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RESEARCH ARTICLE

Conceptual Dynamics of Student Reasoning during Interviews Involving Discrepant Embodied Experiences

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Abstract

Clinical interviews are a research instrument for STEM education that elicit a variety of conceptual dynamics. While some efforts have been made to document what conceptual dynamics take place in such interviews, more remains to be done. This article describes conceptual dynamics observed in two cases where high school students were interviewed and responded to discrepant embodied experiences where what they predicted would take place physically differed from what actually took place. One case involves discussing and enacting projectile motion. The other case involves discussing and trying different configurations of bicycle gearing. The cases illustrate a short-term conceptual change in response to the discrepant experiences in which the same explanatory elements remained in their explanations over time, but how various ideas and perceived attributes of the situation were organized changed. Together, these cases illustrate an additional trigger for conceptual dynamics that have been as yet undocumented in literature about interviews.

Keywords Clinical interviews · Conceptual dynamics · Conceptual change · Embodied cognition · Embodiment · Physics education

Introduction

STEM education researchers have learned and continue to learn a great deal about student thinking and conceptual change from interviews with youth. We have learned, for instance, about complex bodies of prior knowledge, a diversity of intuitive reasoning strategies, and how student understanding of various phenomena can change (or not) as a result of instruction over various periods of time (e.g., Clark 2006; Smith et al. 1993; Ginsburg 1997; Strike and Posner 1992). By their nature as interactional events

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(diSessa 2007), such interviews have the ability to elicit ideas that individuals had prior to the interaction and also produce new expressions of ideas discursively (Roth 2008). Given that such discursive transactions can produce their own "conceptual dynamics", a call has been made in the past few years for education researchers to "begin a program of inquiry into the conceptual dynamics that occur over the course of minutes in interviews focused on science phenomena" (Sherin et al. 2012, p. 170). Such a program, which would involve examining moment-by-moment changes in student thinking, serves to reframe the longstanding debate regarding coherence in student knowledge that had taken place among conceptual change researchers (diSessa et al. 2004; Ioannides and Vosniadou 2002). The debate about coherence has been whether students' naïve understandings and knowledge in transition are reflective of stable or changing structure. The reframing proposed by Sherin et al. is that while there are some fundamental theoretical differences regarding the nature of knowledge as it undergoes conceptual change, there is also a methodological concern. Namely, coherent explanations can form and destabilize within interviews for reasons we do not yet fully understand but can attribute to features of the interview.

In accepting this reframing that coherence can be a momentary phenomenon that is expressed through interactions like a research interview, we should expect that one, none, or many different coherent explanations related to a science topic may emerge depending on the student and the design of the interview interaction. By mapping out how complex conceptual systems give rise to these coherences, we should ultimately make progress in understanding how an individual's knowledge system changes over short time scales and eventually, as brief encounters accumulate, longer time scales. The underlying assumption is that learning involves micro-changes in what knowledge is activated – what coherences are formed – such that normative ideas eventually emerge as a recurrent pattern of ideas.

The original article arguing for a program of research on knowledge change during research interviews by Sherin et al. (2012) identified some conceptual dynamics as manifested by middle school students when talking about the cause of seasonal temperature variation. They identified how a broad set of knowledge may be cued and how different prior ideas may be recruited for constructing an explanation. They also identified a tendency for students to converge on a finite number of explanations based on what knowledge was cued and some common features of the interview interactions that were designed to elicit student ideas. Furthermore, drawings could prompt changes in student explanation, a finding that was further suggested in other conceptual change research (Lee 2008, 2010; Lee and Sherin 2006).

The goal of this current article is to extend the program of research on conceptual dynamics in interviews so that it considers how interviews that were designed to involve embodied experiences influence student thinking. More specifically, the current article considers embodied experiences that are discrepant from what students had initially predicted and given as an explanation. Those constitute a distinct type of interview interaction, and are illustrated with two interview cases. They differ from other studies of discrepant experiences in the literature that have presented discrepancies to students through unexpected behaviors in a computer simulation or microworld (Tao and Gunstone 1999; Zacharia and Anderson 2003) or through teacher demonstrations (González-Espada et al. 2010).

As an example to contrast discrepant experience interviews with more traditional ones, we might expect that a conversation about acceleration and potential and kinetic energy would differ if it were done as a sit-down conversation in a secluded space compared to a situation where it took place with an interviewer and interviewee are riding side-by-side together on a roller coaster. There simply would be different resources to recruit in the process of sense-making and explaining the underlying physics. Indeed, this is suggested anecdotally by in a study of student metacognition related to physics knowledge while at a theme park (Nielsen et al. 2009). Students reportedly recruited their recently embodied experiences to question their prior understandings of physics of motion, although they were not in an interview situation. While the research design presented in this article is not as dramatic as a theme park ride, it is intended to affirm, by way of illustrative cases, that there are indeed some relevant conceptual dynamics at work. Specifically, there are conceptual dynamics that come from enacting physical experiences and reconciling discrepant embodied events. The primary theoretical perspective that I draw from in this article is based on diSessa's "knowledge in pieces" (1988) theoretical perspective. Additionally, I draw from situativity theory and embodied cognition, as described in the next section.

Theoretical and Methodological Perspectives

Knowledge in Pieces

The "knowledge in pieces" theoretical perspective is an approach used to model cognitive processes in terms of various elements that comprise a conceptual ecology (diSessa 2002). It presumes that knowledge can be represented as numerous elements at varying levels of abstraction that are cued in a given reasoning situation. What we see as concepts are patterns of activation of these knowledge elements. The contrasts to knowledge in pieces exist in other cognitive modeling literatures and other senses of what is a concept originating from cognitive science. For instance, concepts such as chair and skunk are among the most classic examples and have been described in terms of categorical membership, exemplars, and essence (Keil 1989; Medin 1989). However, diSessa and Sherin (1998) have argued against using those exclusively as ways to define or model all concepts of interest in STEM education because several concepts do not conform psychologically to those models. Examples of such STEM concepts include number and force, which do not have clear categorical nor exemplar properties.

Knowledge in pieces has had rival perspectives. Included are cognitive science approaches that describe STEM knowledge as being of the form of theories (McCloskey 1983) or synthetic mental models (Vosniadou and Brewer 1992). However, efforts to use those structures on some of the same STEM 'concepts' from which knowledge in pieces originated yielded surprising findings. For instance, Ioannides and Vosniadou (2002) attempted to use the same conceptual apparatus that gave way to synthetic mental models to characterize conceptualizations of force, and they identified a set of stable and coherent meanings. However, in a replication study to test those findings against knowledge in pieces (diSessa et al. 2004), students exhibited more fluid meanings. diSessa et al. argued that a core problem that may have led to this discrepancy was lack of agreement about what was meant by "coherence". This all contributed to the coherence debate about the nature of prior knowledge and whether models described in terms of theories and frameworks were sufficiently precise or if knowledge in pieces led to greater precision.

In some domains and for some topics, it may be that stable models and broader labels for underlying knowledge representation can be adequate. There may be some topics where students have stable and coherent models that do not seem to change in response to new knowledge elements being activated. However, there are also occasions where interview-based conceptual dynamics are easily observed. In those cases, knowledge in pieces and its focus on knowledge element activation seems an amenable perspective.

Among the most well-known knowledge elements in the knowledge in pieces perspective is diSessa's "phenomenological primitive", or p-prim. P-prims serve as important explanatory schema abstracted from bodily experience that seem self-evident as justification for why things behave in the ways that they do. One example is a p-prim that diSessa has called "*Ohm's p-prim*". The schematization of *Ohm's p-prim* involves a causal impetus or actor that is trying to bring about some effect in the face of some resistance. For example, one might be pushing a wheelbarrow across a field. If more bricks were added to the wheelbarrow, we expect that there would be more resistance that is encountered by the person pushing the wheelbarrow, and that would decrease the speed at which the wheelbarrow would be able to go unless the amount of pushing was increased. If bricks were removed, the wheelbarrow could move faster because the resistance decreased. This is sensible due to the cuing of *Ohm's p-prim* which makes this phenomenon self-explanatory. More resistance means more effort must be expended to bring about the same effect.

