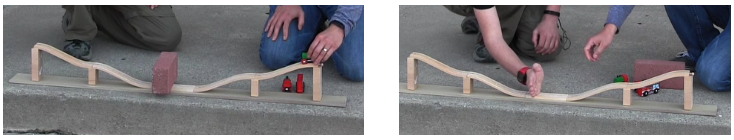

Figure 1. The toy train track used in Interview 2 with a brick (left) and with a hand (right) placed on it.

Analysis

Interview records were all transcribed and iteratively reviewed. While "coding and counting" is not a standard expectation of KA work, all interviews were coded in terms of p-prims and selected other knowledge elements comparable in approach to those documented in Sherin, Krakowski, & Lee (2012). The purpose of this coding was not to generate frequency counts (as frequency can be affected by follow-up questions and student speaking style) but rather to serve as annotation for identifying when knowledge elements were cued, to mark linguistic indicators that served as evidence for inferring particular knowledge elements, and to aid in case selection.

Results

Case 1: Discussing how three balls would differ when thrown

The first case involves Carina (a pseudonym), a Latina student at the STEM high school who reported doing "fine" in physics class, although it was not her favorite subject. For this case, I focus on her discussion of forces involved in the motion of the three aforementioned athletic balls. The argument I make is that both her tactile and sensory experience with the balls led her to shift in how she was reasoning about force.

Before throwing the balls

To begin, Carina was asked about the forces involved in producing the baseball's expected parabolic motion. When given the baseball to hold and asked about the motion that would come from throwing it, Carina immediately talked about a *potential and kinetic energy conversion narrative*. Following an initial discussion of potential and kinetic energy, the interviewer asked Carina about force and to focus on what is happening as the baseball is ascending. (Pauses are marked in parentheses, gestures are described in square brackets.)

> C: It's cause, it's losing force because it's going up [motions hand upward] and not just going down [motions hand downward], cause when it goes down it gets more force because gravity is pulling on it [grasps at the air and pulls downward], but as it goes up [motions hand upward] things are like, it's losing force because things are trying to pull it back down [makes a grasping shape with hand and pulls it downward].
> Int: What is pulling it back down?
> C: Like gravity and, like things are making it stop, like the air [extends arm and makes a pulling motion with her hand toward her body] kind of like makes it draft, have a draft so it is slowing it down [places hands near each other and extends arms outward].

In this excerpt, Carina articulates several different ideas. Many features of her emergent explanation are correct. Carina is aware that gravity is involved in causing a decrease in the upward movement, although she is describing force as being something akin to an impetus that is facing resistance. As far as a p-prim activation goes, it appears that because "things are trying to pull it [the ball] down", *overcoming* is a fine candidate as gravity has some agency and is causing the upward force to decrease and gravity eventually brings the ball down. Other p-prims that could be implicated include *force as a mover,* which would explain why upward movement is expected to be associated with a force (even though the only force being applied is gravity). She also notes how "air kind of like makes it draft" and the draft "is slowing it down". This is one of the first mentions of air and some form of resistance that it creates, potentially pointing toward *Ohm's p-prim*, *overcoming,* and related p-prims.

Following this, the interviewer handed Carina the tennis ball so that she held the tennis ball in one hand and the baseball in the other. She was asked which, if either, would go farther when thrown as hard and as far as she could throw them. She responded that the tennis ball would go farther. Her justification for this was as follows:

> C: Since it is lighter [raises hand with tennis ball slightly] gravity is pulling down on it less so it can go farther because gravity [makes downward pulling motion with tennis ball] doesn't pull down on it as much because the baseball is heavier.