Another related p-prim is *overcoming*. In the schematization, there are multiple competing forces involved in a situation and one force overpowers the other. This would be akin to a game of tug-of-war where one team eventually pulls more than the other team or a team that is faring poorly in a game against another increases their play intensity and ultimately triumphs. In those, there is some opposition at work with one side dominating against the other.

A knowledge-in-pieces perspective does not restrict modeling of knowledge only in terms of p-prims. Another primitive-like construct, in the sense that it is treated as self-explanatory as well although had not been formally designated as a p-prim in early writings, comes from the language of qualitative proportionalities. One of the most detailed treatments of qualitative proportionalities appears in Forbus (1984) in his qualitative process theory. For our purposes, we can see correspondences in one dimension to corresponding to changes in another dimension. For instance, we may expect that as a person becomes larger (such as when they become an adult), they also become stronger. The increase in size is matched intuitively to an increase in strength. Another version of this proportionality is that smaller objects tend to be less noisy, such as when pencil is dropped compared to a large block of wood. An increase in one parameter corresponds with an increase in another.

Beyond these primitives and schemata, other constructs have been introduced in the literature that has been shaped by or otherwise relate closely to the Knowledge in Pieces perspective. These include resources (Hammer et al. 2005), Nodes (Sherin et al. 2012), naturalized axioms (Philip 2011), explanatory primitives (Kapon and diSessa

2012), and Facets of Understanding (Minstrell 1982). For the current article, p-prims and the qualitative proportionality will figure most prominently.

Situativity of Knowledge as Seen in Interviews

Cognitive processes are fundamentally situated (Brown et al. 1989), meaning that the setting, norms, and other participants directly shape what knowledge is developed, expressed, and used. This implies that the practice of interviewing is itself an exercise in situated knowledge practice (Greeno 1998). That is, interviews are a specialized interaction that involves individuals talking in a way that one person – an interviewee – is presenting and performing their understandings for the other in order to help the other – the interviewer – understand what knowledge the interviewee has. Prior research has shown that modifying the interview to better incorporate the artifacts and language of real world phenomena can produce drastically different responses from youth (Carraher et al. 1985; Taylor 2009). That is, when the interview is situated differently, they produce different results.

The observation that interviews done under different conditions can produce different performances of knowledge does not mean that they are fundamentally flawed as research instruments. Interviewing is one of the most direct means available for eliciting student thinking, although it may take on a distinct form through the nature of the interview interaction. Yet a gap between what is exhibited in a classic sit-down-and-talk interview and what is exhibited in other more naturalistic settings appears to remain. Some have sought to bridge this gap by trying to modify and enhance data collection methods to more closely capture how knowledge is being used in more natural settings. For example, obtaining video footage of youth and families doing everyday activities such as gardening (Umphress 2015) or talking about temperature at home (Keifert 2012) has been one way this has been pursued. Another example has been Marin's efforts to study science talk during nature walks (2013). The work of the LIFE center has also continued lines of work to look at how everyday mathematics is enacted in a range of settings (Stevens et al. 2006). Much of this work has been enabled by the use of wearable cameras that can obtain a viewpoint that is closer to that of a participant than that of a researcher. Still, the work of finding such rich data when it happens is challenging and requires careful planning to reduce the amount of video footage that is obtained that is not directly relevant to the research questions at hand. The same holds true for using observational classroom video data as the primary source of students' conceptual knowledge for later analysis. While topics of interest to classroom instruction will appear, the trade-off with observational video is that one cannot go into depth or expect immediate elaborations on ambiguous statements to be given in the moment the data are collected. To obtain such data would require other additional research steps ex post facto, such as stimulated recall (e.g., Calderhead 1981).

The current work attempts to elicit student thinking directly as can be done during an interview but also situate student thinking in a physical task akin to one they would complete independent of the interview. It resituates what may be purely hypothetical to an experience that is actual. The difference from focusing on just the actual as it happens naturally is that by making it part of an interview, more depth can be pursued. This orientation toward a physical task is in contrast to asking students to puzzle through a word problem from a textbook or a hypothetical scenario of a size and scale that cannot be directly physically manipulated. Those have been fruitful for prior interview research that might explain how the moon changes it's apparent shape, but differ in the kinds of props to be included and experiences to be engineered. By emphasizing a physical task with active student manipulation and movement, the immediate setting and actions therein are hypothesized to become more prominent in the interview interaction. In terms of conceptual dynamics, we should be positioned to improve our understanding of how aspects of the physical task shape understanding and the expression of knowledge in this embodied situation.

Embodiment and Embodied Cognition

Finally, the study of how our physical experience with the world influences cognitive processes is the purview of embodied cognition. Embodied cognition, depending on which of the varied facets are foregrounded, often highlights a sensori-motor connection to our conceptual knowledge, appraisals, and decision making. Some examples in the literature in embodied cognition suggests that physical sensation and motor activity will prime the student's thinking in some way. For instance, clenching a fist appears to increase males' power-related self-conceptions (Schubert and Koole 2009). Activating facial muscles involved in smiling and frowning appear to have an effect on how amused a person will be (Strack et al. 1988). Holding a warm drink seems to influence how 'warmly' another person is viewed (Williams and Bargh 2008). Relatedly, experience performing an action can affect how we perceive objects with which we had directly engaged. For instance, Witt and Proffitt (2005) showed that when batters had more success hitting a ball during a softball game, they immediately perceived the ball as being larger. It would seem that perhaps something like that could appear when students are reasoning about science ideas where directly engaging with a phenomenon or otherwise experiencing some bodily manipulation could provoke different kinds of reasoning.

The influence of immediate or recent physical activity as a strand of embodied cognition on science reasoning has not been meaningfully explored. Overall, embodied cognition as a whole has appeared more in mathematics education and been the sensorimotor basis for claims that it is foundational in the development of mathematical ideas (see Lakoff and Nunez 2000). We have reason to expect that sensorimotor foundations of science knowledge is relevant, especially given the knowledge in pieces perspective that informs this research. Related to the origins of p-prims in the knowledge in pieces perspective described earlier, diSessa (1993) offered the following statement:

> "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." (pp. 122-123)

Stated simply, doing things in and to the world around us, noticing those deliberate actions, and feeling ourselves doing those things seems to be how p-prims are established. That would imply that bodily engagement and sensations in the world of things being in balance (with those things being us or a block that we place on a tower) or competing (such as when arm wrestling or pulling on a dog's chew toy while the dog is using it) or being pulled downward (such as when swinging, falling, or hanging from monkey bars) form the core of these primitives.

What I consider in this present article is that immediate or recent kinesthetic experience in a highly embodied interview situation serves a role beyond being the locus of original development for p-prims; they can also cue and maintain cuing of p-prims. Just as holding a cup of warm liquid might make us feel warmly about another person, I speculate that being in a situation where one must feel balanced may make someone more likely to think through a conceptual problem in terms of balance. That would bear some resemblance to some of the findings in embodied cognition research cited above.

Returning to the Witt and Proffitt (2005) example above of estimating baseball size, we know that recent physical experience impacts perception. From other foundational embodied cognition research, we also know that physical experience can influence text comprehension (Glenberg et al. 2004). Moving in specific directions can also influence how children understand the number line (Fischer et al. 2015). Might we expect something similar in intuitive physics? To some extent, this has been explored in mixed reality learning environments, where positive learning gains of physics concepts were found (Lindgren et al. 2016). However, that study examined motion in the context of planetary motion. The current study is focused on motion on a smaller scale.

In light of the previous discussions of disagreements about how students understand physics concepts such as force, it may be too optimistic to think that normative understandings result from a singly specific embodied experience. Indeed, it may be that embodied experiences, which include air resistance and friction, make normative understandings more difficult to obtain. However, the aforementioned research in embodied cognition suggests that even if a non-normative understanding is the result, there may still be some manner of small change in reasoning, particularly when the embodied activity produces results discrepant from what is expected, that could be detected and is worth noting among researchers of interview-based reasoning.

Research Question

If students are involved in physically producing some effect related to how they reason about a topic at hand, then how does that direct experience affect the kinds of thinking students do about the topic? For instance, How would thinking about a projectile be reconciled with experiencing the physical sensation of having to handle a projectile and throw it themselves?[1] This question is being pursued in the context of clinical interviewing, where conceptual dynamics are known to exist. It is not being restricted only to projectile motion, although that example helps to illustrate the nature of the question.

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[1] To some extent, Tscholl et al. (2013) tries to explore this space with mixed reality immersive technologies in which learners kick or launch virtual projectiles in space.

Research Methods

Physically-Engaged Clinical Interviews

The interviews I have designed for this study try to examine the above questions. The approach I take is to make sure that I have a separate videographer and to follow a three-phase sequence in interviewing where we meet in an open space (rather than a laboratory) and a youth is posed with a question, such as how athletic balls of different weights and sizes would differ in their projectile motion when thrown. This phase is the *prediction* phase, so that I can get a sense of how the youth thinks about projectile motion for a given situation and explain given what they know already why that will happen. All discussion about the phenomena to be experienced would be completed. Next, I ask students to perform the actual task that was just discussed. In the case of projectile motion, the student will actually do the work of throwing the objects by herself and discuss what is happening and why. The large open space is necessary to allow for actual throwing activities or whatever else is required in this *enactment* phase. Then, after the activity has been enacted, we go on to an *explanation* phase where the student provides commentary and explanation for what happened in the enactment phase. However, if there were comparisons of similar activities, such as throwing a number of different types of balls, *enactment* and *explanation* phases would alternate and repeat for each ball. This sequence of predict-enact-explain bears resemblance to White & Gunstone's prediction-observation-explanation activity sequence for physics learning activities and interviews (1992). The key difference is the enactment phase. The goal in pursuing this particular modification was to see how having gone through the physical activity and experienced the phenomenon firsthand influenced how the student was thinking at the moment (see Fig. 1). While redundant, I have also used wearable cameras with students as part of this research in order to get something approximating their points of view during these interviews. These cameras have been useful in that they have picked up utterances that were hard to hear from a third-person operated camera.

There could be a range of behaviors we might expect during an interview like what is described above. Should a student have a robust and contextually invariant mental model, then we should expect that how a student predicts what will happen and how they explain what has already happened could look more or less the same. If we

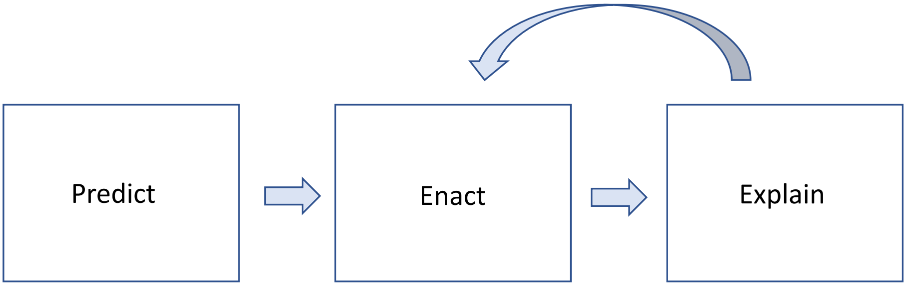

Fig. 1 Phases of physically-engaged interviewing, which should take place in a space and setting where enactment can be done in (semi-)authentic conditions. Discussion of student ideas about the justification for a chain of events will take place in all phases

anticipate that the kinds of explanations that students form are going to exhibit conceptual dynamics (Sherin et al. 2012), then we might expect some discernable changes at the level of the current explanation that the student is producing. Students may even have non-normative ideas that are reinforced through what they noticed in the enact phase of the interview. For instance, seeing a rolled object come to a stop without any human force being applied may contribute to an idea of impetus that wears out over time (McCloskey 1983).

Data Sources

The data for this article comes from a corpus of 25 interviews conducted with high school students in the western United States who had all already taken a year of high school physics. The students were asked to participate in three different physically-engaged interview protocols outside of school time in which the predict-enact-explain sequence was followed. At the onset of this study, the hope was that each student would participate in the three different protocols. Due to attrition, not all students participated in all three interview protocols. Briefly, the interviews ranged from 30 min to an hour in length and were all conducted by the same interviewer. The first interview focused on projectile motion. The second focused on collisions and Newton's Third Law. The third interview targeted gearing and mechanical advantage. The number of participants in each interview were 12, 7, and 6 respectively. Given the modest numbers of participants that were recruited and had participated, the aim of this study had not been to make broadly generalizable claims about students. Rather, it was an effort to examine how student reasoning appeared when an opportunity to enact actual situations was introduced and identify cases for closer inspection of what knowledge was invoked and how that knowledge was used over the short time scale of the interview. Similar to work reported in Sherin et al. (2012), this was an examination and identification of a particular conceptual dynamic that appears within the use of the interview research method.

Data Analysis and Case Selection

The cases for this article followed the recommendations associated with the *knowledge analysis* KA methodology (diSessa et al. 2016). Video, obtained by a research assistant, was collected for all interviews, consistent with the "capture" recommendation of KA. In addition, for interview protocols 1 and 3, chest-worn wearable GoPro cameras were used to obtain records from the interview participants. These interviews were all transcribed and open-coded based on content as well as mention of p-prims as part of the "reduction" phase. Given that p-prims can appear repeatedly and frequency counts in interviews are influenced by length of utterances and the overall interviews, I do not report frequency counts here as they do not contribute to the argument. To quote diSessa et al. (2016) on data reduction in KA:

> Systematic coding of video by KA researchers, though not unheard of, is not a common practice. A more common type of reduction takes the form of the

> selection of episodes that illustrate the phenomenon at issue and the creation of theory-based narrative accounts of these episodes. Furthermore, in prototypical cases of KA practice, there is an iterative process of theory building, in which the researcher goes back and forth between the data and the theory. The data is examined in an open way with respect to a topic of interest, episodes illustrating a particular issue are selected, a theory is built, then reduced narrative accounts of episodes are produced employing the theory, as it currently exists.

For my purposes, the codes served as a form of shorthand annotation to support iterative microanalytic video review and "pattern finding". The main codes that were given were specific primitives that were invoked, specific terminology and schema slot fillers (such as *gravity* as something that can act upon an object), and where the student's perceptual focus was directed. Other codes captured common lines and statements that students offered in their explanations, such as potential energy transforming into kinetic energy. These and other codes were assigned to student utterances. Sample codes are provided in Table 1. In this particular article, there were indications of some degree of explanation changes throughout the entire data corpora that had a variety of cues. For example, extended questioning or verbal prompts to clarify what a student said could lead to slight changes in what knowledge a student cued, as has been documented in Sherin et al. (2012). The two cases that were selected for inclusion here were selected because they allowed for theory building around how an immediately enacted experience, rather than some other feature of an interview such as extended questioning, contributed to a different student response. In the codes, this could be indicated by a difference in what primitive was cued, but could also be due to a difference in perceptual focus or other ideas that were involved. In the two cases presented, the enacted event produced a discrepant experience, relative to what they had predicted, making them worth closer examination. The cases are presented narratively with descriptive analysis to summarize what was inferred from the codes.