Carina has ascertained that the tennis ball was lighter and would travel farther. She had honed in on muscle tension (as suggested by her arm movements) to keep the ball upright as an extraction, which she articulated as an inference that the tennis ball was lighter. However, gravity is discussed in terms of producing some resistance on the upward motion of the tennis ball, but by virtue of having extracted lighter weight from holding the tennis ball, she inferred the tennis ball should be less affected. While it may look similar to *Ohm's p-prim* in that she described gravity as giving the same amount of influence, I contend it is a different element that was cued because the lighter ball received less of that influence due to its reduced weight ("gravity is pulling down on it less…"). While not previously named as a p-prim, this qualitative proportionality (Forbus, 1984) of *smaller is less affected* is consistent with being akin to an explanatory primitive. Here, different elements were cued in response based just on extracted weight.

Carina then returned the tennis ball and was handed the yellow ball, which she then held in one hand while holding the baseball in another hand. She squeezed the ball and then held both balls in front of her. When asked which, if any ball, would go farther and why. Carina answered:

> C: The yellow ball, again it's lighter. And (6.0) [holds baseball and yellow ball next to one another]. It is a little smaller than the baseball too.
> Int: Does being smaller help it?

C: Yeah because it gets- [motions with her hand in front of the yellow ball and pushing fingers in the direction of the ball] air doesn't like press onto it more. Like it gets less drag because it's smaller.

She stated that the yellow ball should go even farther than the tennis ball. While she did not talk about gravity again, her mention of "again it's lighter" suggested that the same justification she offered immediately prior for the tennis ball should apply. Gravity would not push the yellow ball down as quickly because *smaller is less affected* (applied to weight). However, she held the two balls together and extracted size information based on visual appraisal, also concluding that the yellow ball is visually smaller. When asked if that helped, air is revisited as resistance. Again, it resists what appears to be forward motion based on her gestures, and again involves the *small is less affected* primitive, applied to size. Here, extraction of more information, namely apparent size, led to a slightly different articulation of what behavior was predicted. In total, simply by being given different objects to hold and examine, Carina exhibited some changes in what primitives were cued. This becomes more pronounced and changed more abruptly after throwing the balls.

After throwing the balls

Prior to each throw, Carina was reminded to throw every ball as hard and as far as possible each time she used a new ball. The baseball did not go as far as the tennis ball. The interviewer asked what had happened and why.

C: The baseball didn't go as far because it was heavier than the tennis ball [pulls downward with both hands] so gravity was pulling down on it more to make it fall to the ground sooner [continues to pull downwards with hand]. And, um, the tennis ball is also-is also smaller so it has less of an air drag than the baseball.

In this explanation, much of what Carina said was consistent with what she had said earlier in her explanations for the three balls above. Gravity was pulling the tennis ball down less than the baseball because *smaller is less affected* (applied to weight) by gravity's pull. She also added that the size, which she had not extracted before but noted this time as being salient, was different in that the tennis ball was smaller. Therefore, *smaller is less affected* was applied to size, which would be less affected by air drag. Given less resistance from both air and gravity, it was sensible for her to conclude why the tennis ball went farther. She then threw the yellow foam ball, which did not land as far as the other balls. When asked about what happened, she replied as follows.

C: Well, since it was lighter – um, the, it wasn't pushing on the air as much as the tennis ball and baseball. Also, um (4.4) well, that is like the major difference. (2.1) The tennis ball (3.0) I can't really think of it now that they're out of my hands, but um, (3.5) the yellow ball went shorter because …it had more air [opens and closes hands] it couldn't go through the air as easy as the tennis ball and the baseball because it was lighter than them [brings hands together] and it caused more of an air drag and it fell to the ground sooner [pulls hand downward] because it couldn't push [makes swiping motion with hand] through the air as easier.

Of note is her explicit statement, "I can't really think of it now that they're out of my hands," indicating that the immediate sensory information mattered to her. Moreover, in trying to reason through it, Carina had extracted a weight difference. Size was no longer a high priority extraction, and she said the lighter weight made it less able to move through air. This conflicts with what she had said for the tennis ball just prior and for the yellow ball before any throwing. After throwing, *Ohm's p-prim* was cued to explain the reduced distance. In this moment, the sensations she experienced handling and throwing the yellow ball, combined with it landing behind the other balls, led to a shift in what information was extracted and what p-prim was cued to explain the motion. Before the throw, the yellow ball should be less affected because it was lighter. After, the yellow could do less to affect things because it was lighter.