Case 1: Projectile Motion with Three Athletic Balls

The first case comes from an interview done with the first interview protocol related to projectile motion. The discrepancy that is encountered is that the distance traveled by the various projectiles differed from what was predicted. For this interview, the students met individually 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 by the researcher and visible to the student in a pile on the ground. 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. This task was designed with recognition that there could be unexpected variability in how students threw the different balls and variability in any student's throwing ability. However, the underhand throw and decision to give those general guidelines (as hard and as far as can be thrown) were intended to ensure that the student would produce a motion that had a more visible parabolic path. Each student was told repeatedly that they could

Table 1 Sample transcript with codes assigned and rationale for coding described

Utterances	Codes Assigned	Rationale
Int: Will the force of gravity be as much on that [foam] ball as it would be on the baseball?		
A: I think it will be more on the baseball because it has a higher mass so it has more that gravity can work on.	• Qualitative Proportionality: Larger attribute is more affected • Perceptual Focus: Mass • Gravity	More mass leads to more gravity being able to work on it. In other permutations, this can be an instance of Ohm's p-prim, if gravity were the resistance it was encountering. This student is predicting recognizing that the baseball has more mass, hence that is the perceptual focus. Gravity is invoked as what is having "more" [influence] on the baseball.
Int: How about, this is a lacrosse ball. What do you think will happen with that ball?		
A: It's going to be faster than the baseball. It has it's more dense. I can tell by feeling it. You can squish the baseball a little, but not this [lacrosse ball].	• Qualitative Proportionality: Larger attribute is more affected • Perceptual Focus: Firmness • Perceptual Focus: Density	The student is noting he can feel that the ball is more dense. He also mentions "squish" which suggests that the firmness of the material is being registered. More speed due to more density (compared to the baseball) suggests qualitative proportionality, which under some conditions could be Ohm's P-prim. However, resistance is not mentioned.

throw the balls as many times as they wanted or needed to make sure that they threw them as hard and as far as they could. As an additional measure, a high speed camera that could obtain slow motion footage of each throw was set and used to record each throw in order to discern if there were gross differences in throwing technique that were unnoticed by the student but could have greatly influenced the trajectory of the ball (e.g., a delayed or premature release or a shorter wind-up). For the focal student, this was not a concern upon review of her high-speed video (see Fig. 2).

A number of balls were used ranging in size and weight, although 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). These three balls were important and received emphasis for two reasons. First they were thrown early in the interview. (In later portions, the students understandably became less talkative and expressed at times that they were repeating themselves). Second, they were all of comparable size and structure. (Another comparably sized ball was a whiffle ball, but the holes and clearly plastic material often led to changes in conversation that are not relevant for the current article. As illustrated in Table 1, a lacrosse ball was also used, but it was visibly much smaller in diameter.)

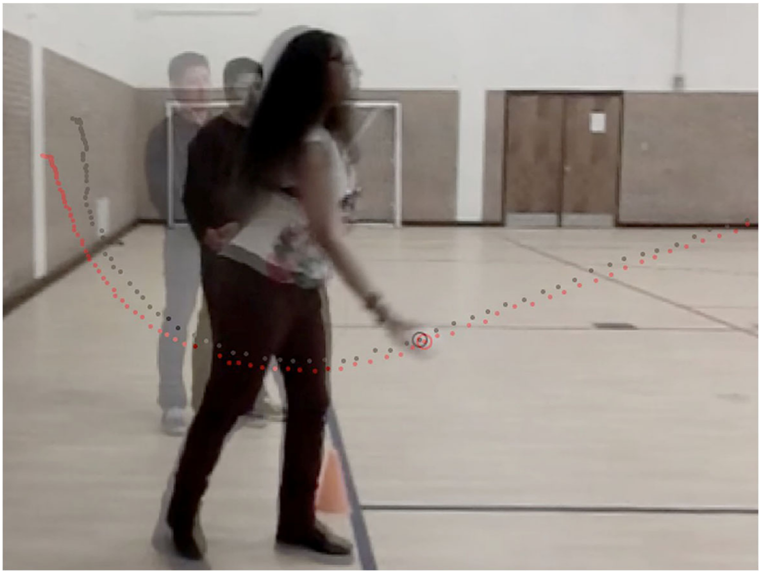

Fig. 2 The traced trajectory of Carina's underhand throws of two balls discussed in the ball tos interview, superimposed upon one another showing that her throwing and release were comparable to one another

For the prediction phase, the student was handed one of the athletic balls and asked what would happen when the ball was thrown underhand "as far and as hard" as they could throw it. If a purely phenomenological description was given (e.g. "It would go up and then down as it goes out"), they were then asked if they could also explain that in terms of forces. Then subsequent balls were handed to them, and the process was repeated. They were told that they could hold onto any balls or grab any that had not been offered to them as they desired or needed.

Predicting What Would Happen when the Balls Were Thrown

The case of ball throwing involves Carina (a pseudonym), a Latina student at a STEM-emphasis high school who reported doing "fine" in physics class, although it was not her favorite subject. To begin, Carina was handed the baseball and asked what would happen when she threw the ball. This was followed by a question about the forces involved in producing the baseball's expected parabolic motion. In response, Carina immediately talked about a *potential and kinetic energy conversion narrative.*

> C: I know that the higher it gets the more potential energy it gains and as it falls, after it reaches its highest point it loses its potential energy and gains kinetic until it hits the ground.

This was a common response from students, appearing in 63% of the students, suggesting it was content covered previously in a high school physics class. Following some talk about 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 consistent with what has been documented elsewhere (e.g., diSessa and Sherin 1998). 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. Potentially related is that a related p-prim is being cued where the upward force is *dying away*. In *dying away*, the effect of some entity should weaken and diminish as time passes or space is traversed, just as a sound may sound softer when the hearer is farther away and the sound must travel farther and *dies away*. However, her statement of something pulling it back down suggests that *overcoming* is especially salient (and potentially reinforced with *dying away* also being cued).

In response to her closing statement that "things are trying to pull it back down" and her gesture of pulling, the interviewer inquired about what was pulling it down. This may have strengthened the cuing of "gravity", which she had mentioned once before. Yet, in addition to this, she also introduced "draft" as something that influences the ball's movement.

Specifically, Carina said "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. The joint cuing and activation of multiple p-prims (*Ohm's, overcoming)* is not problematic. Some p-prims can be supportive of others to certain extents, although we may expect one to be more salient at a single moment. Since she was gesturing horizontally from beside her body to inward, it seems that *Ohm's* was applying to air resistance as the ball moved forward, while gravity was *overcoming* the upward movement.

Following this, the interviewer handed Carina the tennis ball, and Carina opted to hold 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 her prediction was 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.

Of note is that some immediate sensory experience is coming into play because Carina was holding both balls simultaneously. While doing so, Carina observed that the tennis ball was lighter and would travel farther. She had honed in on muscle tension (as suggested by her arm movements when she raised her tennis ball hand slightly). With gravity, she commented that gravity would be "pulling down on it less". While it may look similar to *Ohm's p-prim* in that she described gravity as giving the same amount of influence and the ball being lighter provides less resistance, my interpretation was that this was an instance of the aforementioned qualitative proportionality ("gravity is pulling down on it less…"). As instantiated, the primitive is that an object that is *smaller is less affected*. The reason for this slight change in interpretation is that there is no indication in Carina's language that gravity is behaving differently (although the gravitational force of an object does indeed depend on mass). However, Carina said gravity does not pull down "as much", suggesting gravity does what it does and different objects are differentially affected.

Carina then returned the tennis ball to the interviewer and was then handed the yellow foam ball, which she then held in one hand while continuing to hold the baseball in another hand. She squeezed the yellow ball and then held both balls in front of her. When asked which, if any ball,[2] 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. Because of those actions and her most recent statement about a size difference, the interviewer asked if being smaller helped. In response, air was revisited as resistance. Air would not "press onto it more. Like it gets less drag because it's smaller". Considering what appears to be forward motion based on her gestures, this seemed to be a continued cuing of the *smaller is less affected* primitive, although applied to size instead of weight. Here, extraction of more information, namely

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[2] In all ball tossing questions, the students were given the option of one ball going farther or that the balls could behave the same so as to reduce any interviewer bias that one ball must go farther than another.

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 (Fig. 3).

To summarize, her predictions were that the tennis ball would go farther than the baseball and the yellow ball would go farther than the tennis ball. Weight and size both figured into her justifications, but weight and size were both treated as values that were decreasing. While they were noticed, it appeared that the decrease in those would lead to decreases in the opposing forces (gravity and drag), thus allowing the smaller and lighter objects to travel farther. This was not what happened when she threw the balls, however.

Enacting the Ball Throws and Explaining them

When the time came to throw the balls, Carina was asked to position herself at the same spot in the gymnasium. 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. As it turned out, the baseball did not go as far as the tennis ball. She did not want to re-throw either when given the option. 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 post-enactment 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

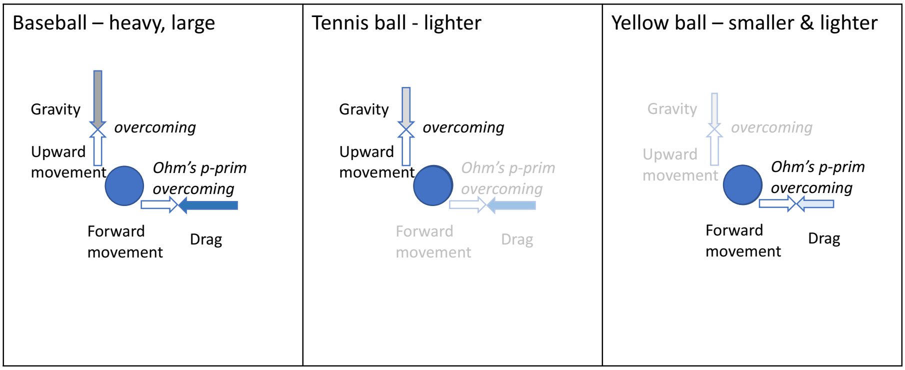

Fig. 3 A depiction of Carina’s predictions of how the balls would travel. Darker hues on arrows indicate greater amounts, as do lengths of the arrows. In the initial case of the baseball, gravity would overcome upward movement and drag would be resistance that would overcome forward movement. With the tennis ball and yellow ball, gravity would overcome but be pulling less. Drag would also decrease. This was based on both appraisals of size and weight. Faded text depicts implied continued processes that were not explicitly mentioned

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. It was facing less resistance overall, an instantiation of *Ohm's p-prim*, although expressed across two dimensions.

Following this, she was then given the yellow foam ball to throw. When she threw the yellow foam ball, following a similar launch and release, it did not land as far as the other balls. When the interviewer asked about what happened and why, 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," suggesting that the immediate sensory information she was able to get from handling the balls mattered to her. Moreover, in trying to reason through it, Carina had extracted a weight difference with the yellow ball in comparison to the tennis ball and baseball. Size was no longer a high priority extraction of perceptual information,[3] and she said the lighter weight made it less able to move through air. This statement conflicts with what she had said for the tennis ball just prior (following enactment of the throw) and for the yellow ball before any throwing had been done. After throwing, *Ohm's p-prim* was cued to explain the reduced distance. The yellow ball could not push through the air as well, which was attributable to a smaller weight giving it less ability. In this moment, the sensations she experienced handling and throwing the yellow ball, combined with the discrepant experience of the yellow ball 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.

What is unusual is that the mechanisms that invoked primitives differentiated, with size and weight taking on different roles and having different influences on the balls. The unexpected outcomes did not lead to a small adjustment to an otherwise consistent explanation. Rather, it honed in on different registered perceptual features and connected those to primitives in idiosyncratic ways. The discrepant event appeared to cause a disruption in the initial explanation (Fig. 4). Many of the same primitives and elements were invoked, but their configurations changed to speak to a specific situation

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[3] In the knowledge in pieces literature, extraction is a term used for the act of obtaining a specialized bit of sensory-based information as part of the activation of a coordination class, a particular model of a 'concept'. See diSessa et al. (2016) for more details on extractions.

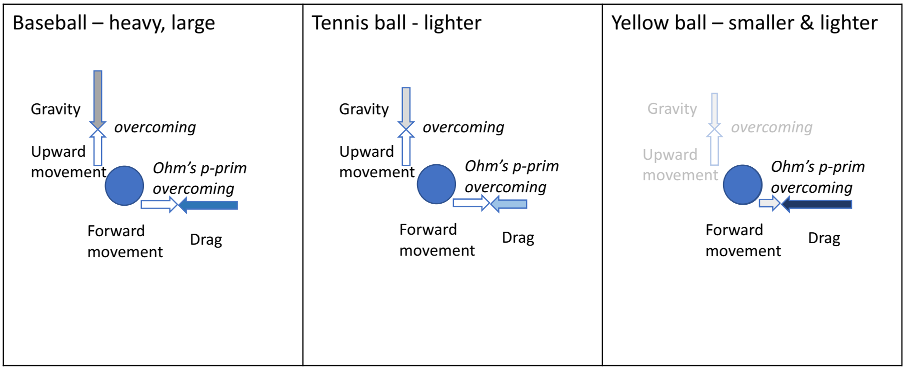

Fig. 4 A depiction of Carina's explanations of why the balls traveled as they did. Darker hues on arrows indicate greater amounts, as do lengths of the arrows. In the case of the baseball, influences were the same as in the prediction (Fig. 3). With the tennis ball and yellow ball, there was implied decrease in gravity's influence. However, the drag would decrease for the tennis ball because it was lighter. The drag would increase for the yellow ball and the yellow ball's forward movement would decrease because it was smaller

rather than to a comprehensive model of how the behaviors of all three balls could be explained. This response to the discrepancy that was enacted will be compared to the case that follows below.

Case 2.Riding a Bicycle in High and Low Gears

The second case that will be discussed involved eliciting student thinking around mechanical advantage. Briefly, the ratio between gears on a bicycle can be manipulated such that as the size of the rear gear on the tire increases, the amount of force that must be exerted on pedals spinning a front chainring to produce a single revolution of the pedals decreases (Fig. 5). As a trade-off, the rear wheel does not produce as many revolutions per pedal revolution. This interview about mechanical advantage was based upon and modified from interviews with elementary school students reasoning about how bicycles work (see Drake and Lee 2013). It involves the youth experiencing a different amount of force than he had predicted for specific gear configurations.

For the interview, the participating youths met the interviewer in a long paved outdoor part of a university campus. The participating youths were first asked to draw a bicycle. From that drawing, students would typically mention and show a region of the drawing that had multiple gears. From that point, the interviewer then asked why bicycles had so many gears in order to elicit some basic knowledge about the role that gearing plays. Following that, a multispeed mountain bike was brought out from a hidden location (hidden so that it would not prematurely influence any drawing work) and the interviewer and interviewee kneeled by the bicycle and examined the rear cassette, where there were several gears. The interviewer asked what would happen if the chain were connected to the largest gear in the rear cassette and then what would happen if it were instead connected to the smallest gear in the rear cassette. That latter portion constituted the *prediction* phase of the interview.