Case 2: Discussing differences in toy train collisions with a brick or a hand

Another student from Carina's school, Isaac, was noted by his peers as an exceptionally strong physics student and science student generally. This case examines how this student responded to questions in interview 2, involving the toy train and collisions with a brick and with his hand (a difference in direct sensory experience).

Before releasing the train

When first shown the brick and asked about what would happen, it was quite evident that *bouncing* was an active p-prim because he explicitly said so: "it [the train] might bounce and stop." Follow up questions were about force and what happened when the train and the brick were interacting with one another at the bottom. (// denotes overlapping speech)

> I: Um, the train is exerting force on the brick. The brick is exerting an equal amount of force. The brick might be (0.8), yeah they are exerting an equal amount of force on each other [shrugs]
> Int: So this is exerting force on the brick [lifts train and hold it near brick] and the brick is exerting a force on the train.
> I: Mm hmm.
> Int: Would that, umm..(1.0) should we expect to see anything happen as a result of that?
> I: The train might bounce back or it might just stop.
> Int: Does one of those seem more likely or less likely to you?
> I: Bouncing back.
> Int: And can you explain how force is involved in making that bouncing back //if it is involved?
> I: //Um…(2.0) The brick isn't completely firm [makes a fist and brings it in toward his body, then releases and lowers] so it would give way, but, er, the-it's actually probably the wood on the train. The train would give away a bit and spring back to its original pos-position exerting whatever force caused it to compress back on the brick [makes fist], pushing the train back [unclenches fist and motions sideways away from brick].

In this transaction, Isaac immediately gave a nominal fact, *equal and opposite reactions,* (diSessa, 1996) consistent with what is frequently said in physics classes in relation to two objects coming in contact with one another. However, when Isaac was pressed about what he thought was a more likely outcome from those two forces, *bouncing* seemed to have a slightly higher activation. Part of the *bouncing* mechanism was unpacked as involving *springiness,* a p-prim involving an object compressing and then returning to its original shape. This was assigned to the wooden train through a perceptual extraction and comparison of firmness between brick and wood. Implicit in Isaac's responses are also the e-prim that *gravity pulls things downward* (Kapon & diSessa, 2012) and also a p-prim for *guiding* that created an expectation of the train staying on track. As will be discussed later, *guiding* was violated when the motion is enacted and the train falls off the track.

For the situation involving predicting what would happen with a hand being placed where the brick was, Isaac had a different expectation even though he invoked the *potential and kinetic energy conversion narrative* and *equal and opposite reactions* nominal fact again.

> I: The train would slide down the track, hit my hand. The train would transfer all of its kinetic energy into my hand [opens hand and jerks it quickly away from the train]. The train would stop, my hand probably wouldn't move [lifts open hand, glances at it, and returns it to lap] because the train isn't very big.
> Int: Okay. Um-and then what's going on with force when the train and your hand [points two open and separated hands toward the center] are interacting with one another?
> I: The train is exerting a force on my hand [extends open hand on lap], my hand is exerting an equal amount of force on the train [jerks open hand forward], which is what causes it to stop.

Starting with the "hand probably wouldn't move because the train isn't very big" implies extractions and comparisons of size of colliding objects and potentially some cuing of *overcoming* or *Ohm's* as a p-prim where the train cannot overcome the size and entailed resistance of his hand. When asked to talk about force specifically, his expectation was for the train to stop – a different expected outcome than what would happen with the brick. The *equal and opposite reactions* nominal fact led to cuing of two forces that *cancel* one another, thus leading the train to stop.

After releasing the train

What happened after the train was released and collided with the brick and the hand was that the behaviors of the train after collisions were quite different from what he had expected. With the brick collision, the train toppled over. Isaac gave the following explanation for what happened.