During the *enact* phase of the interview, the bicycle was adjusted to the appropriate height for the student, and the student was tasked with riding as fast as he or she could

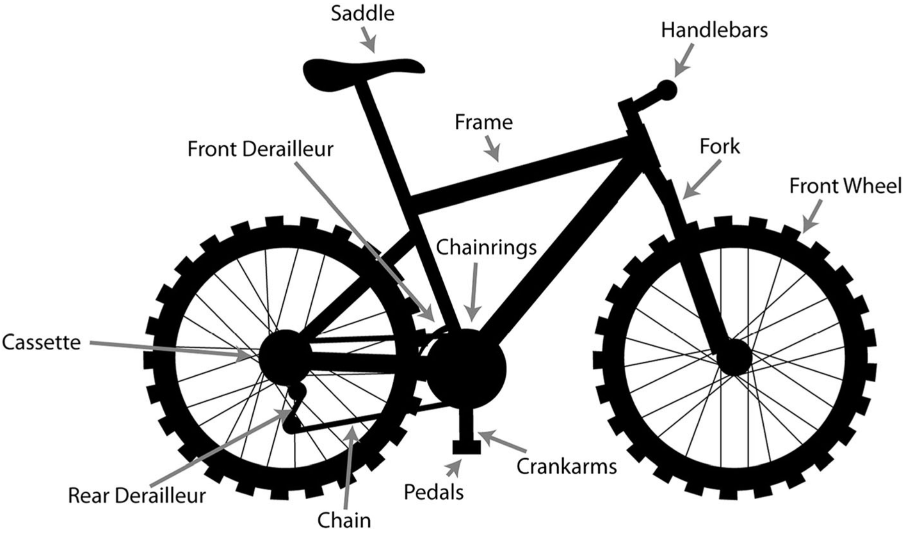

Fig. 5 Bicycle parts diagram

for a set distance with the smallest gear in the cassette (high gear). The mid-sized chainring was used and kept constant throughout the rides. During this time, the student was equipped with a helmet-mounted Go-Pro wearable camera to obtain record of his activity and experience during the ride. Once he returned, there was an *explain* phase about the ride while the gearing was changed by the researcher to the largest gear in the cassette without the student having contact the bicycle (low gear). He then did the same ride again. Upon return, the explain phase was repeated and extended to account for not only that ride but also both the high gear and low gear rides,

Predicting how Gearing Works

Following a drawing and initial discussion to orient Will to talking about how he predicted different gears would change the quality of riding a bicycle, a research assistant wheeled out a 24-speed mountain bike that was then parked immediately in front of Will and the interviewer. Even though Will had initially talked some about how gears worked and would affect pedaling with a drawing, I had felt as the interviewer it was appropriate to also make sure that when an actual bicycle was present and could be examined, Will would be given an opportunity to share his thinking in case any limitations in his original drawing (produced from memory without a bicycle in view) could be appropriately updated or elaborated. It turned out that he did not have much in the way of changes to offer from where he had left off when talking through the drawing. The conversation as it began in front of the bicycle is provided below. The gears being discussed are again those of the rear cassette.

> Int: What we are going to do is, you'll do one ride going as fast as you can with the chain on the smallest gear and you'll do another ride on the same path with

> the chain on the biggest gear. Tell me what you think will be different, if anything, between those two.
> Will: I think on the smaller gear I will get a faster start, but I'll keep the same speed throughout the whole course. With the bigger gear it will take a little bit longer to get it going faster but by the end of it, it will be going faster than the little gear.

Speaking from experience, Will reported on what would indeed happen in certain gearing situations that cyclists call "spinning out". Essentially, the rate at which the rear wheel is turning is faster than what would be the typical cadence for a cyclist. When that happens, the cyclist cannot accelerate the bicycle on flat terrain and will feel their legs spinning around the cranks (pedals) unless they change gears.

Both of these are phenomenological accounts of what he would experience, although his assignment of which sized gear would correspond to which experience was incorrect. He was right in that in one gear configuration, more force would need to be applied to the crank until the bicycle gained momentum. However, that was associated with the incorrect gear. Important to note in his account was his gestures (Fig. 6), in which we assume he was engaging in a form of simulation of what he was expecting (Hostetter and Alibali 2008). His arms imitated his feet on a set of crank arms and moved quickly in circular motions when talking about the small gear. When talking about the larger gear, his hands moved more slowly and the tendons in his hands were visibly tensed or clenched, suggesting the presence of resistance and the need for more effort from his body.

From this gesturing, I began inferring that Will was cuing *Ohm's p-prim*, in which the larger gear should be a situation with greater resistance. His hand movement and hand tensing suggests that the causal impetus is the pushing or pedaling that will be done by him as the pusher and that he was thinking in terms of increased resistance to be overcome. Had he thought resistance would be the same, he would likely have just involved his hands remaining open rather than as closed fists and just moving more quickly. The speed of the bicycle, when not coasting or initially accelerating, will fill the "output" slot for this Ohm's-based explanation.

As confirmation of this, Will offered the following:

> Int: How does that affect the bike moving forward?
> W: I think it affects the speed as well as how hard you have to pedal. With the bigger gear you have to pedal harder to get it to get going with the bigger gear

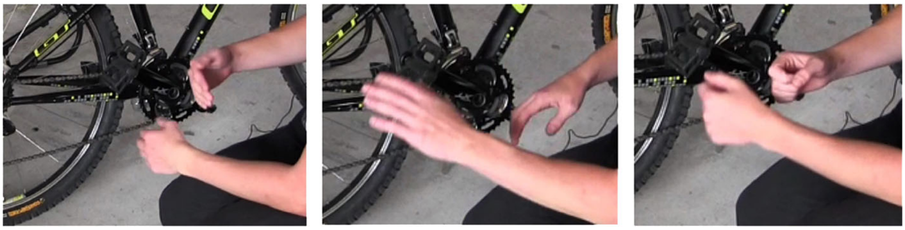

Fig. 6 (Left) Will motions his hands as pedaling when talking about a small gear in back. (Center) Will begins to motion his hands more slowly when simulating the large gear (Right) and then he switches to closed fists that rotate more slowly as he completes his speaking turn

> here [in the cassette], because it is pulling a chain for the other gear that is attached to the other wheel in the back that makes it move forward so it takes more effort to get a bigger gear going because of the size.

In that excerpt, *Ohm's p-prim* was more prominent. The appraisal of gear size was linked to the amount of resistance, suggesting a qualitative proportionality of something *larger having more of an attribute* (in this case, larger gear has larger resistance). That qualitative proportionality is generally embedded in the schematization of *Ohm's*, but in this current example, it is based on a visual appraisal of size from which that inference is being made.

In addition to this, Will made a brief observation that there were also a different number of teeth on the two rear gears and how a different number of teeth will correspond to a single crank of the crank arms.

> Int: Why is it that the different gear sizes will make a difference in how fast you are able to go?
> W: I guess it is how many times the gear rotates around and since this one [small gear in cassette] rotates around with one pedal around, it will rotate once. Since this one [the larger gear in the cassette] is so much larger, I think it has something to do with the little spoke things that go with the chain.
> Int: The teeth things?
> W: Yeah, I don't know how many there are like 10 of them here [in the small gear] and 30 here [in the large gear], if one pedal has 10 teeth then 3 pedals would be 30 teeth.

In his opportunity to examine the actual bicycle in person, the number of teeth around the small gear (estimated at 10) and the large gear (estimated at 30) also fit into a qualitative proportionality and *Ohm's p-prim*. There was something like a fixed ratio of pedal turns to teeth, and so if there were more teeth involved, then the number of pedal turns would increase as well. Note that there are some subtle differences in Will's reasoning where before he had talked about pushing harder but now was talking about pushing more (in terms of frequency).

As a final confirmation, a last line of predictive questioning was offered. This was because Will's prediction was incorrect, and I was trying to see if he would self-correct upon thinking more about the topic.

> Int: You talked before a little bit about how pedaling might be different as you are trying to pedal the bike. What makes the pedaling feel different when you are in those different gears?
> Will: I guess with the smaller gear since it rotates a lot faster than the bigger gear, it [smaller gear] is easier to pedal because you don't have to apply much force to get it going but when you are on the larger gear you have to push harder to get it to rotate all around.

The interviewer – in his wording - deliberately avoided privileging an assertion that a specific gear configuration should feel as if it had less resistance and concentrated on unspecified differences in feelings. Will reiterated again that his statements implied that more push would be necessary for a larger gear to move. This was the extent of how he explained it, suggesting the resistance was ‘just because’ a gear was larger or smaller. I took this to mean that the gear size was being linked to intuitions about resistance.

As such, the predictive portion of the interview seemed to produce reasoning that was fairly consistent with itself (Fig. 7). There were instantiations of *Ohm's p-prim* and qualitative proportionalities that were tied to the size of the gears that were being discussed. At times, the number of teeth were registered as important rather than overall size (such as diameter or area of a gear). It was then time to pursue the enactment and explanation phases of the interview.

The Enactment of the Rides

For the enactment phase, Will was instructed to go as fast as he could in the pre-set gear such that he would pass a certain line ahead at the fastest speed possible before turning around. The interviewer asked Will to stay in the same gear for the ride.

The first gear configuration was with the smallest gear in the cassette (low gear). The second was with the largest (high gear). In both rides, the front chain-ring remained the same. When he rode the bicycle twice down the set path, it turned out that the slow acceleration was encountered first, and spinning out was encountered on the second ride. There were two noteworthy exclamations Will offered without solicitation that were captured on the GoPro camera that was attached to Will's helmet. On the first ride, just as he began and pressed his legs against the pedals, he stated “Oh, Goodness!”. On the second ride, when he began his first pedaling motions, he uttered “Yep!” as if it was confirmation for what he was expecting.

These moments are taken as indicative that Will was surprised by what riding felt like on the first ride, but then had new expectations as a result that were then confirmed on the second ride.

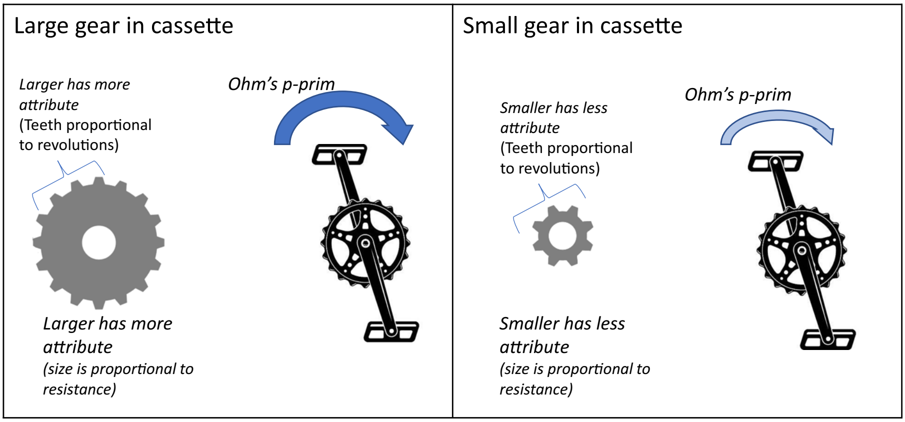

Fig. 7 Will's model of how effort and resistance were related given two different gear selections during the predict phase of the interview

Explaining after the Rides

Following the first ride when he exclaimed “Oh, Goodness!”, the interviewer made a neutral inquiry.

> Int: What was that like?
> Will: It was a lot harder than I thought it would be- since it is on the smaller gear I thought I would just be able to rotate a lot faster, and I wouldn’t have to push as hard, but I ended up having to push pretty hard and get up out of my seat to throw my body weight into it to get it going.
> Int: What do you think was going on with you and the bike that made it all happen?
> Will: I don’t know.
> Int: At some point when you are riding we heard you say “oh goodness”
> Will: That was because when I got on and started going I thought I’d be able to step down and get it going, but I almost lost my balance because I wasn’t prepared to push down on the wheels so it threw me off a little bit.

Clearly, this was different from what Will had said before the ride. When asked about his blurting of “Oh Goodness”, he recounted in some detail what he thought riding with the small gear would feel like and that it almost led him to lose his balance. In the same transaction, he also talked about having to get up out of his seat and pushing pretty hard. These statements suggest that the actual kinesthetic and sensory experiences were salient to him and this was a discrepant event. He had not simply slipped in his previous explanation prior to the ride, but rather by the time he enacted the ride in low gear, he had the expectation that it would be easier. He did not elaborate on the mechanism involved at this point.

The interviewer then asked Will to do the ride in high gear, which the interviewer changed for him. As he began the ride, he uttered “yup!” and completed the ride. When he had returned, he offered the following without solicitation.

> Will: Looks like I had my facts backwards. The bigger gear rotated a lot faster. I had to click it over (change to a lower gear) to come back. Going down it was a lot easier to get started and once I hit going fast enough I couldn’t pedal any faster to get the gear to rotate faster so I guess all my facts are just switched around with the two gears.

At that point, Will was demonstrating awareness that his pre-ride model was incorrect. This was because his “facts are just switched around with the two gears”. In order to see how he incorporated this into a post-enactment model, the interviewer probed further.

> Int: What you said before made sense. Why do you think this is what it ends up being?
> Will: I’m not sure. Maybe it is because going around, the gears rotate at the same speed so it is the same spot, so right here on this gear (points to part of the cassette) is the same as here on this gear (points to a part of the cassette) and when this one (small gear) rotates all the way around this one (large gear) will

> have rotated all the way around. So when it goes around it will come back right to the start at the same time. I guess what it is the bigger gear is easier to get going because it takes longer for it to rotate all the way around but with the little gear since it is the same as the big gear but with a smaller area it is harder to go all the way around, I guess.

As documented elsewhere (i.e., Sherin et al. 2012), a new explanation is being constructed in this portion of the interview. There are numerous discourse markers that are indicative of active sense making in this portion of the interview (Russ et al. 2012) such as hedging language ("I'm not sure, "Maybe", "I guess what it is").

His key observation was that the two different sized gears would need to rotate across the same angles to turn the wheel to which they were both attached. The corresponding portion of the outer circumference of the gears became a focal point for him ("with the little gear since it is the same as the big gear but with a smaller area"). *Ohm's p-prim* was still being invoked, but some of the slots associated with it were being filled in new ways. Rather than the gear's size (i.e., diameter or area) itself being the source of resistance, the portions of the arcs of each gear took on a more prominent roles (larger circumference). The gears would move at the same speed, but the amount of pedaling required to rotate the gear would increase. The amount of effort exerted on the crank would be less per pedal revolution when the rear gear was smaller.

After some exploration of this, he returned to thinking about the teeth on each gear and how the chain pulled on them to turn each gear and that would ultimately turn the bicycle wheel.

> Will: There needs to be a lot more work put into it [pedaling] because the teeth have to work harder to pull the chain all the way through when with the bigger one [gear] there is so many teeth it is easy to pull it all the way through.'

The explanation that Will was constructing involved seeing more work that the teeth needed to do when moving the rear wheel ("the teeth have to work harder") (Fig. 8). In the smaller gear, there were fewer teeth for a given portion of the rear wheel, so to accomplish the same amount of work, they had to work harder (which was *Ohm's p-prim* applied to the teeth). With more teeth that would travel the same arc, there would be many teeth, making it "easy to pull it all the way through". The qualitative proportionality changed to an inverse proportionality such that the more teeth involved, the less work was required because more teeth taking on the same amount of work would be less work for each tooth. With the pedaling being where the work of the teeth originated, this was still Ohm's p-prim with the cyclist providing the effort, but now the resistance changing. In all, this ended up being a reconfiguration of his earlier model of how gear size, teeth, the rear wheel, and pedaling were related with an inverse proportionality being introduced. Teeth and arc length became salient and the number of rotations – the original source of resistance – was then held constant. This new version was more commensurate with what Will had just experienced.