> I: Ok. It run [sic] down the track collecting kinetic energy and then it hit the brick, um, putting all its kinetic energy into the brick. The brick didn't move, um, and the train stopped moving and fell sideways.

Int: Okay, um, so what was happening in terms of force at the bottom right when they're in contact? [releases train from top again, it collides with the brick and falls again]
I: The train is exerting a force on the brick, the brick is exerting an equal amount of force on the train, um, and I guess the reason it fell off is because the train was still trying to exert and go forward but it couldn't go forward so it went sideways.

Following the *energy transformation* narrative, Isaac observed that the brick had no obvious movement, but he noted that the train had fallen over. When asked about the involvement of force, Isaac again gave the nominal fact of *equal and opposite reactions*. Expectations set by the unarticulated *guiding* p-prim were violated since the train was no longer on its track. Surprisingly, even though he had talked about equal amounts of force, he attributed some agency to the train as "still trying to exert and go forward", suggesting that there was some sort of *deflection* – something that reroutes a moving object following contact – that had taken place. This is different from his earlier explanation in terms of *bouncing* and *springiness*. Ultimately, the unanticipated event led him to activate a new set of primitives to explain the deviation, suggesting that while he still cued the nominal fact of *equal and opposite reactions*, a different set of elements were brought to bear. Similar shifts took place when the hand replaced the brick. When the train collided with his hand, it stayed on the track and rolled backward a few centimeters before stopping.

I: The train came down the track collecting kinetic energy. When it hit my hand it transferred that force into my hand. My hand exerted an equal amount of force back. I guess my hand compressed or transferred some of that energy back into the train causing it to slide backwards. My hand, I felt the impact, I shifted back a little bit. Not very much.
Int: Your hand shifted back?
I: Yeah, or I felt it trying to shift it back. I was trying not to move my hand so it didn't move. The force from the train exerted force on my hand and my hand tried to respond and move in the direction the force was going.
Int: Ok. Can you feel the force from your hand pushing back the train? Is that something that-
I: Yeah. I can feel my hand pushing back.
Int: Like-how?
I: You just kind of feel the impact and the compression I guess. It is just something that is there.
Int: Ok. And that is just in the palm of your hand?
I: Yeah I feel something bouncing off of my hand.

Equal and opposite reactions was cued yet again, although he seemed to be exploring two possibilities. The first was that his hand had compressed, suggesting cuing of *springiness*. Note that he had not previously talked about nor explicitly registered *springiness* as being related to his hand before. He also considered that the energy *transferred* back to the train from his hand, where his hand was some sort of conduit ("transferred some of that energy back"). Isaac also offered a description of feeling his hand "trying to shift" and how his hand "tried to respond." In follow up questioning, he struggled to articulate what "pushing" felt like beyond the "impact and the compression." However, thinking about those sensations seemed to favor greater cuing of *springiness* and potentially also *bouncing*. In sum, when he physically experienced the collision and reflected on what he had felt, along with the observed reverse motion of the train, Isaac cued a new set of primitives to think through the situation than when he had been simply predicting the motion before. Before the hand collision, he expected *cancelling*. After the hand collision, he thought in terms of *bouncing*.

Discussion

Through these two cases, of which others also exist in the larger interview corpus, I have sought to demonstrate that for students who have already had formal exposure to physics, the knowledge that is cued can shift depending on what is physically experienced and enacted. In some respects, changes in knowledge activation and cuing are to be expected for relative novices in physics learning according to a KiP perspective. However, this paper has been a deliberate and newly focused inquiry into some of the dynamics of how immediate embodied experience and sensory extraction can shift what knowledge is cued.

While there is much more to do in the future to understand the broad range of knowledge dynamics involved, we can begin to speculate on the importance of such findings. As much research has shown, students can perform well in formal instruction and assessment tasks but struggle with intuitive reasoning that involves hypothetical and everyday situations. That happened here. If engagements with everyday situations are where and how the basic elements of our physical intuitions develop, it makes sense for us to understand how formally taught knowledge is used, if at all, in such situations. At home, toy trains collide and fall off of wooden tracks and we feel objects pressing against our hands. It is not clear that those experiences are being brought into coordination with targeted understandings from school physics. Also unclear is how scientific epistemologies associated with repeated and designed experimentation interact with what students immediately perceive and feel as routine bodily experience.