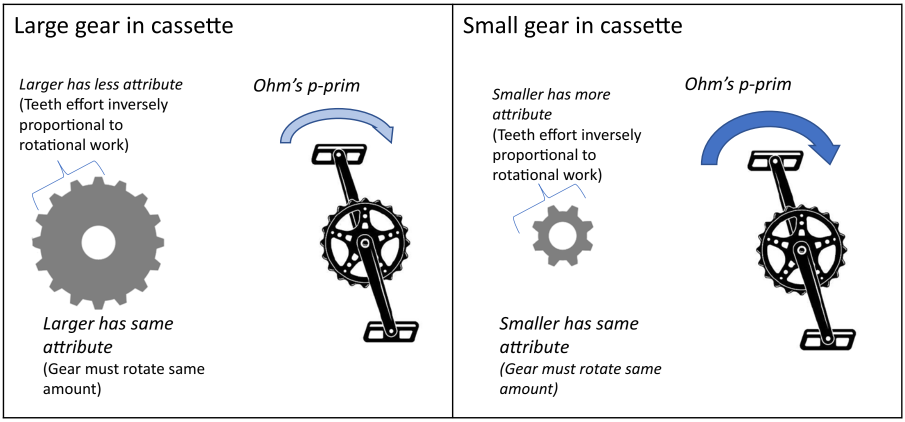

Fig. 8 Will's new explanations for how effort and resistance were related and implicated gear teeth given two gear selections

Summary

With these two cases, we saw students offer changing explanations in response to the same situation. The driver of the change was the opportunity to enact the situations that were being discussed. It turned out for both of these students, these produced discrepant experiences relative to what they had predicted. As a result, there was some effort to reconcile how they would explain those situations.

In both cases, we saw that many of the same ideas were used. With Carina, she focused on some resistance coming from drag, as well as gravity. With Will, there was a focus on effort in pedaling and some sort of resistance associated with making the wheel of a bicycle turn. The prominent explanatory primitives were Ohm's p-prim as well as some qualitative proportionalities in which a change in some attribute would correspond to a similar change in a different attribute. Stated simply, the knowledge elements involved were largely the same.

There were also features that were noticed differently in the situation. These included weight, as perceived by muscle exertion, size as determined by visual appraisal, effort as perceived by leg muscle exertion, and the presence of some features on a given apparatus (such as teeth on a gear). These appeared both before and after students enacted the activities in the interviews.

What seemed to happen was that the connections between these various elements changed to produce a model, which could have been fairly ephemeral, that linked the perceived aspects with the underlying explanatory primitives in new ways. New ideas were not added, although experiences and sensations contradicted the predictions. Previous knowledge elements and observations were retained but momentarily reorganized.

It is through these momentary re-organizations where I believe we see conceptual dynamics in response to discrepant experiences at work. The discrepant experience that was encountered in the interview forced change because of immediate sensory and physical experience. However, the efficient option for these two students appeared to be to try new configurations before abandoning any knowledge elements. Much of the discourse around students' misconceptions highlights their resistance to change in light of corrective feedback. However, it may be that change takes place but does so in an ad hoc manner and with the ways in which the same knowledge is organized. If that is an accurate characterization, then the desirable kinds of conceptual change – where a correct model would be formed immediately and verified – may require a number of encounters and opportunities for explanation of those encounters so that the desirable configuration becomes the default one. It is also worth noting that there seemed to be an element of surprise that drove these changes (i.e., when Will uttered "Oh goodness!"). It may be that creating expectations and experiencing the unexpected serves as an important part of eventual knowledge restructuring. Indeed, this elicitation of curiosity – which can be through surprise and encountering the unexpected - has been noted as an important feature in designed science curricula (Edelson 2001). There can be value in surprising students so as to motivate new learning.

Discussion

This pair of cases ultimately adds to the program of research that seeks to detail conceptual dynamics during interview interactions. In that program of research, some of the debate about coherence of students' conceptual understandings of the natural world are attributed to features of method. That is, in some lines of questioning, students may appear to have knowledge that is theory-like. In other lines of questioning, they may appear to have knowledge that appears to form multiple temporary coherences. The two cases are examples of the latter. The coherences retained many of the same elements but took on different organizations, making the changes subtle but pronounced enough that it makes a theory theory view of student knowledge in this situation more tenuous. What was perceived as relevant by students changed and gained more salience as new coherences formed.

We already know that follow-up lines of questioning can produce this effect, as can the introduction of drawings (Sherin et al. 2012). This has also been detailed in an interaction analysis of tutoring and clinical interview interactions around a chemical phenomenon (DeLiema et al. 2016). These short time-scales of change can also be seen with the use of computational representations (Parnafes 2007). What is added from the current study is the account of how physical experience, with different perceptual features being extracted as movements are produced and enacted can also play a role in driving change. This current study also adds to the extant literature on discrepant experiences (e.g., Tao and Gunstone 1999) and how those impact student thinking, albeit this was done from a knowledge in pieces perspective. That provided for a fine-grained accounting of what changed and what stayed the same over the matter of a few moments of interaction.

This work represents a different approach to interviewing, with a privileging of physical experiences and probing of ideas immediately. I make no claim that this is inherently superior to other techniques that one could use to elicit student thinking, such as think-aloud protocols or stimulated recall interviews. In some respects, this is a type of think-aloud process with specific physical experiences made the topic of interest. Students are reporting on their ideas as they are being cued and formed into explanations. Taken as such, it provides means for examining conceptual dynamics in interview interactions. We have the potential for seeing and tracking knowledge in moments that are surprising or unexpected as they unfold, which may be different from what is recalled retroactively and in the form of explanations of recently experienced physical situations. In a more traditional think-aloud, there may not be the same press on the student for explanations or reconciliation of ideas.

While it is several steps removed, there are some kinds of implications we could draw from work for teaching and learning. One fairly uncontroversial one is the recognition that there can be value in having students predict, experience, and work through explaining embodied phenomena. This is a recommendation for teaching made elsewhere (Stavy and Berkovitz 1980; Strike and Posner 1992). Take for example the common physics demonstration of holding a spinning bicycle wheel while sitting in a chair that can rotate. Often, this is done with a physics teacher providing the demonstration, but having students feel the conservation of angular momentum as they change the orientation of the wheel might attune them to specific perceptual features when they model and explain that phenomenon. Similarly, when examining the thermodynamics of wood and metal heated to the same temperature, there may be a real chance to reflect upon and examine why the wood doesn’t feel as hot (immediately) while a thermometer can report the same temperatures. The current work suggests that these sorts of activities could benefit from being more than thought exercises or demonstrations and instead be phenomena for students to experience and examine. Doing so could lead to slight reconfigurations of knowledge and also motivate the need for explanation that is in line with accepted science principles. These could represent subtle but consequential modifications to the predict-observe-explain approach to demonstrations that has proven successful in the past when eliciting and probing student understanding (White and Gunstone 1992).

For teaching, it means being prepared to anticipate what students will notice in an embodied experience and to consider how perception must be factored into explanations. Experiencing and explaining an immediate and embodied discrepant experience is not a guarantee of a normative understanding resulting, but it does open the door for change in how knowledge is organized, even if momentarily. It can also be useful to think about how to direct perception to support learning. Consider for example that reflected light is necessary for a non-luminescent object to be seen. Many students are used to sitting ‘in the dark’ and still being able to see, thus making the explanation that reflected light is essential one that contradicts with past experience. If this were to be immediately experienced, a thoughtful instructor may direct students to look at and notice where light is entering a ‘dark’ room and make sure they are attuned to that perceptual information in order to help them understand the role that visible light plays. Informally speaking, I had many years ago observed a well-intentioned science teacher do a classroom demonstration like this once (Lee 2008), but he did not direct student attention to sources of light that were entering the room. As a result, in post interviews with students revealed that they did indeed believe that one could ‘see in the dark’ and that they had evidence of that from class. By thinking carefully about how to create the discrepant experience and also how to direct perception, we might be able to better execute such an activity and subsequent discussion.

Overall, this article has hopefully served to reiterate that there are conceptual dynamics at work in interviews that we can elicit and document and that doing so can have value. That value comes in the way that we theorize student knowledge and its stability. It also helps to spotlight to what features of a given setting that student knowledge can exhibit sensitivity. Knowing those more precisely should help us improve our understanding of both the research and practice of STEM education, and particularly the sciences.

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