Still, we can and should consider how we might bridge familiar everyday experiences encountered outside of designed experiment with understandings and models derived from science. While they try, traditional materials do not succeed with this (Lee, 2010). Supportive efforts could be made to deliberately help students to situate science in messy, lived, and sensed experiences. Thus far, a few notable efforts are beginning to be developed in this area (Pauw, et al. 2015), and some inquiry-oriented curricula attempt versions of this as well. However, a way to transform learning of disciplinary content could just involve taking mundane daily experiences and gradually unpacking the physics involved. While intuitive physics conversations attempt to do this, letting bodily sensations be recognized and discussed would be a novel addition. Orchestrating discussions of science content and everyday sensations, experiences, and observations is still a formidable task. However, as more research and development concerned with embodied experience proceed, we will hopefully see efforts that transform what students encounter and feel in everyday life into more robust learning of scientific ideas.

References

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences, 22*(04), 577-660.

diSessa, A. A. (1988). Knowledge in pieces. In G. Forman & P. Pufall (Eds.), *Constructivism in the computer age.* Hillsdale, N. J.: Lawrence Erlbaum.

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*(2&3), 105-225.

diSessa, A. A. (1996). What do "just plain folk" know about physics? In D. R. Olson & N. Torrance (Eds.), *The handbook of education and human development : new models of learning, teaching, and schooling* (pp. 709-730). Cambridge, MA: Blackwell.

diSessa, A. A., & Sherin, B. (1998). What changes in conceptual change? *International Journal of Science Education, 20*(10), 1155-1191.

diSessa, A. A., Sherin, B., & Levin, M. (2016). Knowledge Analysis: An Introduction. In A. A. diSessa, M. Levin, & N. J. S. Brown (Eds.), *Knowledge and Interaction: A Synthetic Agenda for the Learning Sciences* (pp. 30-61). New York, NY: Taylor & Francis.

Forbus, K. D. (1984). Qualitative process theory. *Artificial Intelligence, 24*, 85-168.

Hall, R., & Nemirovsky, R. (2012). Introduction to the Special Issue: Modalities of Body Engagement in Mathematical Activity and Learning. *Journal of the learning sciences, 21*(2), 207-215. doi:10.1080/10508406.2011.611447

Kapon, S., & diSessa, A. A. (2012). Reasoning Through Instructional Analogies. *Cognition and Instruction, 30*(3), 261-310. doi:10.1080/07370008.2012.689385

Lee, V. R. (2010). Adaptations and continuities in the use and design of visual representations in US middle school science textbooks. *International Journal of Science Education, 32*(8), 1099-1126. doi:10.1080/09500690903253916

Lee, V. R. (Ed.) (2015). *Learning technologies and the body: Integration and implementation in formal and informal learning environments*. New York, NY: Routledge.

Pauw, D., Clegg, T., Ahn, J., Bonsignore, E., Yip, J., & Uchidiuno, J. *Navigating Connected Inquiry Learning with ScienceKit*. Paper presented at CSCL 2015. Gotheburg, Sweden.

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

Sherin, B., Krakowski, M., & Lee, V. R. (2012). Some assembly required: How scientific explanations are constructed in clinical interviews. *Journal of Research in Science Teaching, 49*(2), 166-198. doi:10.1002/tea.20455

Siegler, R. S., & Crowley, K. (1991). The Microgenetic Method: A direct means for studying cognitive development. *American Psychologist, 46*(6), 606-620.

Smith, J. P., diSessa, A. A., & Roschelle, J. (1993). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *Journal of the learning sciences, 3*(2), 115-163.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review, 9*(4), 625-636.

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